Title

A Contribution to the West Coast Regional Carbon Sequestration Partnership (WESTCARB), Phase II

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Publication Date

2012-02-01

Public Interest Energy Research (PIER) Program

FINAL PROJECT REPORT

A Contribution to the West Coast Regional Carbon Sequestration Partnership (WESTCARB), Phase II.

Prepared for: California Energy Commission

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FEBRUARY 2012

CEC-500-02-004

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ACKNOWLEDGEMENTS

Since 2006 when this contract was implemented, many people have assisted us in various aspects of the execution of the work leading to this report, most of whom are acknowledged in the appended reports. In addition we would like to express our gratitude to Pat Ross (Princeton Natural Gas, Inc.) for making available the Citizen Green #1 well and his enthusiasm for the Northern California Characterization Well task. We wish to acknowledge guidance from Energy Commissioner Jim Boyd and California Energy Commission staff Mike Gravely, Beth Chambers, Bryan Lee, and from John Litynski, Dawn Deel, and Brian Dressel at the US Department of Energy's National Energy Technology Laboratory. We are especially grateful to Gilda Garcia (California Institute for Energy and Environment) for her expert assistance in preparing the final version of this report.

PREFACE

The California Energy Commission Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

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- Renewable Energy Technologies
- Transportation

A Contribution to West Coast Regional Carbon Sequestration Partnership (WESTCARB), Phase II is the final report contributing to the WESTCARB Phase II project (contract number 500-02-004, work authorization number 045 conducted by the California Institute for Energy and Environment, University of California. The information from this project contributes to PIER's Energy-Related Environmental Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

ABSTRACT

The West Coast Regional Carbon Sequestration Partnership (WESTCARB) is one of seven partnerships that have been established by the U.S. Department of Energy (DOE) to evaluate carbon capture and sequestration (CCS) technologies best suited for different regions of the country. The West Coast Region comprises Arizona, California, Hawaii, Nevada, Oregon, Washington, Alaska, and British Columbia. Both terrestrial and geologic sequestration potential has been evaluated in the Region during Phase II of the project. A centralized Geographic Information System (GIS) database of stationary sources and geologic and terrestrial sink data was enhanced, incorporating relevant project data.

Research work completed under a contract from the California Energy Commission to the California Institute for Energy and Environment (CIEE), University of California, includes the following as part of WESTCARB Phase II:

1. Regional geological characterization, encompassing Alaska, Washington, Oregon, and California. Revised storage estimates are provided.
2. RTIP provides an overview of the status of CCS technology evolution and adoption.
3. Regional Technology Implementation Plan provides an overview of the status of carbon capture and storage technology evolution and adoption in Western North America.
4. Contributions to the regulatory aspects of CCS in California, by providing technical support to the California Carbon Capture and Storage Review Panel. This contract also contributed to research on public acceptance of CCS projects and gained outreach experience in pilot projects.
5. CIEE completed a characterization well situated in Northern California from which useful characterization results were obtained, including initial work on seismicity.
6. An assessment of terrestrial sequestration potential in Washington, Oregon, California, and Arizona is presented in detail. An analysis of fire hazard reduction measures did not achieve anticipated CO_2 emissions. This report reviews afforestation potential land fuels management practices in northern California and south-central Oregon, as well as the potential for fast-growing tree species to generate carbon credits. The rapid development of forested areas to urban use in the Puget Sound area of Washington is evaluated in the context of a potential sequestration loss.

Keywords:

Carbon capture and storage (CCS), carbon sequestration regional partnerships, regional geological characterization, geological sequestration, terrestrial sequestration, carbon dioxide, greenhouse gas (GHG), afforestation, fire fuels management, carbon market validation, geological storage estimates.

Please use the following citation for this report:

Mateer, Niall; Beyer, John Henry; Burton, Elizabeth; Goslee Katie; Hwang, Lorraine; Myer, Larry; Myhre, Richard; Stone, Marian. 2012. ***A Contribution to the West Coast Regional Carbon Sequestration Partnership (WESTCARB), Phase II. California Energy Commission***. Publication number: CEC-XXX-XXXX-XXX

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ACRONYMS

1. AGRC – (Utah) Automated Geographic Reference Center
2. Bcf – billion cubic feet
3. CBM – Coalbed methane
4. C – Carbon
5. CBM – Coal Bead Methane
6. CCS – Carbon capture and sequestration (storage)
7. CDOC – California Department of Conservation
8. CEQA – California Environmental Quality Act
9. CGS – California Geological Survey
10. CH_4 – Methane
11. CO_2 – Carbon dioxide
12. CRT – Certified Reserve Tonne
13. DOGGR – Division of Oil, Gas, and Geothermal Resources
14. DWR – (California) Department of Water Resources
15. DOE – United States Department of Energy
16. ECBM – Enhanced coal-bed methane
17. EGR – Enhanced Gas Recovert
18. EOR – Enhanced oil recovery
19. FFE – Fire and Fuels Extension
20. EPA – United States Environmental Protection Agency
21. FIA – Forest Inventory and Analysis
22. FRAP – Fire and Resource Assessment Program
23. FVS – Forest Verification Simulator
24. GCS – Geological Carbon Storage
25. GHG – Greenhouse gas
26. GIF – (University of California Berkeley) Geospatial Information Facility
27. GIS – Geographic information system
28. Gt – gigatonnes (billion metric tons)
29. LBNL – Lawrence Berkeley National Laboratory
30. LCMMP –Land Cover Mapping and Monitoring Program
31. LLNL – Lawrence Livermore National Laboratory
32. MBF – Million Board Feet
33. mD – millidarcies
34. $MMTCO_{2e}$ – Million metric tons carbon dioxide equivalent
35. MMV – Measurement, monitoring, and verification
36. Mt – Million tonnes
37. MW - megawatt
38. NaCl – Sodium Chloride (salt)
39. NBMG – Nevada Bureau of Mines and Geology
40. NEPA – National Environmental Policy Act
41. NGCC – Natural gas combined cycle
42. NGO – Non-governmental Organization
43. NO_2– nitrous oxide

44. RCSP – Regional Carbon Sequestration Partnership
45. RTIP - Regional Technology Implementation Plan
46. SECARB – Southeast Regional Carbon Sequestration Partnership
47. Tcf – trillion cubic feet
48. UIC – underground injection control
49. USGS – United States Geological Survey
50. WESTCARB – West Coast Regional Carbon Sequestration Partnership

EXECUTIVE SUMMARY

Background

The West Coast Regional Carbon Sequestration Partnership (WESTCARB) is one of seven Regional Carbon Sequestration Partnerships (RCSPs) established by the U.S. Department of Energy (DOE) to evaluate the carbon capture and sequestration (CCS) technologies best suited for different regions of the country. The WESTCARB region comprises Alaska, Arizona, California, Hawaii, Nevada, Oregon, Washington, and the Canadian province of British Columbia. CIEE under contract by the CEC, undertook and managed a significant portion of the Phase II effort via 22 subcontracts and inhouse resources. WESTCARB is a consortium of about 90 organizations, including state natural resource and environmental protection agencies; national laboratories and universities; private companies working on carbon dioxide (CO_2) capture, transportation, and storage technologies; utilities; oil and gas companies; nonprofit organizations; and policy/governance coordinating organizations. Both terrestrial and geologic sequestration potential have been evaluated in the region during Phase II of the project. A centralized Geographic Information System (GIS) database of stationary sources and geologic and terrestrial sinks was enhanced by incorporating relevant project data. The California Institute for Energy and Environment (CIEE) was contracted by the California Energy Commission to manage and undertake a significant portion of the WESTCARB Phase II activity via 22 subcontracts and its own staff. The five major areas of research are addressed in this report are:

Regional Geological Characterization

Studies of geologic sequestration potential in Alaska indicate that the saline and coal sequestration potential are highest in the Cook Inlet basin in south-central Alaska and in a limited area on the central North Slope. Both regions have been subject to significant hydrocarbon exploration increasing the amount of data available and infrastructure in the region. Estimated storage capacity for deep unmineable coal seams in the Northern Alaska Province, Nenana Basin and, Cook Inlet Basin is 49.24 Gt. The sequestration potential in those two locations is likely to be more than adequate to handle the volumes of CO_2 available for capture in Alaska for many years.

Revised estimates in millions of tonnes for the California oil and gas fields ranges from 3,371 (low) to 6,455 (high).

The potential for geological sequestration in Nevada by natural chemical interaction with mafic rocks is limited by unproven technology. Sequestration through enhanced oil recovery mechanisms is possible but at insufficient quantities to warrant commercial development.

Onshore in Washington, the Puget Trough has by far the largest potential for CO_2 sequestration, with average mass estimates ranging from 86.4 to 345.4 Mt. The remaining four Washington basins have a combined average resource potential of between 3.9 and 15.5 Mt. In Oregon, the four onshore basins have a combined average resource potential of between 16.7 and 66.9 Mt. The Tyee-Umpqua Basin has the largest potential in the state, constituting 63% of the Oregon total. Offshore Oregon and Washington sedimentary basins resource estimates range from 0.8 Mt to 3.1 Mt for the smallest basin

(Newport; 4% of the offshore total) to 7.48 Mt to 29.9 Mt for the largest basin (Heceta; 35% of the offshore total).

Outreach

The California legislature requested a report on mechanisms by which California could accelerate the adoption of cost-effective geological sequestration strategies for long-term management of industrial CO_2. The preliminary recommendations focused on identifying the information needed for the state to progress toward commercialization of CCS technology rather than proposing adoption of specific statutory or regulatory actions. The report recommended that (1) any state planning involving energy or greenhouse gas emissions reduction strategies should include consideration of carbon capture and sequestration options, (2) further examination for carbon capture and sequestration adoption based on potentially close-to-favorable business cases. These opportunities may have greater value than as niche applications and may facilitate creation of an in-state market for CO_2 by demonstrating enhanced oil and gas production, (3) closely study other demonstration projects that provide key data to set carbon capture and sequestration policy, (4) California's power imports encourage consideration of carbon capture and sequestration in a regional context. Coordinated investigations of carbon capture and sequestration for power plants should take place involving other states in the Western Electricity Coordinating Council region. This should be done in the context of recognizing the connection between regional climate change and electricity generation objectives and involve consideration of how carbon responsibility should "flow" with electricity.

In early 2010, a California Carbon Capture and Storage Review Panel was assembled to look at regulatory and statutory barriers to implementing CCS in California. The Panel, composed of experts from industry, trade groups, academia, and environmental organizations, was asked to:

- Identify, discuss, and frame specific policies addressing the role of CCS technology in meeting the State's energy needs and greenhouse gas emissions reduction strategies for 2020 and 2050.
- Support development of a legal/regulatory framework for permitting proposed CCS projects consistent with the State's energy and environmental policy objectives.

The Panel held five public meetings in 2010 to arrive at its findings and recommendations. These meetings were designed to solicit input from technical experts and key stakeholders and to allow the Panel to deliberate in an open, public setting. WESTCARB researchers served on the Technical Advisory Committee to the Panel, providing technical expertise through white paters and presentations during the Panel's deliberations.

WESTCARB's outreach activities at both the Arizona and California pilot storage sites provide valuable lessons for future CCS activity in the region. In addition, research was conducted on public perceptions of CCS in local communities. Early engagement and empowerment of local communities is of particular value in assuring the acceptance of CCS projects

Regional Technology Implementation Plan.

The RTIP examines carbon capture and storage in six areas: policy and regulatory development, technology infrastructure, economics, project finance, legal considerations, and public acceptance.

The RTIP concludes that geological storage does not face significant barriers in the western region in term of storage space or the technical feasibility of injecting and monitoring CO_2 in the subsurface. Three significant challenges for geological CCS projects are identified:

- Lack of climate change legislation to serve as a driver for CCS development, and a lack of a clear pathway for CCS where climate change legislation exists.
- CCS developers are currently challenged to make a business case for a government-supported demonstration, let alone a commercial project.
- Geological CO_2 storage is often not well understood by the public, although misconceptions can be corrected through outreach and education. This takes time, resources and goodwill.

Terrestrial carbon storage faces four main challenges:

- Limitations on support due to lack of climate change legislation or policy frameworks,
- Carbon regime integrity that requires GHG reductions to be verifiable, enforceable and permanent,
- Competition from other land uses, such as high-value crops and commercial development,
- Climate change impacts on habitats, and a need to incorporate adaptation planning into long-term terrestrial carbon storage planning.

Geological Storage Pilot Project

Northern California Pilot Well – A thorough characterization of the subsurface in the Thornton area, south of Sacramento was completed in a depleting gas field. However, withdrawal of the industry partner prevented completion of this well. A second site in the Montezuma Hills area was developed and characterized in conjunction with a different industry partner. This too did not materialize when the industry partner withdrew from the project. However, useful modeling on induced seismicity and on leakage risk assessment, which was gained during initial work at the Montezuma Hills site, is summarized in this report.

Terrestrial Pilots Projects

A number of projects were completed by WESTCARB to characterize the role of terrestrial resources in sequestering CO_2 in the region.

Emissions from fire were identified in WESTCARB Phase I as the single largest source of GHG emissions from land use. Research was undertaken to determine if GHG emissions from wildfire could be reduced and provide a potential opportunity for landowners to generate revenue from the sale of carbon offsets. The conclusions are that (1) the fire risk is very low (<0.76%/year), (2) treatment emissions are relatively high and are incurred across the entire treated area, (3) treatment never reduces fire emissions by more than 40% and on average across five sites only reduced emissions by 6%, (4) in the absence of fire, treatment reduces sequestration, (5) retreatment will have to occur with accompanied emissions, and (6) the positive impact of treatment beyond the treated area is not guaranteed and is unlikely to ever be large enough to impact net GHG emissions. Thus, low fire probability is combined with high emissions and low sequestration in the absence of a fire and relatively few emissions reductions in the event of fire.

The fuels management treatments conducted by WESTCARB researchers resulted in overall carbon emissions, and have negative implications for the future potential of fuels treatments as a carbon projects offset category. A significant net emission is apparent despite the benefits from fuels treatments, such as increased ability to successfully fight fires and decreased cost of fire fighting; reduced loss of life and property; and reduced potential damage to wildlife habitat. The results from this study underscore the unsuitability of fuels treatment as a potential GHG offset generating activity. Thus, it is recommended that a shift be made to policies minimizing GHG emissions from wildfires and from fuel treatments, while minimizing wildfire risks to lives, homes, and wildlife habitat in the WESTCARB region.

The Bascom Pacific Forest, California, was the site for demonstrating how baselines and project activities associated with the conservation-based management of a commercially productive forestland site would be interpreted and projected on this site if a CO_2 emissions reduction project were undertaken in accordance with the California Climate Action Registry Forest Project Protocol (Version 2.1). At the LaTour State Forest, California, improved forest management project types on private lands had economic returns of \$217 and \$649 per acre (\$536 and \$1,603 per hectare) assuming a price of \$9.00 a tonne CO_2e. At \$20.00 a tonne CO_2e the economic returns were \$585 and \$1,568 per acre (\$1,445 and \$3,873 per hectare). The use of CVal software rapidly produces an economic analysis of a project based on carbon income and project costs, and is an excellent example of the type of analytic tools needed to build rational ecosystem services markets.

Forests and rangelands in California were responsible for a net removal of CO_2 from the atmosphere of 24.95 $MMTCO_2e$/year. Non-CO_2 GHG emissions from forest and range lands were estimated to be 0.16 $MMTCO_2e$/year, or equivalent to about 0.76% of the removals by these systems. The overall net result was a removal of 23.01 $MMTCO_2e$/year by forests and 1.94 $MMTCO_2e$/year by rangelands.

Afforestation represents the largest single terrestrial carbon sequestration opportunity across the WESTCARB region, and could make a substantial contribution toward the GHG emission reduction goals. It may also offer landowners near-term opportunities to participate in rapidly evolving GHG reporting registries, offset markets and other carbon credit sale opportunities under voluntary and regulated markets. In Shasta County, California, based on 476 acres and twelve landowner agreements, projections of net carbon stocks for conifer plantings after 100 years ranged from 53 to C/acre to 111 to C/acre. The native oak planting had projected net carbon stocks of 24 t C/acre after 100 years. Survival of planted conifer seedlings was high, despite limited rainfall in the year of planting. Project costs ranged from \$354/acre to \$1,880/acre.

Hybrid poplar (*Populus* spp.), a short rotation woody crop, is of growing interest in the West Coast states of California, Oregon, and Washington because of its potential as a bioenergy crop or multiple wood products crop in combination with the potential revenue from carbon credits. Most of the prime lands ideal for hybrid poplar, and where no irrigation or limited irrigation would be needed, are located on the western side of the Cascade Mountains in Oregon and Washington. Washington has approximately 8 million acres of eligible lands, with 82% needing irrigation, 8% needing limited irrigation and 9% needing no irrigation. Oregon has 5 million acres in total, with 59% needing irrigation, 27% needing limited irrigation, and 13% needing no irrigation. California had the most total land eligible, with 14 million acres. However, 96% of the land would need irrigation, with only

3% needing limited irrigation and less than 1% needing no irrigation. If irrigation is supplied to areas where moisture availability is limited, the amount of highly suitable land throughout the West Coast region more than doubles. Growth and yield of hybrid poplar averages from 8-11 green tons/acre/year of above ground biomass on highly suitable sites with ample water, 6-8 green tons/acre/year on moderate sites, and 4-6 green tons/acre/year on poor to moderate sites. This growth and yield relates to approximately 3-4 t C/acre/year on highly suitable sites, 2-3 t C/acre/year on moderate sites, and 1-2 t C/acre/year on poor to moderate sites. Over a 6 year rotation, approximately 20 t C/acre could be achieved, and over a 20 year rotation, 81 t C/acre.

In Arizona, riparian areas are limited and need proper management and restoration to provide carbon sinks. Of approximately 3 million acres (1.2 million hectares) of riparian areas across the state of Arizona, riparian ecosystems account for 4% of the total state area, mostly in Yuma, La Paz and Pinal County (10%, 9%, and 9%, respectively). The estimation of suitable riparian areas on very high geophysical potential accounted for approximately 1.4 million acres (566,000 hectares) for forestation with cottonwood/willow or mesquite, 500,000 acres (202,000 hectares) for forestation with mixed broadleaf trees, and only 7,000 acres (3,000 hectares) for forestation with conifer oak.

Baseline carbon stocks for the forest and agricultural sectors in Arizona during the most recent 10-year period for which data are available identify opportunities where carbon sequestration might be increased through changes in land use and management. An estimated 219,000 hectares (541,000 acres) of forest on federal and non-federal lands were gained in Arizona between 1987 and 1997 at a rate of 21,935 hectares/year (54,201 acres/year). These gains are equivalent to 0.28% of the forest area per year between 1987 and 1997. A gross sequestration of an estimated 9.2 million tonnes CO_2 equivalent ($MMTCO_2e$) occurred between 1987 and 1997 (0.92 $MMTCO_2e$/year) and 42.7 $MMTCO_2e$ (7.1 $MMTCO_2e$/year) between 1997 and 2003. The sequestration rate estimated in a previous study for the State of Arizona in 2000 exceeds the rate predicted in this study, probably due to methodological and terminological differences. Carbon sinks could potentially offset as much as 7% of Arizona's emissions. For just non-federal forested lands, there was a net loss of 69,000 hectares (170,000 acres). Ninety percent of the loss in forested area occurs in the northern counties of the state. This report further provides development, agricultural, and fire baseline data.

The conversion of forest lands to non-forest uses, especially conversion to residential development, is of significant concern to the State of Washington. As a result of a rapidly growing population, the risk of conversion is especially high in Puget Sound's watersheds, where 80% or more of the remaining private forestlands not enrolled in the Designated Forestland Program are at high risk, and in some counties growth controls have exceeded targets. It is estimated that net emissions across three counties of over 7 million tons of CO_2 equivalent per year or 45% of the total from development across the whole state.

The nascent carbon offset market offers a venue for directing funds to innovative terrestrial sequestration project concepts, but must be validated against commonly used criteria for the carbon offset market.

As biochar projects develop and seek to sell their climate benefits as GHG offsets to regulated emitters under a cap-and-trade program, pilot projects are needed for carbon market protocol development.

1.0 SUPPLEMENTAL REGIONAL GEOLOGIC SEQUESTRATION OPPORTUNITY ASSESSMENT

This task was to refine the WESTCARB Phase I (see PIER Contract# 500-02-004, WA# MR-021) geologic characterization of promising geologic formations in Nevada, Oregon, and Washington, and to assess the mineralization-based sequestration potential of mafic and ultramafic rocks in Nevada. In Alaska, this project characterized sedimentary basins outside the North Slope. New characterization data was integrated into the WESTCARB GIS data clearinghouse maintained by the Utah Automated Geographic Reference Center (AGRC) and later by the University of California Berkeley Geospatial Information Facility (GIF).

1.1. Assessment of Geologic Storage Capacity in Alaska

WESTCARB under took two studies examining the CO_2storage capacity in Alaska's deep coal seams and onshore and offshore saline basins (See Appendices 1 & 2). The initial study summarized available geologic information, structural and formation properties for the region and developed initial estimates of storage capacity. The subsequent study considered factors unique to the Alaska environment to constrain previous estimates and applied new data to revise initial coal storage estimates. The revised estimates show that the saline and coal sequestration potential are much lower than initial estimates, and are considered "high" only in the Cook Inlet basin in south-central Alaska and in a limited area on the central North Slope. The sequestration potential in those two locations is likely to be more than adequate to handle the volumes of CO_2 available for capture in Alaska for many years.

Storage in Deep Saline Basins

Alaska's saline aquifer sandstone formations have far greater CO_2 storage capacity than its deep coals. The thickness, lateral and depth distribution, and reservoir quality of sandstone formations in eight of Alaska's largest sedimentary basins, both onshore and offshore, were mapped and analyzed with the exception of the Cook Inlet. The Chukchi Sea and North Slope regions stand out as having particularly large CO_2 capacity. In particular, the Cretaceous Nanushuk Formation in the Colville basin (North Slope) and Chukchi Sea region is a widespread and attractive potential storage unit.

The next five basins with the largest sequestration potential - the North Aleutian/Bristol Bay, St. George, Navarin, Beaufort Sea, and Gulf of Alaska basins, contribute to less than 10% of the overall CO_2 storage potential. Each basin has its unique geologic setting as well as challenges. The eighth basin, the Norton basin, is rather small and has thinner, more limited sandstone targets. Details analyses of these basins can be found in Appendix 1.

All of these basins, particularly the Beaufort, are located in operationally difficult areas challenged by persistent and mobile ice flows. Incorporating additional factors for sedimentary basins such as known and expected water salinity, tectonic environment, distance from infrastructure, as well as difficulties in working in the offshore environments, will significantly constrain resource estimates.

Improved screening data for saline basins were obtained by integrating:

- Amount and quality of data available to screen the basin

- Likelihood of sufficient porosity and permeability, traps, and seals
- Distance from infrastructure and sources of CO_2
- Likely depositional environment (impacting predictions of salinity)
- Contribution of seismic (tectonic activity) risk to long-term storage

Sequestration potential, as shown in Figure 1, is a qualitative estimate of the likelihood a particular basin will be suitable for geologic sequestration of CO_2, and is based on the analysis of the above attributes (see Appendix 2 for more details). Factors that most impacted the ranking were:

1. Degree of uncertainty on the presence of reservoir, seal and trap. This follows from the kinds and types of data available to describe a basin. The attributes describing the number of exploration wells and amount of seismic data were vital in determining the degree of uncertainty. For the many basins defined primarily on gravity data (little or no well or seismic data collected), the degree of uncertainty is very high. If the knowledge of reservoir, seal or trap is very low this leads to a sequestration potential categorization of 'Low.'

2. Hydrocarbon exploration activity. If wells are being drilled or planned in a basin, the sequestration potential is rated higher, as oil and/or gas exploration success would provide both a confirmation of reservoir, seal and trap as well as improvements to infrastructure. For those basins with current exploration interest, further exploration with well log and seismic data will increase the knowledge base leading to higher ranking of potential. For the Nenana, Yukon Flats, and much of the Colville basin the sequestration potentials were raised from 'Low' to 'Moderately Low' based on exploration interest.

3. Distance from infrastructure. Many basins are far from CO_2 sources and the road system. Offshore basins (with the exception of the Cook Inlet Basin) are considered inaccessible to reflect that working offshore in harsh weather environments and ice coverage is currently not economically feasible. However, oil or gas exploration success in one of those basins could also prove up sequestration potential for CO_2 emissions generated as part of oil and/or gas production operations.

4. Hydrocarbon production. Current evidence of hydrocarbon accumulations is weighted heavily. For example, the Cook Inlet Basin is categorized as 'High' sequestration potential, in spite of the fact that it is also in the highest category of seismic risk. The trapped hydrocarbons are proof that the high current seismicity does not impact the sealing capacity for reservoirs in this basin.

Pore space will not be the limiting factor in the successful implementation of CCS in Alaska; it will be the economics of capture and transport. The high storage potential that exists in the proven oil and gas basins on the North Slope and the Cook Inlet (in enhanced hydrocarbon recovery, in depleted fields, and in saline reservoirs near, above and below hydrocarbon reservoirs) needs to be further delineated in order to maximize the potential of geologic sequestration in Alaska. Detailed studies are needed to further delineate the sequestration potential in:

- Enhanced oil recovery in the existing North Slope oil fields
- Enhanced oil recovery in Cook Inlet oil fields

- Depleted oil and gas fields
- Saline reservoirs already delineated in and around the existing North Slope and Cook Inlet fields, and
- Undiscovered saline reservoirs, using the US Geological Survey reserves estimation methodology

It is important to obtain realistic estimates for storage potential in Alaska's saline basins. That information, along with significantly improved economics for CO_2 capture, transport, injection, and long-term monitoring, and the establishment of laws and regulations for CO_2 storage, will maximize the chances of effective implementation of CCS technology in Alaska.

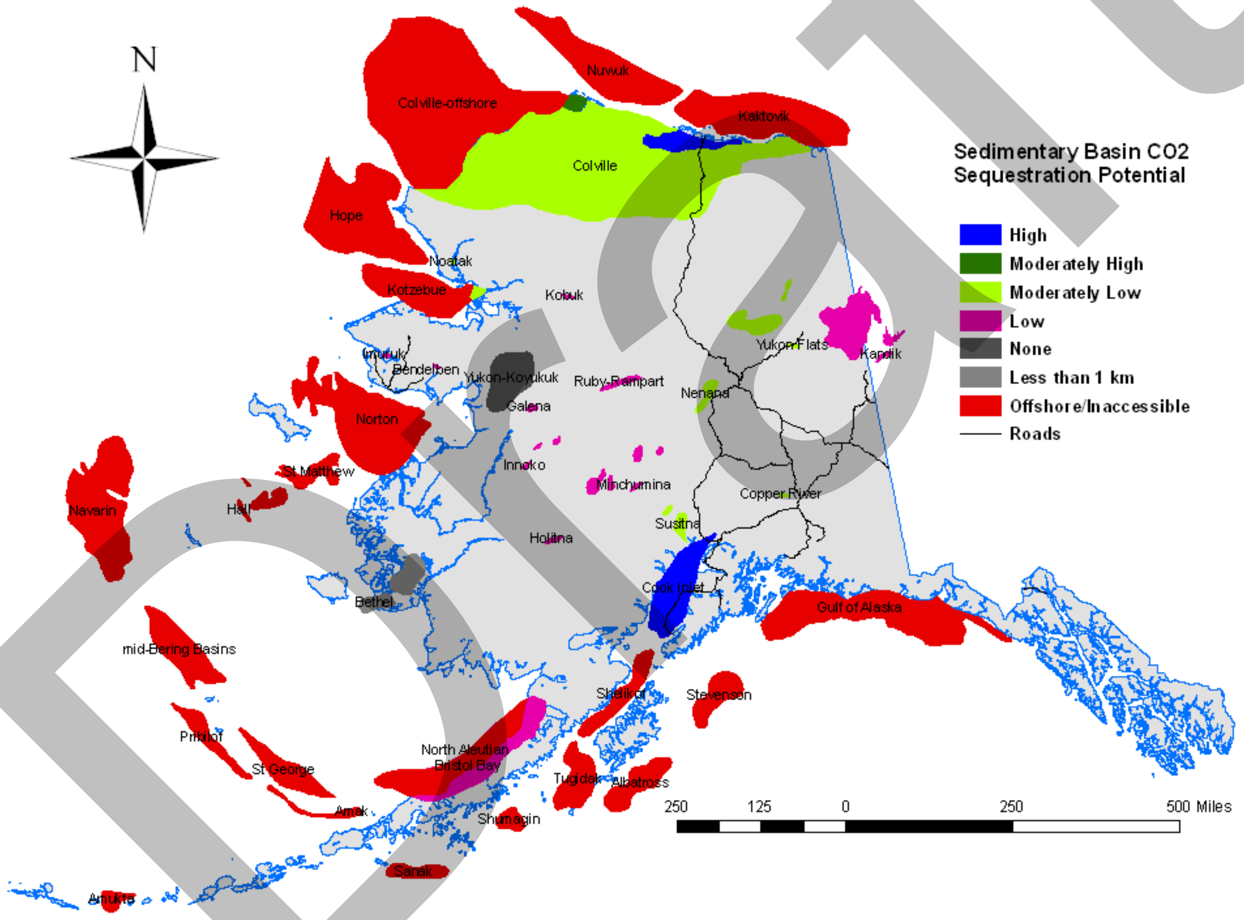

Figure 1 Alaska Saline Sedimentary Basin CO_2 Sequestration Potential

Storage in Deep Coal Seams

Alaska has enormous deposits of coal, with hypothetical coal resources estimated to be in excess of five trillion metric tons. Nineteen onshore basins are initially screened for their sequestration potential incorporating factors such as coal rank, coal volume, coal quality, coalbed methane presence and quantification, coal permeability, and permafrost presence and depth (Figure 2). See Appendix 2 for details.

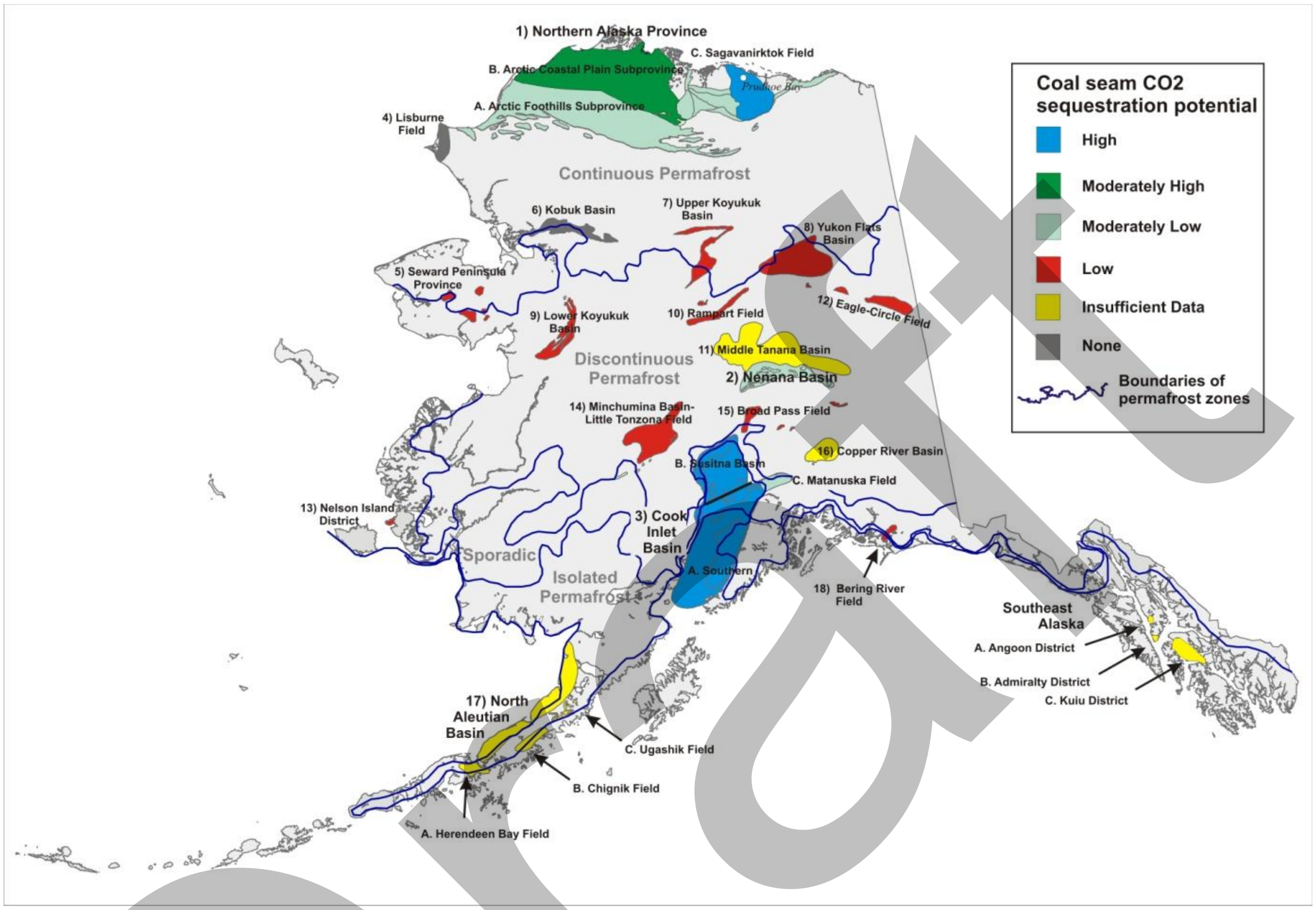

Figure 2 Alaska Coal Seam CO_2 Sequestration Potential

The vast majority of Alaska's coal resources occur in three major geologic provinces: 1) Northern Alaska Province, 2) Nenana Basin and, 3) Cook Inlet Basin. These provinces have sufficient and reliable subsurface and coal quality data to make reasonable estimates of CO_2 coal seam storage capacity and are in proximity to existing or potential future infrastructure. These areas have also demonstrated coalbed methane potential from both published reports and unpublished information. Appendix 1 and 2 contain detail descriptions of the geology, gas infrastructure, coal resources, CBM resources and CBM testing for these regions.

A preliminary published estimate of Alaska CO_2 coal seam storage capacity for the WESTCARB project, based on an estimate of 776 Tcf CBM resources, was 84 Gt. This estimate was subsequently revised to 120 Gt of CO_2 storage capacity. Factors such as permeability, seam geometry, surface access, faulting and site-specific conditions remained unaccounted. Details on coal cleating and fracture density, along with coal seam porosity is totally lacking in the available literature. However, using improved estimates of permafrost thickness and CO_2:CH_4 storage ratios based on varying coal rank, storage capacity estimates have been revised downward to 49.25 Gt (see **Error! Reference source not found.**, column 8).

(1) REGION	(2) IDENTIFIED & HYPOTHETICAL COAL RESOURCES (billions of short tons)	(3) AVERAGE COAL RANK	(4) ARI Estimated CBM Resources (based on daf) (Tcf)	(5) ARI Estimated CO2 Storage Potential		(6) USGS Estimated CBM Resources* (Tcf)	(7) CO2 Storage Potential based on USGS CBM Resources*		(8) REVISED ESTIMATE OF COAL SEAM CO2 STORAGE POTENTIAL (this report) (Gt)
				(Tcf)	(Gt)		(Tcf)	(Gt)	
1) Northern Alaska Province	3,753.00		621	1,862	98	17.2	120.4	6.32	5.83
A. Arctic Foothills Subprovince	1,290.00	Bituminous	No Data	Not Subdivided		15	105	5.53	5.08
B. Arctic Coastal Plain Subprovince	1,910.00	Subbituminous							
C. Sagavanirktok Field	553.00	Subbituminous				2.2	15.4	0.79	0.75
Total North Slope	**3,753.00**		**621**	**1,862**	**98**	**17.2**	**120.4**	**6.32**	**5.83**
2) Nenana Basin	17.00	Lignite to subbituminous	1	3	0	1	10	0.52	0.41
3) Cook Inlet Basin. Includes A. Southern, B. Susitina and C. Matanuska resources	1,570.30	Subbituminous to anthracite	136	407	21	140	980	50.58	43.00
TOTAL ALL "BASINS"	**5,340.30**		**758.00**	**2,273**	**120.00**	**158.20**	**1,110**	**57.32**	**49.24**

*North Slope based on Roberts et al., 2008

Table 1. Summary table of estimates of deep coal seam CO_2 storage potential in Gigatons (Gt). See Appendix 2 for details.

The Northern Alaska Province lies entirely within the continuous permafrost region, where depths to the base of the permafrost are as great as 660 meters in the vicinity of Prudhoe Bay to 20 meters or less near the base of the Brooks Range. Of all of the factors influencing storage of CO_2 in deep, unmineable coal seams, the presence of a thick permafrost cap has the greatest impact in reducing potential storage capacity. A permanently frozen coal reservoir detrimentally blocks permeability pathways due to incipient ice-filled cleat fracture system. Therefore, the CO_2 storage capacity of the Northern Alaska province is significantly reduced in areas of currently deep permafrost conditions.

The Nenana Basin contains Tertiary-age coals ranging from lignite to subbituminous in rank. There is little available data on the coalbed methane content of these lower rank coals. Although lower rank coals are more favorable for CO_2 sequestration, having up to a 10:1 replacement for methane, they are higher in ash and poorly cleated and the total resources are small, compared to the Northern Alaska Province and the Cook Inlet Basin. Recent oil and gas exploration in the deeper portion of the Nenana Basin indicates the presence of a fairly thick section of coal-bearing rocks with the potential for CO_2 sequestration in an enhanced CBM production process. Should storage be found to be feasible in coals in the Nenana basin, they could provide storage for CO_2 captured in and near Fairbanks, including the existing coal-burning power plant in nearby Healy.

The Cook Inlet Basin contains extensive Tertiary-age coal resources in the Tyonek Formation at favorable depths for CO_2 sequestration. Coal rank ranges from subbituminous to high-volatile bituminous coal. The estimate of CO_2 sequestration includes both onshore and offshore Cook Inlet subsurface coal seams. The higher resource estimate utilized a different CO_2:CH_4 coal storage ratio and a higher coal resource.

Of the three coal-bearing basins evaluated, the Cook Inlet Basin has the greatest potential for near term CO_2 sequestration in deep, unmineable coal seams (43.0 Gt, Table 1). Infrastructure consisting of numerous roads and pipelines surrounds much of the northern and eastern portion of the basin, and it sits adjacent to major CO_2 emission sources.

Future work should include laboratory sorption isotherm measurements of Alaska coal seam candidates to determine methane and CO_2 storage capacity and behavior. In-situ well testing of coal seam permeability, hydrology, and stress also is needed, ideally with an industry partner in the

CBM-prospective onshore Cook Inlet basin. As oil and gas development moves westward across the Northern Alaska Province, this region is likely to become more prospective for injecting CO_2 emissions from oil and gas activities into deep coal seams.

1.2. Regional Study of Geological Storage Capacity in California

[See Appendix 3 for the full discussion.]

The California Department of Conservation, California Geological Survey (CGS) conducted an assessment of geologic carbon sequestration potential in California during Phase I. This involved identifying and characterizing porous and permeable rock formations and defining areas within the state's sedimentary basins that may be geologically suitable for carbon sequestration in saline aquifers or producing or abandoned oil and gas reservoirs.

As part of the WESTCARB Phase II program, CGS conducted a preliminary regional geologic assessment of the carbon sequestration potential of the Upper Cretaceous Mokelumne River, Starkey, and Winters formations in the Sacramento Basin. These formations contain the most aerially extensive sandstone units within the Sacramento Basin that meet minimum depth requirements for supercritical-state CO_2 injection. Sandstones within these formations also account for a large part of the natural gas production in the southern Sacramento Basin, and comprise the bulk of the saline aquifers within this part of the basin.

Phase II involved the review and correlation of approximately 6,200 gas well logs in the region. Cross sections were prepared to establish regional correlations and a series of three maps were prepared for each formation. First, gross sandstone isopach (thickness) maps were prepared to define the maximum regional extent and to illustrate the thickness of porous and permeable sandstone available within each respective formation. Depth-to-sandstone maps were then generated and used to identify areas of shallow sandstone that might not be suitable for supercritical state CO_2 injection. Finally, isopach maps of overlying shale units were prepared for each formation. The overlying shales are the potential barriers to vertical migration of CO_2 and comparison of the sandstone isopach map and the shale isopach map aids in identifying areas with both the necessary reservoir capacity and seals for carbon sequestration. Information was compiled in digital GIS and other digital formats to facilitate access and use by other partnership participants.

The relationships between the isopach and depth maps for each formation were analyzed to better identify those areas with carbon sequestration potential. GIS map overlays were used to facilitate analysis which consisted of a simple process of elimination. Gross sandstone maps were evaluated to determine the maximum areal extent (square miles) of sandstone within each formation. The total area for each formation was then reduced by areas, if any, where sandstone has been eroded by younger Paleocene submarine canyons. The resulting maps were then overlain by their respective depth-to-sandstone maps, allowing the removal of areas of shallow sandstone. A depth of 3,280 feet (1,000 meters) was selected as a minimum depth for supercritical-state CO_2 injection. Finally, the overlying shale isopach maps were overlain to identify and remove areas with thin seals, and arrive at an estimate for each formation meeting all three parameters. For the purpose of this investigation, a minimum seal thickness of 100 feet (32.5 meters) was used.

The Mokelumne River, Starkey, and Winters formations all contain significant thicknesses of porous and permeable sandstone that may be suitable for carbon sequestration. Large areas meeting minimum depth requirements of 3,280 feet (1,000 meters) and seal thickness of over 100 feet (32.5 meters) exist for each formation. Approximately 1,045 square miles are underlain by Mokelumne River sandstone, 920 square miles by Starkey Formation sandstone, and 1,454 square miles by Winters sandstone. Since the formations are vertically stacked, 2,019 net surface square miles meet depth and seal criteria. Stacking provides the potential for much thicker total sandstone sequences than individual formations. The estimated storage resource for the portions of the three formations meeting depth and seal criteria is 3.5 to 14.1 Gt of CO_2.

The Winters Formation sandstones appear to offer the best potential for carbon sequestration. While gross sandstone achieves considerably greater thicknesses in the Mokelumne River Formation, Winters Formation sandstones can exceed 1,500 feet (500 meters) in thickness. Additionally, about 95% of the Winters sandstones are below 3,280 feet (1,000 meters). Depth provides additional benefits including a greater number of overlying shale units increasing the likelihood of containment. Winters sandstones are also appealing from a stratigraphic standpoint. Unlike the Mokelumne River and Starkey formations which are overlain up-dip to the east by porous sandstone, the Winters sandstone pinches out up-dip within a thick section of marine shale along most of its eastern margin. This configuration creates the potential for large-scale stratigraphic containment.

1.3. CO_2 Resource Assessment – Oil and Gas Fields of California

Using production and reserve records (rather than volumetric data), high and low estimates were made for both onshore oil and gas reservoirs in California on a field basis based on historical production and field pressure and temperature data obtained from the 2005 annual oil and gas report by the California Department of Conservation (CDOC). The sum of the estimates obtained from oil and gas data gave a total estimate for the CO_2 storage capacity in a given California field. Estimates were also obtained for each California basin by summing the estimates of the fields within each basin, and for the entire state of California. Table 2 in Appendix 3 summarizes the total oil and gas records obtained for 2005 by basin.

However, revised estimates (2; see analysis at the end of Appendix 3) are significantly smaller than those developed using the volumetric approach by CDOC. The new oil (high) estimate is approximately 33% of the original oil field volume, and the new gas (high) estimate is 0.3% of the original value.

Table 2. Revised CO2 resource assessment of California oil and gas fields (millions of tons)

Basin	No. Fields	Oil		Gas		Total	
		Low	High	Low	High	Low	High
Central Valley	276	124.19	770.913	1,842.57	3,285.95	1,966.76	4,056.86
Cuyama	9	8.404	43.362	55.24	113.23	63.64	156.59
Eel River	2	<0.01	<0.01	18.15	18.15	18.25	18.25
La Honda	4	0.099	0.121	0.05	0.06	0.15	0.18
Livermore	2	0.088	0.187	28.2	34.82	28.29	35.01
Los Angeles	70	137.643	326.887	705.1	1,076.52	842.74	1,403.41
Orinda	2	<0.01	<0.01	0.12	0.12	0.22	0.22
Salinas	11	4.939	8.085	5.77	6.33	10.71	14.42
Ventura	87	59.906	127.204	380.68	643.77	440.59	770.97
TOTALS	**463**	**335.269**	**1276.759**	**3,035.88**	**5,178.95**	**3,371.35**	**6,455.91**

1.4. Assessment of the Potential for CO_2 Sequestration by Reactions with Mafic Rocks and by Enhanced Oil Recovery in Nevada

The potential for geologic CO_2 sequestration in Nevada was assessed more thoroughly by evaluating the potential for CO_2-enhanced oil recovery (EOR) and the potential for reaction of CO_2 with naturally occurring minerals in mafic rocks (Appendix 4).

In Nevada, there are sufficiently large volumes of basalt (a rock rich in the oxides of magnesium, iron, and calcium) to consider reaction of those rocks with CO_2 from coal-fired power plants. This process has theoretical advantages over some other forms of carbon sequestration in that it would be essentially permanent disposal, with no possibility of leakage from a geological environment, (or from the threat of CO_2 emissions from wildfires, as is possible with terrestrial sequestration in trees or other biomass). Nonetheless, the technology for mineral reaction is unproven. Considerably more research is needed before a commercial operation can be considered.

When and if commercial viability is demonstrated, areas most likely to be of interest in Nevada would be the ones with large volumes of basalt or chemically similar rock that are located near railroads and major power lines. Such areas would most likely be northwestern Washoe County; southern Washoe and parts of Storey, Lyon, Churchill, and Pershing Counties; the Humboldt lopolith in Churchill and Pershing Counties; the Battle Mountain area in Lander and Eureka Counties; and southwestern Mineral and northwestern Esmeralda Counties.

A preliminary assessment of the potential CO_2-EOR in Nevada compiled data on the 15 oil fields with historical production (Appendix 4). Critical factors in the assessment included depth, temperature, and cumulative production. Most Nevada oil reservoirs are considerably hotter than ideal conditions for maintaining a dense CO_2 phase underground. Furthermore, none of the Nevada oil fields is large enough to accommodate all the CO_2 from a large coal-fired power plant. The cumulative volume of oil and associated water production from all Nevada oil fields is about two orders of magnitude less than what would be needed to sequester a significant amount of CO_2 from a power plant. The study concluded that there is little potential in Nevada for CO_2 sequestration through EOR.

1.5. Storage Estimates – Washington and Oregon Sedimentary Basins

The estimated storage CO2 capacity for the onshore and offshore sedimentary basins in the states of Washington and Oregon are attached in Appendix 5.

Onshore Sedimentary Basins

The sedimentary basins identified in the Phase I in the states of Washington and Oregon include basin area estimates, and indicators of whether representative well logs exist, whether the basin is deeper than 2,600 feet (800 meters) and if a resource estimate can be made. Storage estimates could only be made for basins for which the target formation had reservoir volume below 2,600 feet (800 meters) and for which logs were available to determine porosity and lithology.

Recent geologic data have been collected for four basins in the two states; the Willapa Hills and Puget Basins in Washington, and the Astoria-Nehalem and Tyee-Umpqua basins in Oregon. The new data consist of published borehole logs for hydrocarbon exploration wells. The data for the Washington basins were obtained from log databases provided by M.J. Systems, Inc., and the data for the Oregon basins was obtained from Oregon's Department of Geology and Mineral Industries log database.

The new data enabled basin-specific estimates of sandstone porosity to be made. For the purpose of estimating the resource volumes, a porosity of zero was assumed for other geologic units such as siltstone, shale, claystone and coal. The analyses used lithologic and neutron-density logs. First, the lithologic logs were used to determine the percent of sandstone in each borehole. Basin-wide sandstone percentages were calculated by averaging the values from the available logs in each basin.

Offshore Sedimentary Basins

Table 6 in Appendix 5 summarizes the resource estimates (mass of CO_2) for the six offshore basins. Resource estimates are included assuming both low and high Efficiency Factors (E) of 0.01 and 0.04, respectively, for an average basin effective sediment thicknesses. Both resource estimates for each basin are included in the GIS database.

The resource estimates range from 0.8 Mt to 3.1 million tons (Mt) for the smallest basin (Newport; 4% of the offshore total) to 7.48 Mt to 29.9 Mt for the largest basin (Heceta; 35% of the offshore total).

1.6. WESTCARB GIS Data

Data integration and dissemination is a critical component to WESTCARB's mission. Data includes both geologic and terrestrial carbon sequestration assessments as well as a wealth of supporting geologic and geographic GIS data. All WESTCARB data layers and ancillary information are vetted and then archived and maintained in a central location. Assessment information is viewable through a publicly accessible portal: http://www.westcarb.org/carbonatlas.html. These data layers are also downloadable through this website for further manipulation and analysis on a user's desktop.

Information from WESTCARB assessments form the basis for WESTCARB's contribution to the *Carbon Sequestration Atlas of the United States and Canada*, editions 1-3, and the National Carbon Sequestration Database and Geographic Information System (NATCARB) – the interactive website. Utah Automated Geographic Reference Center (AGRC) manipulated datasets and produced maps for these efforts as well as responded to WESTCARB team special requests.

GIS data was initially processed by the Utah AGRC and managed using ESRI's ArcGIS software. Utah AGRC maintained and upgraded WESTCARB's servers as needed. This included upgrades to the latest software versions.   The WESTCARB database is currently housed and maintained by the University of California, Berkeley Geospatial Information Facility .

2.0 ENHANCED TERRESTRIAL SEQUESTRATION OPPORTUNITY ASSESSMENT AND PILOT SITE IDENTIFICATION

This task aimed to update and expand regional characterization of the carbon sequestration potential for riparian restoration and/or reforestation of rangelands, the potential for "plantations" of fast-growing trees adapted to regional sites, and the potential for regional carbon storage by improved fire management and/or conservation of forested lands. A further goal was to identify potential terrestrial pilot sites in Washington and Arizona for future terrestrial sequestration validation or demonstration projects.

2.1. Hybrid Poplar Study

[Refer to Appendix 6 for the full discussion.]

Hybrid poplar (*Populus* spp.), a short rotation woody crop, is of growing interest in the West Coast states of California, Oregon, and Washington. This increased interest has been driven in recent years by hybrid poplar's potential as a bioenergy crop or multiple wood products crop in combination with the potential revenue from carbon credits. The study aimed to identify eligible lands within the West Coast states for the planting of hybrid poplar crops using a GIS framework.

There is interest in hybrid poplars because they are one of the fastest growing tree species in North America. This species is typically established on marginal agricultural lands or conservation reserve lands and as wind breaks, to reduce soil erosion, as riparian buffers, and as crops on marginal lands for generating income from secondary forest products. Over the past 10-15 years there has been increased interest in using these fast growing woody crops for large scale bioenergy crops and multiple wood product crops in combination with carbon credits

Purpose

As part of the WESTCARB's terrestrial carbon sequestration component, Winrock International undertook a regional characterization study of areas suitable for hybrid poplar afforestation projects in the West Coast Region). The regional characterization study first identified areas eligible for hybrid poplar plantations. "Eligible" is merely an indication that the land could support hybrid polar plantations ecologically and topographically; it does not address current land use, so does not necessarily mean that the area is available. Second, environmental datasets were analyzed to identify suitability classes for the growth and production of hybrid poplar. Suitability classes ranged from "high suitability" to "not suitable," based on factors of climate, soil and slope. Using the suitability map and growth and yield curves for hybrid poplar, the potential yield and carbon sequestration of hybrid poplar on different sites was modeled. This report will be helpful for project developers interested in large scale hybrid poplar plantation. This report is primarily focused on the potential for large-scale hybrid poplar afforestation and reforestation projects that would provide carbon credits in combination with revenue from biomass for bioenergy plants, or from multiple market wood products crops that produces things like lumber or veneer.

Project Results

The final suitability map defined 18 different suitability classes ranging from “highly suitable” to “not suitable” using environmental variables of climate, soil and slope (Figure 3). The suitability classes were stratified by areas where irrigation would be needed, limited-no irrigation would be needed and where no irrigation would be needed based on precipitation and evapotranspiration rates.

Results show that most of the prime lands ideal for hybrid poplar, and where no irrigation or limited irrigation would be needed, are located primarily on the western side of the Cascade Mountains in Oregon and Washington State. Washington has approximately 8 million acres of eligible lands, with 82% needing irrigation, 8% needing limited irrigation and 9% needing no irrigation. Oregon has 5 million acres in total, with 59% needing irrigation, 27% needing limited irrigation, and 13% needing no irrigation. California had the most total land eligible, with 14 million acres. However, 96% of the land would need irrigation, with only 3% needing limited irrigation and less than 1% needing no irrigation. If irrigation is supplied to areas where moisture availability is limited, the amount of highly suitable land throughout the West Coast region more than doubles.

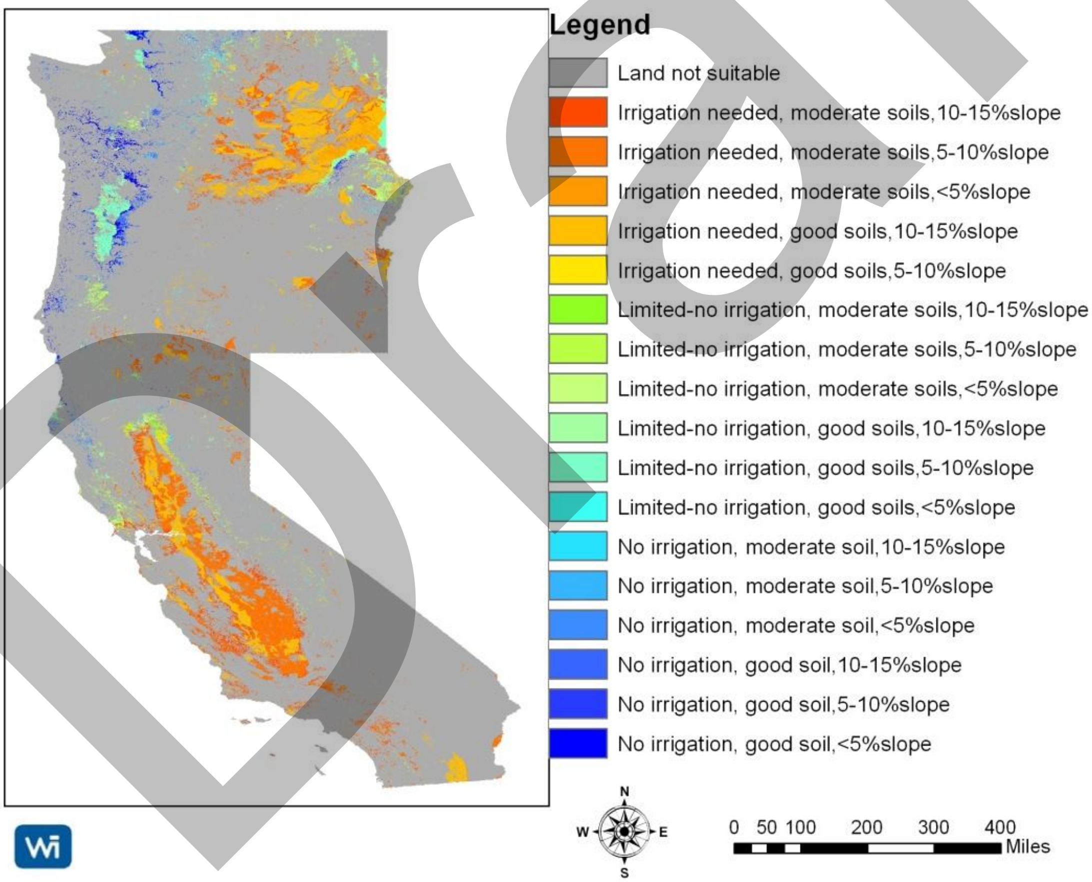

Figure 3. Final suitability map for the west coast region

Using the suitability map and published literature for hybrid poplar, growth and yield was estimated, and subsequently carbon sequestration. Growth and yield of hybrid poplar averages from 8-11 green tons/acre year of above ground biomass on highly suitable sites with ample water, 6-8 green tons/acre year on moderate sites, and 4-6 green tons/acre year on poor to moderate sites. This growth and yield relates to approximately 3-4 t C/acre year on highly suitable sites, 2-3 t C/acre year on moderate sites, and 1-2 t C/acre year on poor to moderate sites. Carbon sequestration per year was modeled with irrigation (Figure 4), and without irrigation (Figure 5). These results indicated that over 6 year rotation approximately 20 t C/acre could be achieved, and over a 20 year rotation 81 t C/acre.

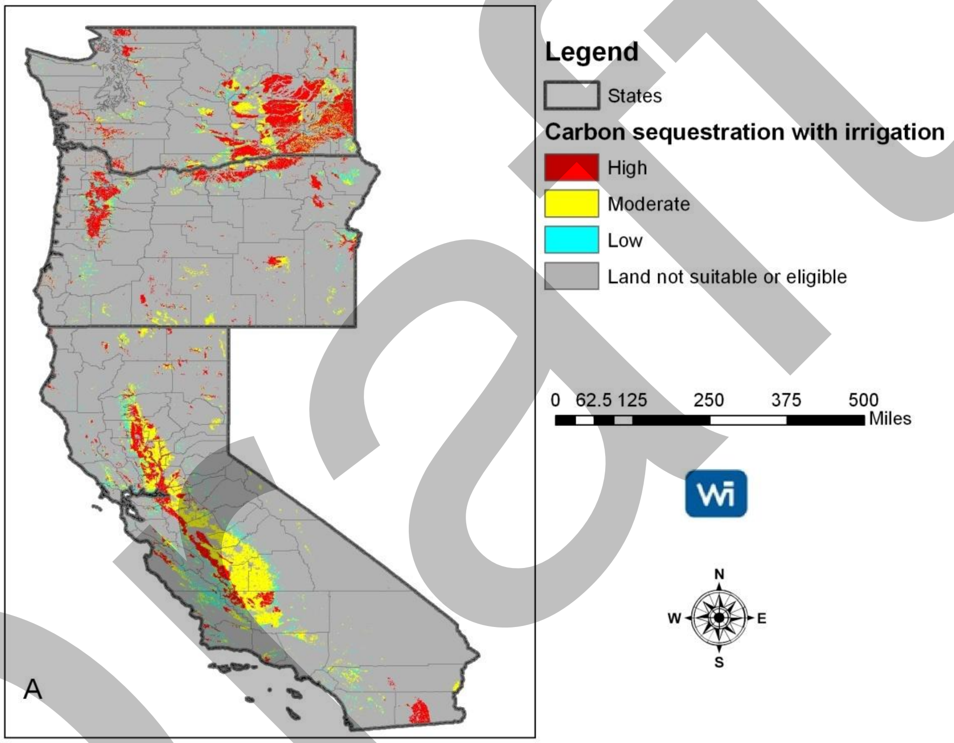

Figure 4. Potential carbon sequestration across the west coast region with irrigation, based on the suitability map

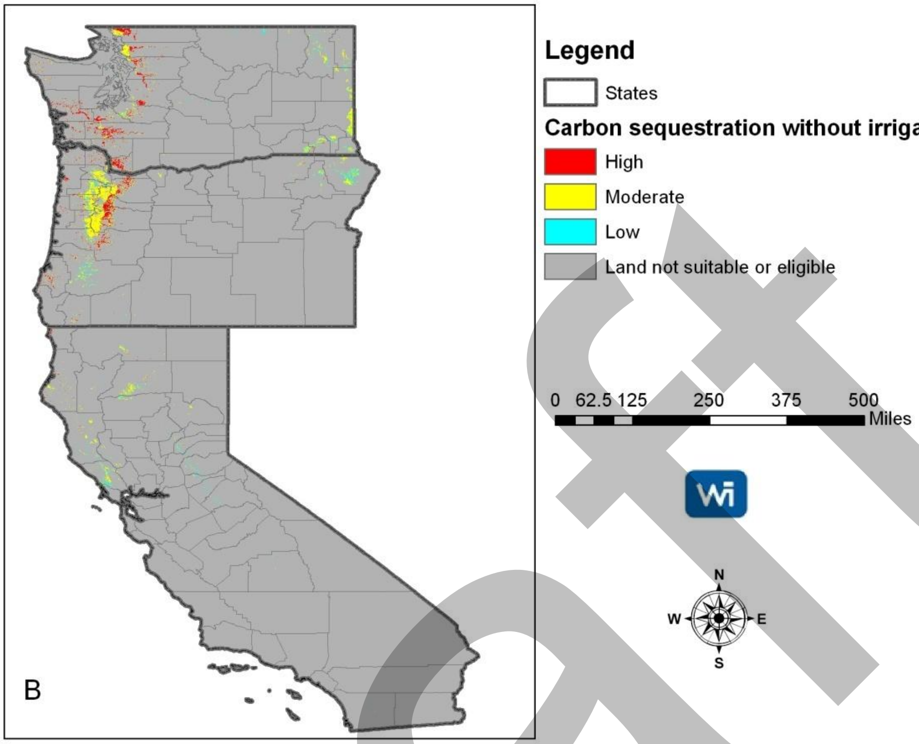

Figure 5. Potential carbon sequestration across the west coast region without irrigation, based on the suitability map

The financial analysis of large scale hybrid poplar plantations showed that a dedicated biomass energy crop could earn estimated revenue of $737-$976/acre with $86-$325/acre of that being earned from carbon credits. For a multiple market wood product crop the revenue over a 20 year rotation is estimated to be $9,396-$10,989/acre with $425-$1,592/acre of that being earned from carbon credits.

The results from this study will be useful to project developers interested in identifying counties or locales that would be productive for investing in and establishing hybrid poplar crops. Project developers identifying areas for investment will be able to use this study to gauge the level of investment and resources need to establish a hybrid poplar plantation. This study should be used to identify counties or local regions where more detailed spatial analysis can be done.

2.2. Regional Characterization for Arizona: Potential of Riparian Areas for Carbon Sequestration

[Refer to Appendix 7 for the full discussion.]

Riparian areas are a small portion of the Arizona landscape, but need proper management and restoration to provide their vital functions. Restoring the extent of the riparian forest could result not only in converting these areas into carbon sinks, but also improving the vital functions of riparian ecosystems. Approximately 400,000-450,000 acres (162,000 – 182,000 hectares) of riparian vegetation were historically estimated to exist in the Lower Colorado River between Fort Mohave and Fort

Yuma, while currently riparian vegetation in this section of the river sums to approximately 89,000 acres. (36,000 hectares) In Arizona, riparian areas are important because of the limited amount of water and rapid population growth, which leads to the need for better management of riparian areas.

Purpose

The spatial analysis presented in this report aims to identify riparian areas that could reforested or afforested (termed in this report as forestation) and serve as potential carbon sequestration projects. For this purpose, the potential riparian areas that could be used for forestation were modeled and the potential carbon benefits from tree planting in identified riparian areas were estimated.

A spatial analysis of potential riparian area that could sequester carbon through forestation with native riparian woody species was conducted through the following steps:

- Modeling the extent of potential riparian areas.
- Defining geophysical potential for native woody riparian vegetation.
- Identifying opportunities for carbon sequestration through forestation with native woody vegetation within the potential riparian areas.

Project Outcomes

The study used a modeling approach (PATHDISTANCE) incorporating river and water bodies as well as elevation and slope to model the extent of the riparian areas. This model resulted in predicting the potential riparian area in natural shapes rather than creating buffers around the rivers. The total modeled riparian area was estimated at 3 million acres (1.2 million hectares), which is approximately 4% of the total area of Arizona. The results showed that Yuma, La Paz, and Pinal County have the largest extent of potential riparian area as a percent of the total county area 10%, 9%, and 9%, respectively.

For this analysis, four riparian woody vegetation types were considered: cottonwood/willow, conifer/oak, mesquite, and mixed broadleaf. Researchers calculated the distribution of these four vegetation types across landform, rock formation and soil type classes. They created landform, geology, and soil factor maps based on the percent distribution of each native woody vegetation type per landform, geology and soil class. Then all factor maps were combined using weighted averages to create a single geophysical potential map for each native woody vegetation type. Researchers analyzed the geophysical potential scores for conifer/oak, cottonwood/willow mesquite, and mixed broadleaf on shrub/scrub land cover category across the tree elevation strata for (1) less than 3,280 feet (1,000 meters), (2) between 3,288 and 6,560 feet (1,000-2,000 meters), and (3) greater than 6,560 feet (2,000 meters). The area available for forestation on shrub/scrub riparian land was refined by dividing the geophysical scores for each woody vegetation riparian type into four equal intervals to represent low, moderate, high and very high class of geophysical potential. The results showed that 88% of the total area was suitable for cottonwood/willow, 87% for mesquite, 33% for mixed broadleaf, and just 10% for conifer/oak located on very high geophysical potential class.

Data on carbon stocks in riparian areas in southwest of the United States are very sparse, therefore applying standard forest growth rates will lead to overestimations of carbon stocks. Winrock conducted measurements of mesquite, willow, and cottonwood riparian areas along the Lower Colorado River in 2007. Due to the paucity of data at this time, no separate carbon accumulation rates for the four proposed woody tree vegetation types could be provided: conifer/oak, cottonwood/willow, mesquite, and mixed broadleaf. The total amount of carbon that could be sequestered by forestation of riparian areas with high and very high geophysical potential after three time periods (20, 40, and 80 years) varies by native woody riparian vegetation type. The analysis showed that areas defined as suitable for forestation with conifer/oak (69,000 acres, or 30,000 hectares) on high and very high geophysical potential classes could sequester more than 4 x 10^6 tons CO_2e after 80 years. Riparian areas identified as suitable for growing cottonwood /willow, mesquite, and mixed broadleaf species have a larger potential for carbon sequestration after 80 years, 97 x 10^6, 98 x 10^6, and 89 x 10^6 CO_2e, respectively.

Conclusions

The approach used to map the extent of the riparian areas for the state of Arizona is robust because it allows calculating a surface of relative cost of moving from the stream or water source up into the stream valley, accounting for slope and elevation. This method resulted in mapping approximately 3 million acres (1.2 million hectares) of riparian areas across the state of Arizona, which accounted for 4% of the total state area. The result showed that Yuma, La Paz and Pinal County have the largest extent of potential riparian area as a percent of the total county area—10%, 9%, and 9%, respectively, while Greenlee and Gila County have the least extent of potential riparian area as a percent of the total county area—approximately 1%.

The analysis illustrated that approximately 59% of the mapped riparian area was occupied by shrub/scrub according to the NLCD 2001 across the whole range of the geophysical potential scores for the native woody riparian vegetation. Considering equal interval partition of the geophysical potential scores for each of the native woody vegetation, researchers selected riparian areas currently occupied by shrub/scrub in the high and very high geophysical potential class. The estimation of suitable riparian areas on very high geophysical potential accounted for approximately 1.4 x 10^6 acres (566,000 hectares) for forestation with cottonwood/willow or mesquite, 500,000 (202,000 hectares) for forestation with mixed broadleaf trees, and only 7,000 acres (3,000 hectares) for forestation with conifer oak.

Recommendations

The preliminary analysis presented in this report highlighted the needs of further research with an interest in restoration of riparian areas. Further research and analysis is needed particularly in the following areas:

1) Threshold selection of the relative cost surface

> More in depth analysis and some empirical data collection are needed to select the correct threshold of the relative cost surface created through PATHDISTANCE. Aerial photographs or high resolution images can be used to develop a relationship between the value of the relative cost surface and the furthest and closest distance of riparian area edge per river class and/or elevation.

2) Collection of empirical data

> Additional empirical data should be collected though field work and/or from aerial
>
> photographs or high resolution images to develop a relationship between the geophysical potential scores and location of existing native woody vegetation. This will allow for accurate determination of the interval of geophysical potential scores representative of each of the native woody vegetation.

3) Cross discipline analysis

> The selection of sites that could be afforested within the identified riparian areas should consider additional functions of riparian forests such as water quality, stream integrity, wildlife habitat, and flood and storm water runoff. Information and data produced for the Arizona statewide freshwater assessment by the Nature Conservancy could be considered when selecting sites for forestation.

It is recommended that these further analysis and data collection are carried out at the county level. As indicated from this analysis, Pima, Navajo, and Yavapai counties have the largest estimated areas suitable for forestation cottonwood/willow and mesquite, mixed broadleaf and conifer/oak, respectively and could be good candidates for further analysis.

2.3. Baseline Greenhouse Gas Emissions and Removals for Forest and Agricultural Lands in Arizona

[Refer to Appendix 8 for the full discussion.]

This project sought to establish the baseline carbon stocks and changes in stocks for the forest and agricultural sectors in Arizona during the most recent 10-year period for which data are available (generally the 1990s). Such baselines can assist in identifying opportunities where carbon removals (sequestration) in each sector might be increased, or carbon emissions decreased, through changes in land use and management.

Project Outcomes

Baseline for Forest Lands

The forest baseline is separated into three component parts: a general forests baseline, a baseline effect of development, and a baseline effect from fire. The general forests baseline is presented at the state level for all forestlands, based on U.S. Department of Agriculture's Forest Service data, detailing change in forest area and change in carbon stocks, but with no attribution to the causes for the change. Using additional databases, the specific cases of emissions associated with development and emissions associated with fire are further examined.

General Forestlands Baseline

Between 1987 and 1997 there was an estimated increase in Arizona's forest area of 500,000 acres (202,000 hectares), a mean of 54,000 acres (22,000 hectares) per year. This is equivalent to an increase of 9×10^6 metric tons CO_2 equivalent (MMTCO$_2$e), or 0.92 MMTCO$_2$e/year between 1987 and 1997.

The estimated increase in carbon stocks of 0.92 $MMTCO_2e$/yr is substantially lower than the estimated sequestration in soil and forests reported by the Arizona Climate Change Advisory Group of 6.7 $MMTCO_2e$ in 2000. However, some of this divergence can be accounted for by the inclusion of soil carbon sequestration in the Climate Change Advisory Group analysis. In addition, there is some uncertainty on whether the carbon is artificially inflated due to a U.S. Department of Agriculture Forest Service change in forest definition from 10% cover to 5% cover in the study period.

Baseline Effect of Development on Forest Lands

The baseline for emissions from development was created using land use data from the

National Resources Inventory of the United States Department of Agriculture and carbon data derived from the U.S. Department of Agriculture's Forest Service Forest Inventory and Analysis Database for the period 1987 to 1997. Because of data limitations, the analysis is limited to non-federal lands and to the gross CO_2 emissions from aboveground live-tree biomass on conversion of non-federal forestland to developed land uses. Because the focus is on non-federal lands, the analyses should be used only to explore decisions on private lands.

Between 1987 and 1997, 3,499 acres (1,416 hectares) of non-federal forest in Arizona were converted to development, which is equal to just 350 acres (140 hectares) per year. All of this area was located in the north part of the state. For gross carbon emissions, two scenarios were considered. Under Scenario 1, all tree biomass in the converted area was immediately emitted as carbon dioxide. Under Scenario 2, for developed areas of less than 10 acres (4 hectares), it was assumed that 50% of the carbon was retained in the form of residual trees. Under Scenario 1, an estimated 152,000 tons of CO_2 equivalent (t CO_2e) were emitted due to development, or 15,200 t CO_2e/year. Under Scenario 2, 145,000 t CO_2e were emitted, or 14,500 t CO_2e/year.

These emissions compare with the estimated gross sequestration from forests in Arizona of 0.92 $MMTCO_2e$/yr between 1987 and 1997 and gross emissions for the state of 99 $MMTCO_2e$/yr (from Arizona Climate Change Advisory Group). Emissions from deforestation therefore represent a fraction of a percentage of the total emissions in the state.

Baseline Effect of Fire on Forest Lands

The emissions from fire were examined by overlaying the wildfire database for Arizona on the National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer satellite imagery showing change in normalized differential vegetation index. (The normalized differential vegetation index measures "greenness" of landscapes; greenness decreases immediately after fire.) This process determined the location, size, and intensity of fires between 1990 and 1996. Carbon values were applied to these fires using data from the United States.

Forest Service Forest's Forest Inventory and Analysis Database and proportional emissions from the detailed baseline fire analysis for California. The analysis considered all forests and rangelands in Arizona, federal and non-federal.

Across the seven years analyzed, fires with a total area of 1.08 x 10^6 acres (437,700 hectares) were recorded. This is equivalent to 154,000 acres/year or 62,500 hectares per year Emissions totaling

904,000 tons of carbon or 3.3 $MMTCO_2e$ were estimated to have occurred from fire during the analysis period. This is equivalent to an emission of 0.47 $MMTCO_2e$/year.

Eighty-five percent of the burned area was on rangelands, but 42% of the emissions were from the 15% of burned area that was forest. Fire incidence varied by year, with high emissions in 1993 to 1996 (>168,000 t C) and low emissions between 1991 and 1992 (<23,000 t C). Fires occurred throughout Arizona during the study period, and there was no apparent geographical relationship between either area burned or carbon emissions from fire and geographic location.

These emissions compare with the estimated gross sequestration from forests in Arizona of 0.92 $MMTCO_2e$/year between 1987 and 1997 and gross emissions for the state of 99 $MMTCO_2e$/year (from Arizona Climate Change Advisory Group). During the analysis period, emissions from fire therefore represented only about 0.5% of the state's total emissions.

Baseline for Agricultural Lands

Agricultural land area in Arizona amounts to about 1.5% of the total land area. The state lost agricultural land area during 1987–1997 through conversion to other land uses, in particular to urban development/transportation and from retiring agricultural land from cultivation. In some counties, the area of woody cropland actually increased, but these increases were more than offset by decreases in non-woody cropland.

Accompanying these losses in area were losses in standing carbon stocks on agricultural land, so that conversion of agricultural land to other uses was responsible for a net annual source (emission) of CO_2 to the atmosphere. Losses of agricultural carbon stocks over the 1987–1997 period were estimated at 99,000 tons. The estimated net annual source from Arizona agricultural lands was 0.04 $MMTCO_2e$.

Emissions of CO_2 from agricultural land conversion represent only a portion of the total GHG emissions attributable to the agricultural sector. The primary non-CO_2 greenhouse gases associated with agricultural activities are nitrous oxide (N_2O) and methane (CH_4). N_2O (emitted from agricultural soils, especially after fertilizer application) has approximately 296 times the global warming potential of CO_2, and methane (emitted by livestock and through manure management) has approximately 23 times the global warming potential of CO_2. Examination of data from Arizona indicated that GHG emissions from N_2O and CH_4 in the agricultural sector dwarf the annual CO_2 source from agricultural land conversion. In fact, CO_2 emissions from land conversion represented less than 1% of the total CO_2 and non-CO_2 greenhouse gas emissions attributable to the agricultural sector.

Conclusions

General Forests Baseline

- An estimated 541,000 acres (219,000 hectares) of forest on federal and non-federal lands were gained in Arizona between 1987 and 1997 at a rate of 54,201 acres/year (21,935 hectares/year). These gains are equivalent to 0.28% of the forest area per year between 1987 and 1997.

- A gross sequestration of an estimated 9.2 x 106 metric tons CO2 equivalent (MMTCO2e) occurred between 1987 and 1997 (0.92 MMTCO2e/year) and 42.7 MMTCO2e (7.1 MMTCO2e/year) between 1997 and 2003.
- The sequestration rate estimated in a previous study for the State of Arizona in 2000 exceeds the rate predicted in this study, probably due to methodological and terminological differences.
- Carbon sinks could potentially offset as much as 7% of Arizona's emissions.
- For just non-federal forested lands, there was a net loss of 170,000 acres (69,000 hectares). Ninety percent of the loss in forested area occurs in the northern counties of the state.

Development Baseline

- An estimated 3,499 acres (1,416 hectares) were lost to development in Arizona between 1987 and 1997 at a rate of 351 acres (142 hectares) per year. This forest loss is equivalent to a gross emission of between 0.145 and 0.152 MMTCO$_2$e, or 0.0145 to 0.0152 MMTCO$_2$e per year. The emissions were exclusively in the north part of the state.
- Emissions from deforestation represent a fraction of a percent of the state's total emissions.

Fire Baseline

- Across the seven years analyzed, researchers recorded fires with a total area of 1.08 x 10^6 acres (437,000 hectares)—equivalent to 154,000 acres/year, or 62,500 hectares/year. Emissions totaling 904,000 tons of carbon or 3.3 MMTCO$_2$e were estimated to have occurred from fire during that period—equivalent to an emission of 0.47 MMTCO$_2$e/year.
- Eighty-five percent of the burnt area was on rangelands, but 42% of the emissions were from the 15% of burned area that was forest. Fire incidence varied by year with high emissions in 1993 to 1996 (>168,000 t C) and low emissions between 1991 and 1992 (<23,000 t C).

Agricultural Baseline

- In 1997, agricultural land represented 1.5% of the total land area, and non-woody crops were 93% of all agricultural land. Both woody and non-woody cropland are concentrated in the southern counties.
- Statewide, there was a loss of agricultural land of 6.6% between 1987 and 1997.
- Total carbon stocks in all agricultural land types in Arizona were estimated at 1 million tons. Between 1987 and 1997, there was a total loss of about 99,000 tons of carbon, or 9.4% of the carbon stored in agricultural lands in 1987.
- In CO_2 equivalent terms, total agricultural carbon stocks in Arizona in 1997 were 3.5 MMTCO$_2$e, and the net loss 1987–1997 disregarding non-CO_2 greenhouse gas emissions was 0.4 MMTCO$_2$e—equivalent to an annual source of 0.04 MMTCO$_2$e.
- Non-CO_2 greenhouse gas emissions from N_2O (emitted from agricultural soils after fertilizer application) and CH_4 (from livestock and manure management) dwarf the annual CO_2 source from agricultural land conversion in Arizona.

2.4. Afforestation/Restoration of Riparian Areas along the Santa Cruz River, Arizona

[Refer to Appendix 9 for the full discussion.]

This project idea note is for a potential project for the re-vegetation of riparian areas along the Santa Cruz River in Arizona. The Santa Cruz River forms a bi-national ecosystem that has its headwaters in the United States, flows southward crossing into the Sonora desert in Northern Mexico and turns and re-enters the United States just east of Nogales. This unique system supports tall and shaded forests in an arid climate, forming an oasis for vegetation, wildlife, and people. Unfortunately, the riparian forests along the Santa Cruz have been historically mismanaged due to agricultural land expansion and are mostly inexistent from the borders of the river.

This project aims to analyze the viability of re-vegetating the riparian forests using the revenues generated from carbon credits as a result of the carbon sequestered by the established trees. The goal is to quantify the amount of carbon sequestered and potential revenues from credits in a regulatory market. As proposed, this project intends to revegetate a total of 6,500 acres (2,634 hectares) of land distributed over five different properties in the Southern portion (within the United States border) of the river.

The implementation of this project would generate the following direct social and environmental benefits to the local communities:

- Water quality maintenance;
- Storm water regulation and storage;
- Biodiversity maintenance and habitat enhancement;
- Sediment and nutrient retention;
- Improvement of human recreational activities; and
- Improvement of landscape aesthetics.

The establishment of this project would result in the sequestration of over 150,000 t CO_2e over its entire duration of 40 years. The uptake of carbon would be greater in the early growth stages of established vegetation and would slowly decrease over time. Costs of establishment however, as a result of the vast area to be revegetated, were estimated to be large, at the order of $4,700,000 at the beginning of the project. Over time as plants uptake carbon and credits can be generated, this project would be able to balance costs with benefits.

To break-even between investments and revenues (internal rate of return – IRR ≥ 0%) in the 20 years subsequent its implementation the negotiated price of the Verified Emission Reductions (VERs or carbon credits) would have to be at the order of $67 per t CO_2e. This price is high because the project would have to operate for five years without crediting, as carbon sequestered would be dedicated to pay off emissions from removing existing vegetation during the project implementation process.

Due to the high cost of implementation, this project was considered not economically feasible. Current market prices for VERs of $7 would have to rise to a level unlikely in today's or any near future market ($110) in order for the IRR of the project to reach over 5%. Therefore, it was concluded that this project is not practical in economic terms if only using revenues generated from carbon offsets.

2.5. Greenhouse Gas Emissions Associated With Urbanization in Washington

[Refer to Appendix 10 for the full discussion.]

The conversion of forest lands to non-forest uses, especially conversion to residential development, is of significant concern to the Washington State Legislature and Washington Department of Natural Resources.

As a result of a rapidly growing population, the risk of conversion is especially high in Puget Sound's watersheds, where 80% or more of the remaining private forestlands not enrolled in the Designated Forestland Program are at high risk. Although the aim of planning under the Growth Management Act in Washington State is to control population growth in rural areas, growth in unincorporated areas of King, Pierce, and Snohomish Counties has exceeded targets.

In WESTCARB Phase I, the baseline for emissions from development in Washington State was estimated over a ten year period from 1987-1997 an estimated 246,000 acres (99,600 hectares) were deforested for urban development across the state. Forty-two percent of this area was in the King, Pierce and Snohomish counties even though these counties represent just 8% of the State. Pearson et al. (2007) estimated net emissions across the three counties of over 7×10^6 tons of CO_2e per year or 45% of the total from development across the whole state.

The estimates of Pearson et al.[1] represent a first order approximation based on available data at the time on forest carbon stocks, forest cover change, and approximations of changes in carbon stocks. Furthermore, these results indicate that urban growth around the city of Seattle in King, Pierce, and Snohomish counties is an important source of emissions from land use change in Washington State. To improve understanding of this process, Winrock International carried out a study of emissions from conversion of forest to urban area in the Puget Sound region—King, Pierce, and Snohomish counties.

Purpose

The objective of this project is to develop a regional characterization study for Washington State that defines residential development as it is implemented in the Puget Sound region to estimate the emissions associated with conversion of forested land for residential development. Although studies of urban forests and ecosystems in the United States and their associated carbon stocks exist, there is little information on carbon stock changes and GHG emissions associated with the conversion process itself. In addition, existing studies of urban forests have focused on average crown cover across urban land, and have not produced a consistent set of definitions of land classes within urban

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[1] Pearson, T.S., Brown, S., Martin, N., Martinuzzi, S., Petrova, S., Monroe, I., Grimland, S. and Dushku, A. 2007. Baseline Greenhouse Gas Emissions and Removals for Forest and Agricultural Lands in Washington State. *California Energy Commission Publication* 500-07-026

and suburban areas that could be used to estimate carbon storage per unit of land class within settled areas.

The characterization will define residential development in the Puget Sound region in terms of the most common lot size and change in vegetation cover and associated carbon stocks. This regional characterization could be used both for full accounting of greenhouse gas emissions associated with development and also potentially to develop a class of offset projects permitting market pressures and incentives to decrease total net greenhouse gas emissions and retain forests in the Puget Sound region.

Project Results

Hearing Examiner decisions on applications for subdivision of land in rural and urban residential zones from 2000 to 2010 were reviewed to determine the zones where development is most intense in terms of total single-family residential lots created in each county. As most of the lots in the subdivision applications reviewed in Pierce and King Counties were located in zones with minimum lot size 0.25 acres (0.1 hectares) or smaller, it was inferred that the most common lot size for development of residential subdivisions in unincorporated areas of Pierce and King County is 0.25 acres (0.1 hectares) or smaller. Development in unincorporated areas of these two counties is relatively dense compared to development in unincorporated Snohomish County, where the most common lot size in reviewed subdivision applications was one acre. (0.4 hectares)

Parcel boundaries for the subdivision plat were overlaid with a series of orthorectified aerial images from multiple time points to characterize the change in area of forest cover associated with development of the subdivision. The GIS analysis includes roads internal to subdivisions only, although the creation of residential subdivisions may influence the construction of access roads external to the subdivision. There is therefore the necessity for ongoing work to determine the total impact of development incorporating the dedicated roads and emission associated with clearing forest for road construction.

Development in King and Pierce Counties, where the most common lot size was 0.25 acres or less, resulted in clearing of 62% to 98% of forest cover. Development of these small lot sizes resulted in clearing of relatively more forest cover compared to 1 acre lots in zone R-5 in Snohomish County, which resulted in less than 50% clearing of forest cover for all but one of the subdivisions assessed. Proportion of existing forest cover cleared was also related to the total size of the development. Mean total development area in King and Pierce Counties and in zone R-9,600 in Snohomish Counties ranged between 3.3 to 9.5 acres (1.3 to 3.8 hectares) with deforestation between 75% and 95%, while in zone R-5 in Snohomish County where the mean total development area was 30 acres (12 hectares) only 33% of original forest cover was cleared.

To determine the direct change in carbon stock resulting from development, forest carbon stocks within the boundaries of each subdivision plat were determined by overlaying the parcel boundaries with the U.S. Forest Service's FIA biomass stock map. The loss in forest cover through development led to average changes in stock in live trees of 289 t CO_2e/acre, 1,237 t CO_2e/acre, and 1,044 t CO_2e/acre for King, Pierce, and Snohomish Counties, respectively.

The average total emissions from forest conversion per subdivision, accounting for the quantity of cleared timber that is converted to harvested wood products resulting in long-term storage of carbon, and assuming that the remainder of cleared vegetation is diverted to energy recovery, was 235 t CO_2e and 959 t CO_2e for King and Pierce Counties respectively, and in Snohomish County 1,202 t CO_2e for development in zone R-5 and 495 t CO_2e for development in zone R-9,600.

A sample of subdivisions developed in the last ten years in the zones with the highest level of development was selected for field measurements to estimate carbon stock recovery post-development. Total stocks vary from 1.27 tons of carbon in a 0.1 acre lot to more than 39 t C in a 2 acre lot.

Full accounting of development emissions must capture both the emissions from clearing the forest and the sequestration that occurs after development. Net emissions in King County ranged from 70 t CO_2e to 177 t CO_2e per development. In Pierce County net emissions ranged from 412 t CO_2e to 1,418 t CO_2e per development. In Snohomish County, development resulted in net emissions for some subdivisions while other subdivisions showed net sequestration (negative net emissions). Net emissions ranged from 12 t CO_2e to 670 t CO_2e. Net sequestration ranged from 8 t CO_2e to 335 t CO_2e.

Net emissions from development was impacted by initial forest cover and by area of forest cleared for development. While the initial forest cover pre-development varied, a relationship existed between total area of development and percentage of original forest cover remaining after development. Forest cover cleared during development varied from 57-100% in areas of less than 16 acres but averaged 35% for development areas that exceed 16 acres (6.5 hectares)

This relationship could form the basis of a future performance standard for development projects such that if a developer exceeded the defined area of forest retained by 10% or more then the carbon stocks of the retained forest would be creditable. For example, the resulting available offsets range from approximately 136 tons for a 10 acre (4 hectare) development to almost 3,000 tons for a 60 acre (24 hectare) development in an area with forest carbon stocks of 100 t C/acre.

This study represents an initial analysis of development and associated emissions in three counties of the Puget Sound. The analysis shows the potential value of further examination of this category in the region. Emissions are large and are likely largely unaccounted for in inventories of greenhouse gas emissions. These emissions also present an opportunity for the creation of an offset project category. Where emissions can be reduced without leakage then these emission reductions should be creditable to developers and local authorities.

The limited time and resources for this study meant that only a limited number of development sites could be examined from limited zoning categories. A future study should look more exhaustively at development that has occurred over the last 10 years over a larger sample of counties and zoning areas within the state and should use a similar methodology to calculate forest loss, the emissions resulting from forest loss and post development carbon stock recovery.

3.0 OUTREACH

The Outreach tasks were to develop partnership-level external communications, conduct four annual public/business meetings, participate on the DOE Outreach Working Group, provide pilot-specific public outreach planning, facilitate key stakeholder communications, and conduct research on the public perception of carbon sequestration. CIEE managed a blue ribbon panel appointed jointly by the California Energy Commission, the California Public Utilities Commission, and the California Air Resources Board. This panel, represented by national experts, looked at the regulatory challenges in implementing CCS projects in California.

3.1. WESTCARB Annual Business Meetings

CIEE attended and presented at all WESTCARB Annual Business meetings that were held in 2005 to 2011 in Berkeley, Phoenix, Seattle, Anchorage, Phoenix, Sacramento, and Lodi, respectively. Details of these meetings, including the presentation slides, can be found at www.westcarb.org/technicalpresentations.html.

3.2. The California Carbon Capture and Storage Review Panel

California's Greenhouse Gas Reduction Requirements

To stem the effects of global warming, the Global Warming Solutions Act of 2006 (Assembly Bill 32, or AB 32), commits California to (1) the achievement of a statewide greenhouse gas (GHG) emissions limit by 2020 based upon emission levels in 1990, and (2) the adoption of rules and regulations to "achieve the maximum technologically feasible and cost-effective" GHG emission reductions from specified sources or source categories. AB 32 followed Executive Order S-3-05, in which the Governor of California established three emission reduction targets: (1) by 2010, reduce GHG emissions to 2000 levels; (2) by 2020, reduce GHG emissions to 1990 levels; and (3) by 2050, reduce GHG emissions to 80% below 1990 levels. These goals are consistent with U.S. goals as reflected in the Copenhagen Accords and the recent United Nations Climate Change Conference agreements in Cancun.

The major sources of GHG emissions identified by the California Air Resources Board (ARB) are the transportation, electric power, industrial, commercial and residential, and agricultural sectors. While several long-lived gases contribute to GHG emissions, by far the dominant GHG in the State is CO_2 emitted from the combustion of fossil fuels used for transportation, electric power generation and industrial operations. Deep reductions in CO_2 emissions are thus required to meet California's commitments under AB 32.

Toward this end, considerable efforts are being focused in California on improving end-use energy efficiency and increasing the amount of electricity produced from renewable energy resources. These measures, as well as other mitigation options such as sustainable biofuels and smart growth, reduce the consumption of fossil fuels and will thus play important roles in California's energy future. Nonetheless, fossil fuels, including oil for transportation and natural gas for electricity production, will constitute a substantial component of California's emissions for some time to come. In order to utilize fossil fuels and meet the 2050 GHG emissions reduction goal, it will be necessary to deploy additional technologies. CCS is a technology that may need to be deployed on a significant scale to curb CO_2 emissions from power plants and industrial sources.

Creation of the Carbon Capture and Storage Review Panel

Recognizing the importance of CCS for California's industrial and electricity sectors, the California Public Utilities Commission (CPUC), California Energy Commission (Energy Commission), and ARB created a CCS Review Panel in February 2010. The Panel, composed of experts from industry, trade groups, academia, and environmental organizations, was asked to:

- Identify, discuss, and frame specific policies addressing the role of CCS technology in meeting the State's energy needs and greenhouse gas emissions reduction strategies for 2020 and 2050.
- Support development of a legal/regulatory framework for permitting proposed CCS projects consistent with the State's energy and environmental policy objectives.

The Panel held five public meetings on April 22, June 2, August 18, October 21, and December 15, 2010 to arrive at its findings and recommendations. These meetings were designed to solicit input from technical experts and key stakeholders and to allow the Panel to deliberate in an open, public setting. WESTCARB researchers served on the Technical Advisory Committee to the Panel, providing technical expertise through white paters and presentations during the Panel's deliberations.

During the time that the Panel was meeting and deliberating, other significant events occurred on the international, federal, and state levels. The recent international meeting in Cancun of the Conference of Parties to the U.N. Framework Convention on Climate Change recognized that CCS "is a relevant technology for the attainment of the ultimate goal of the Convention and may be part of a range of potential options for mitigating greenhouse gas emissions" and prescribed specific conditions and modalities for its eligibility under the Clean Development Mechanism. The federal government recently completed a multi-agency task force study that emphasized the importance of CCS for reducing GHG emissions and identified measures to help facilitate its use.

Additionally, the United States Environmental Protection Agency (EPA) recently issued new regulations under the Underground Injection Control (UIC) Program for the injection of CO2 into subsurface formations for the purpose of sequestration, as well as a subpart to the Greenhouse Gas Reporting Rule for annual reporting of emissions from geologic sequestration projects. These regulations by EPA are designed to safeguard underground sources of drinking water and to provide for the monitoring, reporting, and verification of injected CO2, and releases, if any. To a large extent, the rules for the new Class VI injection wells under the UIC program clarified a number of issues and needs identified by the Panel in its deliberations by defining the minimum requirements for implementing a CCS project. Nonetheless, a number of key issues facing CCS projects in California remain to be resolved.

What Are the Key Issues Facing CCS Projects in California?

The Panel identified a number of key legal and regulatory issues that require greater clarity and possible legislative action before CCS can be broadly deployed as a GHG mitigation measure under state laws and policies to reduce CO_2 emissions. Key questions include:

- Will CCS be eligible to meet the requirements of AB 32 or other relevant California laws and policies?
- Is there a clear regulatory framework and related permitting pathway for CCS projects in California?
- Are there clear agency rules that would allow for early CCS demonstration projects in the State?
- What additional considerations must be addressed and resolved to allow for the deployment of CCS?

Key Findings and Recommendations

The Panel deliberated on the issues enumerated above and put forth the following key findings and recommendations for consideration by the three principal agencies and the legislature. The body of this report provides more extensive background discussions of these key findings and recommendations, which were adopted at the Panel's final public meeting on December 15, 2010. As part of this issue analysis, a companion report, Draft White Papers: Carbon Capture and Storage in California, which contains extensive appendices, was also developed. All documents prepared by this Panel are available at www.climatechange.ca.gov/carbon_capture_review_panel/meetings/index.

Key Findings

- There is a public benefit from long-term geologic storage of CO_2 as a strategy for reducing GHG emissions to the atmosphere as required by California laws and policies.
- Technology currently exists for the safe and effective capture, transport, and geological storage of CO_2 from power plants and other large industrial facilities.
- High costs, inadequate economic drivers, remaining uncertainties in the regulatory and legal frameworks for CO_2 storage, and uncertainties regarding public acceptance are barriers to the near-term deployment of commercial-scale CCS projects in California.
- There is a need for clear rules under AB 32 regarding the treatment of CO_2 emission reductions from CCS projects involving capped and uncapped emission sources.
- Multiple state and federal agencies are currently responsible for permitting CCS projects in California.
- There is a need for clear, efficient, and consistent regulatory requirements and authority for permitting all phases of CCS projects in California, including CO_2 capture, transport, and storage.
- Standards are needed to ensure the safe and effective operation of geologic storage projects.
- Consistent requirements are needed for monitoring, measuring, verifying, and reporting injected CO2, and releases, if any, and for GHG accounting protocols necessary to comply with federal and state laws and policies to reduce CO_2 emissions.
- There is a need to establish clear financial responsibility for the stewardship of geologic storage sites during the (a) operating phase; (b) post-injection (pre-closure) monitoring phase; and (c) post-closure phase.

- The right to use subsurface pore space for geologic storage needs to be clarified.
- There is a need to address any potential environmental justice aspects of CCS projects.
- There is a need for increased public understanding of CCS benefits and risks.
- Absent new initiatives, economic barriers to early CCS deployment will delay the technological learning needed to drive down the costs of CCS.

Recommendations

To ensure that CCS can play a role in meeting California's requirements for GHG emission reductions:

> The State should recognize appropriately regulated CCS as a measure that can safely and effectively reduce atmospheric emissions of CO_2 from relevant stationary sources, including power plants and other industrial sources. To that end, and conditioned on compliance with all applicable federal and state requirements, ARB should: (a) for capped sources under AB 32, recognize CO_2 sequestered by CCS projects as having not been emitted to the atmosphere (with the result that an allowance is not required to be held for each ton of CO_2 that is captured and geologically stored) and define accounting protocols for sequestered CO_2; and, (b) for uncapped sources under AB 32, decide whether offset protocols for CCS projects within the State should be adopted.

To address regulatory and permitting issues related to CCS projects:

- The State should evaluate current EPA regulations and determine which, if any, State agency should seek "primacy" for permitting Class VI wells under the UIC program.
- The State should designate the California Energy Commission (Energy Commission) as the lead agency under the California Environmental Quality Act (CEQA) for preventing significant environmental impacts in CCS projects (both new and retrofit projects).
- The State should clarify that the State Fire Marshall is indeed the lead agency for regulating the safety and operation of intrastate CO_2 pipelines.
- The Energy Commission should consult with the responsible permitting agencies in carrying out its responsibilities as the CEQA lead agency for CCS projects. Specifically, the Energy Commission should:
    - Designate the Division of Oil, Gas and Geothermal Resources to be the responsible agency for activities related to the subsurface.
    - Coordinate the development of performance standards for CCS sites that would include design requirements and other operational measurements consistent with the goals of protecting the groundwater and preventing emissions of CO_2 to the atmosphere.
    - Designate the California Air Resources Board as the responsible agency for air-related aspects of CO2 monitoring, reporting, and verification requirements.
    - Designate the State Fire Marshall as the responsible agency for CO_2 pipelines.

  - Designate the State Water Board as the responsible agency for impacts to water quality.
  - Designate other agencies as appropriate.

To address key legal issues and uncertainties related to CCS projects:

- The State should consider legislation establishing an industry-funded trust fund to manage and be responsible for geologic site operations in the post-closure stewardship phase. In addition, California should proactively participate in federal legislative efforts to enact similar post-closure stewardship programs under federal law.
- The State legislature should declare that the surface owner is the owner of the subsurface "pore space" needed to store CO_2. The legislature should further establish procedures for aggregating and adjudicating the use of, and compensation for, pore space for CCS projects.
- The State should consider whether legislation is needed to extend to CO_2 transportation infrastructure for CCS projects the current authority for acquiring the rights of way for the siting of transportation infrastructure for natural gas storage projects.

To ensure the safe, equitable, and cost-effective use of CCS in California:

- It should be State policy that the burdens and benefits of CCS be shared equally among all Californians. Toward this end, the permitting authority shall endeavor to reduce, as much as possible, any disparate impacts to residents of any particular geographic area or any particular socio-economic class.
- The Panel endorses the need for a well-thought-out and well-funded public outreach program to ensure that the risks and benefits of CCS technology are effectively communicated to the public.
- The State legislature should establish that any cost allocation mechanisms for CCS project should be spread as broadly as possible across all Californians.
- The State should evaluate a variety of different types of incentives for early CCS projects in California and consider implementing those that are most cost-effective.

3.3. Outreach in Support of Geologic Pilot Projects

Arizona

Although CIEE was not responsible for the geologic pilot injection well in Arizona, the outreach component was under the responsibility of CIEE's subcontract to Bevilacqua Knight, Inc., and therefore reported here. A full description of the Arizona pilot is provided in the WESTCARB Phase II Final Report (under review).

The Cholla Well

Along with industrial partners, WESTCARB held two meetings in Holbrook, Arizona, (population of about 5000, U.S. Census, 2005). Holbrook is the largest community near the site of the Cholla well. Meetings were held on August 1, 2007, and on November 11, 2008. In both instances, a session with formal presentations was held first for public officials and community leaders, followed by a public open-house. Attendance at these events was moderate. People were interested and asked questions, and there were no negative comments.

During well drilling, daily progress reports were posted in the project section of the WESTCARB website. Other project-specific webpages featured field photos and detailed information on characteristics of the formations at the project site. WESTCARB's 2009 annual meeting in Scottsdale concluded with a tour of the drill site and of Arizona Public Service's Cholla Power Plant.

Black Mesa Basin

The Hopi Tribe's Water and Energy Team expressed interest in working with WESTCARB to drill a characterization well on tribal land in the Black Mesa Basin. The WESTCARB project team gave presentations on CCS and the proposed project, which did not include CO_2 injection, to the Hopi Tribal Council on June 17, 2010. A follow-on webcast with similar presentations to the Hopi Natural Resources Division was held on June 29. The Tribal Council approved the project, however, written affirmation that would allow the project to proceed was not forthcoming.

Three articles that were critical of the Council's actions and contained significant inaccuracies about the project were published in local newspapers. In response, WESTCARB staff assisted the Water and Energy Team by preparing a letter to the editor correcting the major errors. Approval for the project was subsequently rescinded by the Hopi Tribal Council.

California

On January 28, 2010, WESTCARB and its industrial partner, Shell/C6 Resources, co-hosted an open house in the town of Rio Vista, eight miles east a proposed CO_2 injection well site in the Montezuma Hills. The event featured sequential information tables that exhibited various aspects of CCS and provided details about the project. The open house, which was attended by about 100 people, was staffed by representatives from Shell, WESTCARB, and the California Energy Commission, who answered questions and listened to concerns.

The project team also presented the project at meetings of the Rio Vista Chamber of Commerce, the Rio Vista Lion's Club, and the Highway 12 Committee. This last group was concerned with safety on the local Highway 12, a section of which is referred to as "blood alley" because of its high rate of fatal accidents. In order to avoid further congestion that could have arisen from trucks hauling CO_2, C6 Resources planned an alternative route that avoided the highway.

Solano County planners requested a study of faults and the risk of induced seismicity for the proposed project area. Earth scientists at LBNL and LLNL, along with a seismic consultant, prepared and submitted a report. Additionally, two temporary seismic monitoring stations were set in place by LBNL to collect baseline data on background noise and noise from the wind turbines in the Montezuma Hills. Following the withdrawal of C6 Resources from the project, all activities, including outreach, were suspended.

WESTCARB's project experience highlights the importance of early engagement to a broad section of the community. Although each community is unique, major groups to consider in outreach planning include elected and safety officials; neighboring landowners and tenants; business, civic, environmental, and religious groups; neighborhood associations; schoolteachers; and local media. Contacts within such groups or organizations can assist with public notice of local meetings.

Strong outreach teams harness the talents of scientists, technical staff, and outreach personnel, and can require the participation of representatives from major project partners and contractors to ensure a cohesive and thorough effort. Planning for outreach should be integrated into all project phases, and a project can benefit by learning about a proposed host community early on—through interviews, focus groups, or informal conversations for example—to help determine what concerns the community may have.

3.4. Community Perceptions of Carbon Sequestration: Insights from California

[Refer to Appendix 11 for the full discussion.]

Given the potential importance of sequestration in U.S. energy policy, the views of communities that may be directly impacted by the siting of this technology were explored. Focus groups in two communities located near potential sites for WESTCARB's geologic storage pilots, were conducted. Communities want a voice in defining the risks to be mitigated as well as the justice of the procedures by which the technology is implemented. A community's sense of empowerment is key to understanding its range of carbon sequestration opinions, where 'empowerment' includes the ability to mitigate community-defined risks of the technology. This sense of empowerment protects the community against the downside risk of government or corporate neglect, a risk that is rarely identified in risk.

3.5. Environmental NGOs' Perceptions of Geologic Sequestration

[Refer to Appendix 12 for the full discussion.]

Non-governmental organizations (NGOs) have historically been influential in shaping public perceptions of environmental problems, their causes and their potential solutions. They are therefore an important part of the political process of creating and enforcing environmental laws. This paper investigates the current and future roles of NGOs in the United States in shaping public perceptions of CCS.

Over the last decade, many in the expert and advocacy communities have begun to think that CCS (and therefore geologic sequestration) may be a viable and important technological response to climate change. In recent years, U.S. political leaders have begun to talk about geologic sequestration as well. Little research has been done, however, to understand what NGOs' views are of these technologies, or if and how they plan to share them with the public. This study explored the following issues: How do leading environmental NGOs active in the United States perceive geologic sequestration? What might explain variations among NGO positions on this topic? And, how do they plan to share their views with the public, and otherwise engage in the politics of geologic sequestration and climate change?

The political impetus for geologic sequestration as part of U.S. energy policy is growing. Increasingly, political leaders and advocates speak as if geologic sequestration were a well-understood, reliable technology, ready to be used in large scale in conjunction with continued fossil fuel use.

Over the past few decades, however, conflicts over unpopular energy policies such as nuclear power have demonstrated the importance of societal acceptance for the successful implementation of new technologies. Evidence suggests that the lay public tends to trust information presented on energy technologies by NGOs, and environmental public-interest groups in particular, more than similar information presented by corporations or even government agencies.

The confluence of these environmental, political, and social factors suggests that NGOs' views of geologic sequestration may play an important role in shaping future energy policy. NGOs represent and, in a sense, speak for the public, especially the part of the public that constitutes their support and donor base. The study investigated how environmental NGOs perceive geologic sequestration, how and why their perceptions and strategies might differ, and how they plan to share their views with the public. A further analysis will be accomplished through the results of one-on-one interviews with representatives from selected NGOs, as well as a review of NGO histories of activism and sources of funding.

3.6. The Role of Social Factors in Shaping Public Perceptions of CCS: Results of Multi-State Focus Group Interviews in the United States

[Refer to Appendix 13 for the full discussion.]

Three of DOE's Regional Carbon Sequestration Partnerships analyzed community perspectives on CCS through focus groups and interviews in five communities. These perspectives were analyzed in the context of each community's history and its social and economic characteristics. The results were analyzed to gain insight into specific concerns within each region, as well as to assess inter-region commonalities. In all cases, factors such as past experience with government, existing low socioeconomic status, desire for compensation, and/or perceived benefit to the community were of greater concern than the concern about the risks of the technology itself.

4.0 REGIONAL TECHNOLOGY IMPLEMENTATION PLAN

[Refer to Appendix 14 for the full discussion.]

4.1. Purpose of the Regional Technology Implementation Plan

Studies of GHG mitigation pathways internationally and in the United States have identified carbon capture and storage (CCS) as critical to meeting emissions reductions. For timeframes from 2030 to 2050, deployment of CCS technologies is expected to be one of the largest contributors to CO_2 emissions reductions.[2,3]

This Regional Technology Implementation Plan (RTIP) provides an overview of the status of CCS technology evolution and adoption in the western region of North America, where GHG emissions under several climate change mitigation regimes set forth by states and provinces are targeted for significant reductions by 2050.

The RTIP does not predict to what degree CCS will contribute to these reduction goals. Rather it examines factors for successful CCS deployment, as well as issues that could limit or delay application of CCS technologies, and solutions for overcoming these issues. The RTIP aims to inform the discussion among parties concerned with lowering the region's GHG emissions—state and provincial policymakers, public interest nonprofits, regulated industries, and project developers—who recognize the need to include CCS among the technologies that will enable the region to meet climate change mitigation goals.

The RTIP discusses three types of CCS:

- Carbon capture and geologic storage:
  CO_2 from stationary industrial sources such as power plants, oil refineries, cement plants, and ethanol/biofuels plants is separated from fuel or exhaust gases and transported to a storage site for long-term storage in deep underground rock formations.
- Carbon Utilization:
  Revenue-generating uses for captured CO_2 that also contribute to GHG reduction goals (e.g., CO_2 injection for enhanced oil or natural gas recovery or enhanced geothermal energy systems).
- Terrestrial carbon storage:
  Optimizing the earth's natural absorption of CO_2 and retention of carbon in biomass and soil to increase the amount of carbon stored (e.g., tree planting and changes in forest management) or to preserve previously stored carbon (e.g., forest conservation).

Terrestrial carbon storage, carbon capture and geologic storage, and carbon utilization have the potential to significantly reduce GHG emissions in the WESTCARB region. The degree to which these climate change mitigation practices actually contribute to a low-carbon future will depend

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[2] *Advanced Coal Power Systems with CO_2 Capture: EPRI's CoalFleet for Tomorrow Vision—2011 Update: A Summary of Technology Status and Research, Development and Demonstrations.* EPRI, Palo Alto, CA: 2011 1023468.

[3] *Energy Technology Perspectives 2008: Scenarios & Strategies to 2050*, International Energy Agency, 2008: http://www.iea.org/textbase/nppdf/free/2008/etp2008.pdf

largely upon policy and economic drivers and the commitment of the citizens of the western region to pursue a course toward lower GHG emissions.

4.2. RTIP Findings for Carbon Capture and Geologic Storage

The RTIP examines carbon capture and geologic storage in six areas: policy and regulatory development, technology infrastructure, economics, project finance, legal considerations, and public acceptance. Major findings are outlined below. The RTIP concludes that geologic storage does not face significant barriers in the western region in terms of available storage space or the technical feasibility of injecting and monitoring CO_2 in the subsurface.

Estimated capacity in the region's broadly distributed sedimentary basins is enough to store hundreds of years of CO_2 emissions from industrial point sources. Opportunities for enhanced oil recovery combined with long-term CO_2 storage may be found in southern California and Alaska. CO_2 storage in coal seams, along with enhanced coal bed methane production, may prove beneficial in Alaska, Oregon, and Washington. Source-sink matching studies indicate generally favorable distances between the region's large point sources and potential sinks.

Injection and monitoring of CO_2 is unlikely to present industry-wide barriers. Both nationally and internationally, experience in oil and natural gas extraction and storage, the use CO_2 for enhanced oil recovery, and a small number of successful CO_2 storage projects lend confidence that CO_2 can be injected safely and monitored to establish long-term storage security.

The RTIP identifies and discusses three significant challenges to CCS, which are not unique to the western region.

1. ***Lack of climate change legislation to serve as a driver, and lack of a clear pathway for CCS where climate change legislation exists***

In the United States, anticipation of climate change legislation has served as a driver for developing CCS technologies. In the continuing absence of such legislation, the impetus for lowering GHG emissions is coming from rulemaking by the U.S. Environmental Protection Agency (EPA) under the Clean Air Act and from legislation enacted by some states. This "patchwork" approach fails to provide the legislative/regulatory certainty desired by industries when undertaking long-term planning and financial investments.

In California, where cap and trade regulations are being developed for implementation beginning in 2013, CCS has only been partially integrated into the state's GHG compliance framework. A further gap may open up if adoption of the 2050 GHG emissions reduction goal of 80% below 1990 levels is not enacted. Achieving this target without widespread deployment of carbon capture and geologic storage is considered by many analysts to be unlikely. However, the impetus for undertaking a long-term CCS project with high capital investment is missing until the 2050 target is codified into law.

In Washington, CO_2 injection and storage regulations that were adopted in 2007 as part of ESSB 6001 will now be subject to review and revision to be in compliance with the U.S. EPA's UIC Class VI well category, established in 2010.

2. *Costs*

The RTIP discusses the relatively high current costs of CO_2 capture and geologic storage. At this early stage, project developers are challenged to make a business case for a government-supported demonstration, let alone a commercial project. It is anticipated that costs will decrease as CCS technologies—particularly for CO_2 capture and compression—evolve and incorporate lessons learned. Ideally, CCS technologies will reach this stage of maturity before regulations compel widespread deployment. Under this scenario, the economic impact of achieving GHG emissions reductions would be significantly less.

3. *Public awareness and understanding*

Geologic CO_2 storage is often not well understood in public discourse. CO_2 itself is sometimes mistaken for a toxic or explosive substance. The risk profile for CO_2 storage is sometimes confused with pressurized pipelines at the surface or natural CO_2 releases associated with volcanic activity. Although misperceptions can be corrected through outreach and education, this takes time and resources, and depends upon the willingness of audiences to participate in the process.

CCS projects tend to be better understood and accepted in communities where oil and gas production or natural gas storage are common or where local educational institutions contribute to an understanding of subsurface operations, where project developers have an established presence and are trusted, or where benefits such as jobs creation or retention are aligned with community interests. Nonetheless, good geology for CO_2 storage will not always align with the locations of communities predisposed to hosting CCS projects, and this could affect siting.

4.3. RTIP Findings for Carbon Utilization

The RTIP notes the economic benefit of coupling CO_2 injection for enhanced oil recovery (EOR) with long-term CO_2 storage where opportunities exist. Revenue and CO_2 storage may also be realized from CO_2 injection for enhanced coal bed methane production, enhanced natural gas recovery, and enhanced geothermal energy systems. Novel CO_2 utilization technologies such as incorporation into building materials, use in fuel and chemical production, and expanded industrial applications are in earlier stages of development.

Successful deployment of CO_2-EOR in the WESTCARB region will require affordable supplies of CO_2. In California, sufficient volumes of CO_2 are not available locally and CO_2 pipeline transport from outside the state has not been economic. Thus, CO_2-EOR awaits the development of local CO_2 supplies via capture at industrial facilities and power plants. Additionally, in order to quantify and credit emissions reductions for CO_2-EOR projects, monitoring, reporting, and verification methods will need to be established and incorporated into state regulations and coordinated with federal regulations.

4.4. RTIP Findings for Terrestrial Carbon Storage

Terrestrial carbon storage projects have been a staple of voluntary carbon markets since their inception. Public perception of terrestrial carbon storage is generally positive when it accords with land-use practices such as conservation and restoration. Many landowners are motivated to undertake projects both as a means of generating income and to improve the state of their lands. Development and evolution of protocols/methodologies by independent carbon registries enable more project types to enter the voluntary carbon market and provide a basis for the development of offset protocols for compliance markets.

The RTIP finds that terrestrial carbon storage faces four primary challenges, which are not unique to the western region:

1. *Limitations on support due to lack of climate change legislation or structuring of policy instruments*

Widespread deployment of terrestrial sequestration depends upon climate change legislation and policy provisions allowing terrestrial carbon storage as a compliance option under a cap and trade program or offering other financing/incentive mechanisms. Although some states in the WESTCARB region have passed climate change legislation and are moving forward with GHG reduction programs, others await federal legislation, which is not an eminent prospect. This limits the compliance-driven demand for terrestrial carbon storage, as well as other types of offset projects.

Policy mechanisms include terrestrial carbon storage to varying degrees. For example, California's cap and trade program limits offsets to 8% of a regulated business's compliance obligation. However, given the projected size of the California carbon market and the assumption that regulated entities will utilize offsets to the fullest extent possible, this 8% limit is not expected to be a significant barrier to offset projects during the early years of the program.

In the case of Oregon's Climate Trust, the price of an offset is determined by the state's Energy Facility Siting Council and was about $1.40 per metric ton of CO_2 in 2011. By law, this can be raised every other year by 50%. These parameters constrain the cost of GHG compliance to facilities and customers but limit the level of funding the Trust has available for offset projects. Thus, project developers would be expected to seek funding from multiple sources.

Within a carbon market, terrestrial carbon storage projects compete with other types of offset projects. Internationally, forestry projects under the Clean Development Mechanism have been placed at a disadvantage because the risk of reversals has been handled by issuing credits that have to be replaced upon expiration by the buyer, and which therefore command lower prices than credits from other offset activities. The EU-ETS, the world's biggest carbon market, does not accept these temporary credits, which has limited funding for forest projects.

As the above examples illustrate, terrestrial carbon storage receives varying degrees of support under carbon regimes, which balance multiple objectives including cost containment, achievement of GHG reductions across multiple sectors, and assurance of offset quality and permanence.

2. *Establishing standards to ensure the quality of offsets*

The integrity of a carbon regime requires that GHG reductions be real. Offsets must be additional, verifiable, enforceable, and permanent. Thus far, there is little experience in the United States with

GHG offsets in a compliance market.[4] A 2008 report by the Government Accounting Office (GAO) on the voluntary market found that "participants in the offset market face challenges ensuring the credibility of offsets, including problems determining additionality, and the existence of many quality assurance mechanisms. GAO, through its purchase of offsets, found that the information provided to consumers by retailers offered limited assurance of credibility."[5]

Factors that help assure the quality of offsets include transparent, publically accessible project documentation, tracking, and accounting systems; third-party verification by qualified reviewers; and regular review and adjustment of offset program requirements to allow the program to respond to changes in science, technology, regulations, market conditions, or other relevant factors.[6]

Regional cap and trade programs in the United States and Canada are pursuing a standardized approach to qualifying offset projects, which establishes program requirements up-front, instead of evaluating projects on an individual basis, as is the case for the Clean Development Mechanism. A standardized system minimizes the potential for subjective evaluation in determining project eligibility. Projects are limited to certain categories for which sufficient market data are available and for which robust quantification, monitoring, and verification protocols already exist or can be readily developed.[7]

3. *Competition from other land uses*

Many lands in the western region that are favorable to terrestrial carbon storage can command high values from uses such as forest products, viticulture or other high-value crops, or conversion to development. In most instances, income from carbon storage alone will not provide sufficient incentive for landowners to undertake projects. The RTIP notes how increased carbon storage can be accomplished in conjunction with other land uses or, in the case of development, how CO_2 emissions can be kept to lower levels. Nonetheless, competition from other lands uses will undoubtedly limit the application of terrestrial carbon storage projects in some instances.

4. *Climate change impacts to habitats*

Although terrestrial carbon storage is a climate change mitigation strategy, there is a recognized need to incorporate adaptation planning into longer-term terrestrial carbon storage project planning. Successful adaptation will depend upon landowners and managers having timely access to information on anticipated changes in local conditions (e.g., soil moisture) and response options (e.g., which species can thrive in lower moisture/warmer temperature regimes and resist threats such as pest infestations). Climate change will also become an increasingly relevant factor in land-use decisions where the timing of costs and returns is spread over decades.

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[4] The Regional Greenhouse Gas Initiative accepts five types of offsets including CO_2 sequestration from afforestation.

[5] *Carbon Offsets: The U.S. Voluntary Market Is Growing, but Quality Assurance Poses Challenges for Market Participants*, GAO-08-1048, August 2008.

[6] *Ensuring Offset Quality: Design and Implementation Criteria for a High-Quality Offset Program*, developed by the Three-Regions Offsets Working Group, May 2010.

[7] Ibid.

Strategies for adapting to changing climate conditions will come from many sources. Analysts call for improved coordination among federal, state, and local agencies in conducting research and addressing situations where jurisdictions overlap.

5.0 THE NORTHERN CALIFORNIA CO_2 STORAGE PILOT PROJECT

5.1. Introduction

The revised overall goal of the Northern California CO_2 Storage Project was to gain practical experience in and demonstrate the potential for CO_2 storage in deep underground geologic formations in settings with high storage capacity near large CO_2 point sources. This involved development of a plan for field characterization of formations within the Central Valley depleted gas reservoir formations and underlying saline formations, to develop a safety plan and outreach plan for, and to drill and complete a geological characterization well. Additional work was undertaken to investigate the potential relationship between sequestration and seismicity in the area, and to evaluation a certification framework that would integrate seismicity.

The northern California pilot injection test was attempted at several locations with two separate industry partners. Originally the Northern California CO_2 Storage Project involved Rosetta Resources, Inc., an oil and gas exploration and production company. Two different sites were considered during the partnership with Rosetta, both near Thornton, California, south of Sacramento. However, internal decisions at Rosetta resulted in the company being unable to continue as WESTCARB's industry partner. Subsequently, C6 Resources, LLC, a Shell Oil Company subsidiary, approached WESTCARB about the possibility of performing a pilot test at another site in the Montezuma Hills near Rio Vista in Solano County. However, because of a continued lack of clarity in California regarding the status of CCS in the GHG regulatory framework and the outcome of corporate strategic business decisions, Shell decided to withdraw from the project.

5.2. Rosetta Resources Project Activity

The Central Valley of California, composed of the Sacramento River basin in the north and San Joaquin River basin in the south, contains numerous saline formations and oil and gas reservoirs that could be used for geologic storage of CO_2. The saline formations alone are estimated to have a storage capacity of 100 to 500 gigatonnes (Gt) CO_2, representing a potential CO_2 sink equivalent to greater than 500 years of California's current large-point source CO_2 emissions. In addition to being representative of very large sinks, there are over 11 megatonnes/year of CO_2 emissions, or sources, within the southern Sacramento River Basin. Depleted petroleum reservoirs are especially promising targets for CO_2 storage because of the potential to use CO_2 to extract additional oil or natural gas. The benefit of EOR using injected CO_2 to swell and mobilize oil from the reservoir toward a production well is well known. Enhanced gas recovery (EGR) involves a similar CO_2 injection process, but relies on sweep and methane displacement. There is need for field validation tests of this technology. CO_2 injection may enhance methane production by reservoir repressurization or pressure maintenance of pressure-depleted natural gas reservoirs or by preferential desorbing more methane in any gas-bearing formation. Based on favorable results of numerous EGR modeling studies, Thornton Gas Field (abandoned) was selected for the purpose of studying EGR processes. Depleted natural gas reservoirs are attractive targets for sequestration of CO_2 because of their demonstrated ability to trap gas, proven record of gas recovery (i.e., sufficient permeability), existing infrastructure of wells and pipelines, and land use history of gas production and transportation.

Site Description

The Northern California CO_2 Storage Project site (Rosetta) was located in southern Sacramento County in the heart of the Great Central Valley's fertile agricultural production region. (Figure 6). The proposed site was approximately 27 miles south of Sacramento, 23 miles north of Stockton, and two miles north of the unincorporated town of Thornton California, (population 1467), which was the closest town. Thornton contains several small businesses, a church, school, firehouse and residences. It does not have a town government; therefore, citizens rely on San Joaquin County to provide emergency services including police, fire and medical. Demographic highlights from the 2000 U.S. Census indicate that the Thornton area consists of 59.3 % Hispanic or Latino, 46.9% White, 3.5% Asian, 1.8% Black or African American, and 0.7% American Indian and Alaska Native.

The site is located within a couple of miles of U.S. Interstate 5, providing ready access to California's major ground transportation corridors, serving the San Francisco Bay, Sacramento, and Stockton metropolitan areas. CO_2 purchased from sources located in any one of these metropolitan areas could be easily trucked to the pilot location, eliminating the need for on-site CO_2 storage tanks during testing.

Regional Geology

The California Geological Survey divided California into 11 Geomorphic Provinces based on a common geologic record, landscape, or landform. Each province represents a unique area of the state with distinct geology, structure (i.e., faulting), topographic relief and climate. The pilot site is located in the Great Valley Geomorphic Province, a structural trough or basin filled with up to 40,000 feet (12.2 kilometers) of Jurassic to Holocene marine and nonmarine clastic sediments. Marine and deltaic sediments were deposited along the western convergent margin of the Cordilleran Mountains, which underwent rapid uplift and erosion during the Late Jurassic to Late Cretaceous Cordilleran Orogeny.

Thick marine sediments continued to accumulate along the Farallon-North American Plate boundary during the early Cenozoic era before the California Coastal Range began its rapid uplift during the middle Cenozoic. Cenozoic evolution of the Coastal Range, characterized by intense faulting and alternating periods of uplift and subsidence, created the western boundary of the structural trough. Corresponding uplift and subsidence of the Central Valley resulted in deposition of alternating layers of undifferentiated nonmarine and marine sediments, respectively, across the basin.

Sacramento Basin Province

The Sacramento Basin Province of the Pacific Coast Region is a gas-producing province with 73 gas fields throughout the province and two small oil fields in the southern part of the basin. The Domengine Formation, a late Eocene sandstone, provides most of the gas production in the southern Sacramento Basin; however, other reservoir rocks include sandstones in the Winters Formation, Starkey sands, Mokelumne River Formation, Martinez Formation, Capay Formation, Nortonville Shale, Markley Formation, Lathrop sands, Tracy sands, Blewett sands, Azevedo sands and Garzas sand. Most of these sandstones are of marine origin, ranging in thickness from 4 to 550 feet (1.2–168 meters) and having porosities and permeabilities ranging from 10 to 34% and 5 to 2406 milliDarcy (mD; 4.9E-15–2.37E-12 m^2). Organics in the Winters Shale or Sacramento Shale are suspected of being the source of hydrocarbons for the Winters-Domingene natural gas system.

Thornton Gas Field

The abandoned Thornton Gas Field was the host for the proposed pilot test. It is located near the southern end of the Sacramento Basin Province gas production from the Thornton gas field began in the mid-1940s and continued through the late 1980s, producing nearly 53.6 billion cubic feet (Bcf; 1.52 x 10^9 m^3) of natural gas from approximately 15 now abandoned wells. Commercial gas deliveries began in December 1946.

The formations at the Thornton Gas Field are representative of dozens of gas-producing fields in California, the cumulative storage capacity of which is estimated at 1.7 Gt CO_2. Storage capacity of Rio Vista is estimated to be over 300 megatonnes (Mt) CO_2, sufficient to accommodate CO_2 emissions for over 80 years from a nearby 650 MW gas-fired power plant.

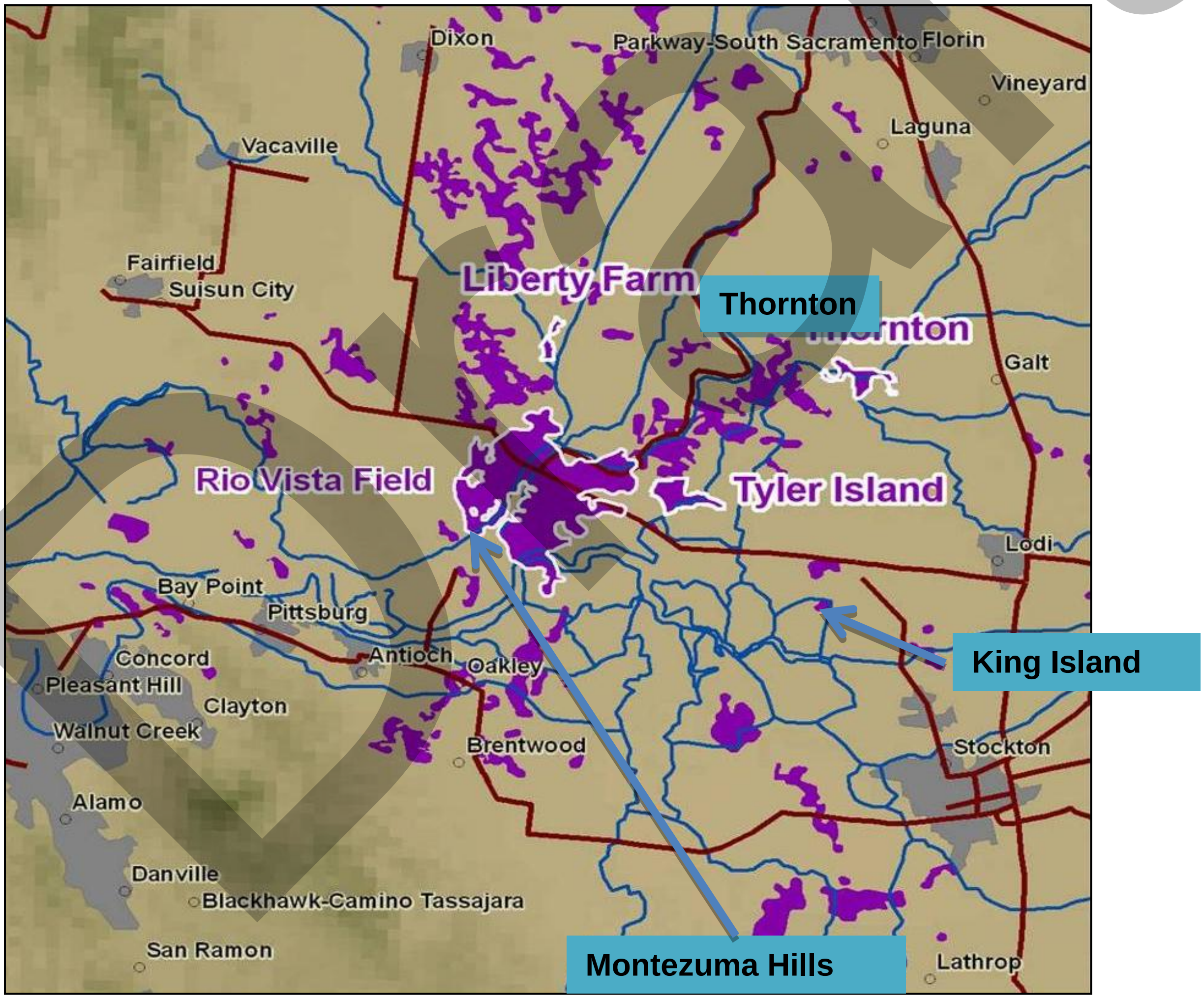

Figure 6. Gas fields of the southern Sacramento-northern San Joaquin Basins and locations of the WESTCARB candidate sites: Thornton Gas Field, King Island Gas Field, and Montezuma Hills area.

Structure and Faulting

The Thornton Gas Field consists of an east-west trending anticline structure with an estimated maximum productive area of approximately five square miles. The original gas-water contact was reportedly at a depth of 3,360 feet (1,024 meters). Natural gas was produced primarily from the top of the Mokelumne River Formation (known locally as the Capital Sand) with smaller localized plays found in the overlying Domengine sandstone (known locally as the Emigh) and sand stringers in the Capay Shale and Nortonville Shale. The proposed pilot test location where a new injection well and observation well were to be drilled is near the top of the anticline structure.

The Midland fault is the closest major fault zone to the Thornton Gas Field, located approximately 10 to 15 miles (16–24 kilometers) west of the pilot site. The Midland fault does not exhibit a surface trace; rather it is thought to be a blind, high-angle west-dipping normal fault with a north-northwest trend or strike. The Midland fault trace was identified and mapped using subsurface correlation between stratigraphic units and seismic reflection data derived from wells and geophysical surveys collected during gas exploration. The Midland fault accommodated extension and subsidence that occurred in the late-Cretaceous to early-Tertiary Sacramento Valley forearc basin. Normal displacement along the fault ended by the Eocene epoch; however, minor normal displacement may have occurred in late Miocene time. Seismic reflection data indicates that post-Miocene reactivation of the Midland fault occurred to accommodate reverse slip caused by horizontal shortening of the crust. Estimates for the long-term average slip rate for the Midland fault range between 0.004–0.02 inches/year (0.1-0.5 mm/year).

There are very few faults identified in the immediate vicinity of the pilot test. Two minor faults are identified on the California Division of Oil and Gas structural contour map of the top of the Capital Sand and these faults are located outside the productive area. The faults have normal displacement and strike north-south.

Stratigraphy

A detailed look at the stratigraphy of the Rio Vista field shows that units lying east of the Midland fault in the Rio Vista area are also present at a slightly shallower depth in the Thornton Gas Field. The field was discovered in May 1943 with the drilling of "Capital Co. 1" well by Amerada Hess Corporation. The well was drilled to a total depth of 8,367 feet (2,550 meters) and completed in the Capay Sand at a depth of 3,380 feet (1,030 meters). The primary production zone was in the Capay Sand (later called the Capital Sand) of the late Cretaceous Mokelumne River Formation. This pay has an average depth of 3,280 feet (1,000 meters) and an average net thickness of 30 feet (9 meters). The Mokelumne River Formation consists of a series of interbedded sands and shales deposited in a deltaic system.

A regional unconformity separates the Mokelumne River Formation from the younger Eocene Capay Shale. The intervening Paleocene sediments including the McCormick Sand, Anderson and Hamilton sands and Martinez and Meganos Shales are missing from the stratigraphic column and were either removed by erosion or not deposited when the Midland fault was active up through the early Eocene.

Additional gas production zones were identified at the Thornton Gas Field in the 1960s and 1970s including those found in the Eocene age Capay Shale, Domengine Sand and Markley-Nortonville Formation. These units are conformable with each other. Thin pay zones were produced from these three units at various depths ranging from 2,313 to 3,050 feet (705–930 meters) with an average net thickness of only 16–26 feet (5–8 meters). These zones were much less productive than the deeper Capital Sand. The lower Capay Shale was deposited in an outer neritic environment and the upper Capay was deposited in an inner-neritic to brackish water environment, implying a partial shoaling of the basin during the Eocene. The Domengine Sand consists of alternating layers of marine sand and shale with sand being the dominant lithology. The Markley sand is a poorly consolidated deltaic deposit containing interbedded sand and shale[8]. The Eocene sediments are unconformably overlain by approximately 2,000 to 2,300 feet (610–701 meters) of Miocene and Pliocene undifferentiated nonmarine strata.

Target Reservoirs

Saline Zone Test

The preliminary target depth for the Saline Zone CO_2 injection test is in the Mokelumne River Formation at a depth of 3,400-3,500 feet (1,036–1,076 meters). Depth intervals are based on logs from abandoned production well Capital Co. 2 and dry hole TransAm 1. Geologic logs and electrical logs were reviewed to look for a saline-test zone beneath a competent shale layer located below the original gas-water contact (-3,360 feet; -1,024 meters). Selecting a CO_2 injection zone below a shale and the original gas-water contact serves two purposes: 1) it keeps the CO_2 from contaminating any natural gas that might remain in the top of the original trap or reservoir (i.e., Capital Sand) that could potentially be produced in the future; and 2) the CO_2 is injected beneath the trap's thick seal (i.e., Capay Shale) minimizing the potential for CO_2 leakage out of the reservoir. Estimated depth to the bottom of the shale unit below which the saline formation test could take place is 3410 feet (1039 meters). Core collected from deviated well Bender #1 at a true vertical depth of approximately 3,330-3,400 feet (1,015–1,036 meters) have permeabilities ranging from 46 to 1,670 mD (4.5E-14–1.65E-12 m^2) and porosities ranging from 26.5 to 28.8% for the sands in the upper Mokelumne River Formation. The California Division of Oil and Gas reports pool data for the Mokelumne River Formation ranging from 31-35% for porosity, 40-45% for water saturation, 55-60% for gas saturations, and water salinity (NaCl) of 14,379 parts per million.

Gas Zone Test

Geologic logs and electrical logs were consulted a second time to look for a thin sand layer in the middle Capay Shale where gas was produced from abandoned production well Capital Co. 2. This thin sandy unit is continuous across the section, expressing itself in several well logs throughout the area. Gas was produced from a depth of 3,044 to 3,049 feet (927.8–929.3 meters) from 1962 to 1967 and

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[8] Johnson, D.S. 1990. Rio Vista Gas Field – USA, Sacramento Basin, California. *In*: Structural Traps III: Tectonic Fold and Fault Traps, *AAPG Treatise on Petroleum Geology, Atlas of Oil and Gas Fields*, vol. A-019, pp. 243-263

the well was plugged and abandoned in 1975 after first producing gas from a shallower interval in the Deadhorse Formation. Numerous shale layers occur in the Nortonville Sand and Markley Sand above the target zone, forming a thick seal for the proposed gas reservoir pilot test in the Capay sand stringer.

The Capay sand stringer may be a depleted, depletion-drive gas reservoir, whereas the deeper Capital Sand, where most of the natural gas production took place, is known to be a water-drive system. The reason for selecting a depletion-drive over a water-drive system was to understand the displacement of methane by CO_2 in a relatively simple compartmentalized system before studying a complicated water-drive gas reservoir. A compartmentalized reservoir will also ensure that the CO_2 gas will remain in place after the experiment concludes.

Reservoir properties were not available for the Capay Shale, so production data were analyzed using the transient wellhead pressure response matched to the Theis[9] type curve (i.e., exponential integral solution). The wellhead pressures were not converted to equivalent bottom hole pressures, and the natural gas was assumed to be ideal and flowing under isothermal conditions. Therefore, the permeability value of 4 mD (4E-15 m^2) determined using this approach should be considered a rough estimate of the Capay's true permeability. Furthermore, late time data were not used in the type curve match because the well started to produce water at the end of its production cycle. Approximately 0.9 Bcf (2.5E+07 m^3) of natural gas was produced from the Capay Shale sand stringer and well Capital Co. 2 during its five-year production history.

The pilot site lies within the Central Valley Hydrogeologic Province in the Cosumnes Subbasin (groundwater basin 5-22.16, DWR). The Rosetta Resources CO_2 Pilot Test site is located along the western boundary of the Cosumnes Subbasin. The Cosumnes Subbasin is defined by the aerial extent of unconsolidated to semi-consolidated sedimentary deposits that are bounded on the north and west by the Cosumnes River, on the south by the Mokelumne River, and on the east by consolidated bedrock of the Sierra Nevada Mountains. Annual precipitation ranges from approximately 15 inches (0.38 meters) on the west side of the subbasin to 22 inches (0.56 meters) to the east.

The Cosumnes Subbasin aquifer system is made up of three types of deposits including younger alluvium, older Pliocene/Pleistocene alluvium and Miocene/Pliocene volcanics (DWR, 2003). The cumulative thickness of these deposits ranges from a few hundred feet near the Sierra foothills to nearly 2,500 feet (762 meters) at the western boundary of the subbasin. The younger alluvial deposits include recent sediments deposited in active stream channels, overbank deposits and terraces along the Cosumnes, Dry Creek, and Mokelumne Rivers. These unconsolidated sediments primarily consist of silt, fine to medium sand, and gravel with maximum thickness approaching 100 feet (30.5 meters). The courser sand and gravel are highly permeable and produce significant quantities of water. Calculated specific yields for the younger alluvial deposits range from 6% for the alluvium to 12% for the channel deposits. These deposits form the near-surface aquifers at the pilot site.

The older Pliocene/Pleistocene sediments were deposited as alluvial fans along the margin of the Central Valley. These sediments consist of loosely to moderately consolidated silt, sand and gravel

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[9] Theis, C.V. 1935. The Relation Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Ground-Water Storage. *Transactions, American Geophysical Society*, 519-524.

deposits ranging from 100 to 650 feet (30.5–198 meters) thick. The older alluvial sediments are exposed between the foothills of the Sierra Nevada and the overlying younger alluvium near the western margin of the subbasin and valley center. Calculated specific yields are about 6 to 7% and the aquifers in this unit exhibit moderate permeability.

The Mehrten Formation (Miocene/Pliocene volcanics) consists of alternating layers of "black" sand, stream gravels, silt and clay, with interbedded layers of tuff breccia. The gravel aquifers are highly permeable and the interbedded tuffs serve as confining layers. Wells completed in this unit typically have high yield. The deposit ranges in thickness from 200 to 1,200 feet (61–366 meters) and forms a discontinuous band of outcrops along the eastern margin of the basin. Specific yields range from 6 to 12%.

Data for State Well Number 05N05E28L003M (California Department Water Resources monitoring network) located 0.5-miles (0.8-kilometer) west of the pilot location indicates that depth to groundwater ranges from 1.5 to 12 feet (0.46–3.6 meters) below ground level, depending upon the time of year. Shallow groundwater at the pilot site is also expected to be within a few feet of land surface and expected to respond to seasonal changes in surface water levels in the adjacent rivers and slough, similar to well 05N05E28L003M.

Regional groundwater elevations in the adjacent Sacramento Valley Groundwater Basin indicate that a steep hydraulic gradient exists at the margins of the Central Valley and Sierra Nevada mountains, where valley recharge takes place. Groundwater discharges near the axis of the Central Valley as base flow, adding to the overland component of the surface water runoff derived from snow pack and precipitation originating in the adjacent Sierra Nevada Mountains. The Thornton field site is located in a low-lying swampy area with groundwater elevations near land surface, characteristic of a regional groundwater discharge location.

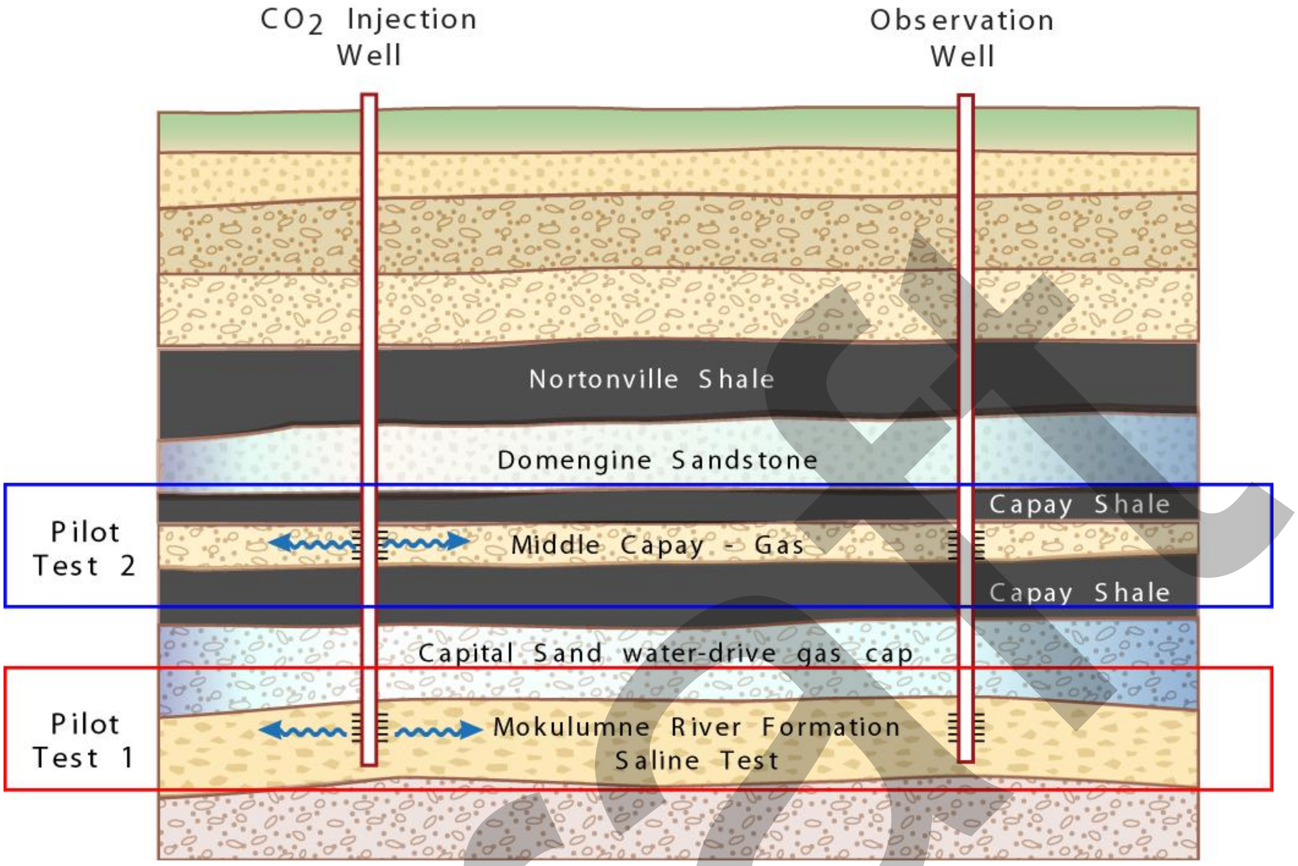

Figure 7. Proposed pilot test configuration*

**Pilot tests 1 and 2 were to be performed in a saline formation and abandoned gas reservoir, respectively, using the same pair of wells.*

Test Overview

Figure 7 provides a simplified chronology and visual overview of the original Rosetta Resources CO$_2$ pilot test program. The plan called for two wells to be installed, perforated, and utilized for both pilot tests. One of the wells was to be used as a CO$_2$ injection well and the second as an observation well. Both wells were to be drilled from a single drill pad at land surface to a maximum depth of 4,000 feet (1,220 meters). Drill core was to be collected during drilling for subsequent off-site testing and mud logging will be conducted on-site for each hole to provide input to the site geologic conceptual model. Open and cased well logs were to be performed to further characterize site geology and to determine reservoir conditions and parameters. Baseline site characterization activities were to consist of geophysical measurements, pressure-transient testing, and baseline monitoring of reservoir fluid composition, reservoir static pressure and temperature, shallow groundwater quality and water level, and leak detection around a now-abandoned nearby gas production well.

Upon completing the baseline activities, up to 2,000 tonnes of CO$_2$ were to have been injected into the saline formation at an anticipated depth of 3,400-3,500 feet (1,035-1,065 meters) (Pilot Test 1). The injection period would be approximately 10-14 days in duration with a series of measurements performed to track the spread of CO_2 as it moves through the formation. Post-injection monitoring of the CO_2 plume would be conducted for a three-six month period following injection to look for CO_2 leakage from the saline formation into overlying formations and to track the movement of the buoyant CO_2 after injection ends. The well perforations were to be cemented shut after the saline formation pilot test is complete and new perforations will be shot through the well casing across the targeted gas reservoir in preparation for the gas reservoir pilot test (Pilot Test 2). Up to 2,000 tonnes of CO_2 were to be injected into the gas reservoir at an anticipated depth of 3,045-3,050 feet (~930 meters). Again, the injection period would be approximately 10-14 days in duration. Monitoring of CO_2 was to be repeated for the gas reservoir to characterize and track CO_2 movement over a second three-six month period. Commercial grade, manufactured CO_2 was to be trucked in and used for both pilots. Upon completion of the project, the wells were to be abandoned in accordance with California State law and the site restored.

5.3. C6 Resources Project Activities

Following the withdrawal of Rosetta Resources from the Northern California CO_2 Storage Project, a partnership with C6 Resources, LLC, an affiliate of Shell Oil Company, was discussed and WESTCARB's intended pilot test site was shifted to the Montezuma Hills of Solano County, California. C6 Resources was interested in evaluating the site's potential for a commercial-scale CCS project to sequester captured CO_2 from Shell's Martinez refinery.

WESTCARB and C6 planned to jointly (1) undertake a pilot injection test and supporting outreach and permitting activities, (2) coordinate geophysical, hydrological, geochemical, and geomechanical characterization work (3) explore options and perform background work to support a possible scale-up from a small-volume (6000 tonnes) CO_2 injection pilot to a Phase III large volume (several hundred thousand metric tons) injection project to a commercial-scale (1 million tonnes per year). Outreach activities and permitting applications were pursued successfully for the 6000 tonne test. However, in mid-August 2010, Shell informed WESTCARB that a corporate decision had been made not to pursue CCS activities further at the Montezuma site. This decision precluded WESTCARB from continuing any of its work at the site as well.

Leakage Risk Assessment

LBNL undertook a preliminary leakage risk assessment for the Montezuma Hills site using the Certification Framework methodology (Appendix 15).

Through a phased process that involves drilling an appraisal well and injecting CO_2 on a small scale, along with thorough analysis of data and modeling of the system, the goal of the project is to assess the deep geologic formations in the area for Geologic Carbon Sequestration (GCS), and if favorable, inject CO_2 currently emitted to the atmosphere from nearby refinery facilities at industrial scales on the order of one million tonnes of CO_2 per year. The deep geology at the site is considered very favorable for GCS by virtue of the numerous sandstone formations which are potentially capable of storing large amounts of CO_2 and which are vertically separated by thick shale formations that prevent CO_2 from migrating upward. This general geologic environment is a proven trap for natural gas over geologic time as evidenced by the nearby Rio Vista Gas Field. Assuming step-by-step progress through the various stages, the Montezuma Hills project will involve drilling an appraisal well to over 10,000 feet (3,500 meters) depth, carrying out a small-scale evaluation injection of 6,000 tons of CO_2, and evaluation of the feasibility of developing the site for a large-scale injection (e.g., one million tonnes of CO_2), and further consideration of the site for an industrial-scale GCS operation (e.g., 0.75 million tonnes CO_2/year for 25 years).

Because GCS is not widely carried out either in the United States or abroad, there is very little experience upon which to base estimates of performance of GCS systems. In the absence of a long track record, leakage risk assessment methods are needed to address concerns by the various stakeholders about the effectiveness of CO_2 trapping and the environmental impacts resulting from CO2 injection. For the last two years, investigators at the Lawrence Berkeley National Laboratory, the University of Texas at Austin, and the Texas Bureau of Economic Geology have been developing a framework called the Certification Framework for estimating CO_2-leakage risk for GCS sites. Risk assessment methods such as the certification framework rely on site characterization, predictive models, and various methods of addressing the uncertainty inherent in subsurface systems. This report presents a discussion of leakage risk issues for the Montezuma Hills project and an outline of the research that needs to be done to carry out a leakage risk assessment by the certification framework approach.

Seismicity Characterization and Monitoring at WESTCARB's Proposed Montezuma Hills Geologic Sequestration Site

WESTCARB, in collaboration with C6 Resources performed site characterization for a potential small-scale pilot test of geologic sequestration of CO_2 at the Montezuma Hills site (see Appendix 16). During the process of injection at a CO_2 storage site, there is a potential for seismic events due to slippage upon pre-existing discontinuities or due to creation of new fractures. Observations from many injection projects have shown that the energy from these events can be used for monitoring of processes in the reservoir. Typically, the events are of relatively high frequency and very low amplitude. However, there are also well documented (non-CO_2-related) cases in which subsurface injection operations have resulted in ground motion felt by near-by communities. Because of the active tectonics in California (in particular the San Andreas Fault system), and the potential for public concern, WESTCARB developed and followed an induced seismicity protocol. This protocol called for assessing the natural seismicity in the area and deploying a monitoring array if necessary. Appendix 16 presents the results of the natural seismicity assessment and the results of an initial temporary deployment of two seismometers at the Montezuma Hills site. Following the temporary array deployment, the project was suspended and the array removed in August of 2010.

Initial investigation of natural seismicity in the Montezuma Hills area found that the publicly available data sets were useful in characterizing historical seismicity, but that the locations of events in those databases were not very good for the study area. Our relocation of events showed a significant shift in locations. This highlights the need for dedicated monitoring stations designed for accurate locations in the area of study. The temporary array at Montezuma Hills was successful in characterizing noise sources, sensitivity and data recording parameters.

Induced Seismicity Risk

To address the risk of induced seismicity, LBNL and LLNL searched the literature for data about regional geologic stress, and the orientation and activity on faults in the area (Appendix 17) to analyze the potential for induced seismicity due to a proposed small-scale CO_2 injection project in the Montezuma Hills. Researchers reviewed currently available public information, including 32 years of recorded seismic events, locations of mapped faults, and estimates of the stress state of the region. They also reviewed proprietary geological information acquired by Shell, including seismic reflection imaging in the area, and found that the data and interpretations used by Shell are appropriate and satisfactory for the purpose of this report.

The closest known fault to the proposed injection site is the Kirby Hills Fault. It appears to be active, and microearthquakes as large as magnitude 3.7 have been associated with the fault near the site over the past 32 years. Most of these small events occurred 9-17 miles (15-28 kilometers) below the surface, which is deep for this part of California. However, the geographic locations of the many events in the standard seismicity catalogue for the area are subject to considerable uncertainty because of the lack of nearby seismic stations; so attributing the recorded earthquakes to motion along any specific fault is also uncertain. Nonetheless, the Kirby Hills Fault is the closest to the proposed injection site and is therefore our primary consideration for evaluating the potential seismic impacts, if any, from injection. Our planned installation of seismic monitoring stations near the site will greatly improve earthquake location accuracy. Shell seismic data also indicate two unnamed faults more than three miles east of the project site. These faults do not reach the surface as they are truncated by an unconformity at a depth of about 2,000 feet (610 meters). The unconformity is identified as occurring during the Oligocene Epoch, 33.9–23.03 million years ago, which indicates that these faults are not currently active. Farther east are the Rio Vista Fault and Midland Fault at distances of about 6 miles (10 kilometers) and 10 miles (16 kilometers), respectively. These faults have been identified as active during the Quaternary (last 1.6 million years), but without evidence of displacement during the Holocene (the last 11,700 years).

The stress state (both magnitude and direction) in the region is an important parameter in assessing earthquake potential. Although the available information regarding the stress state is limited in the area surrounding the injection well, the azimuth of the mean maximum horizontal stress is estimated at 41° and it is consistent with strike-slip faulting on the Kirby Hills Fault, unnamed fault segments to the south, and the Rio Vista Fault. However, there are large variations (uncertainty) in stress estimates, leading to low confidence in these conclusions regarding which fault segments are optimally oriented for potential slip induced by pressure changes. Uncertainty in the stress state can be substantially reduced by measurements planned when wells are drilled at the site.

Injection of CO_2 at about two miles depth will result in a reservoir fluid pressure increase, which is greatest at the well and decreases with distance from the well. After the injection stops, reservoir fluid pressures will decrease rapidly. Pressure changes have been predicted quantitatively by numerical simulation models of the injection. Based on these models, the pressure increase on the Kirby Hills Fault at its closest approach to the well due to the injection of 6,000 tonnes of CO_2 would be a few pounds per square inch (psi), which is a tiny fraction of the natural pressure of approximately 5,000 psi at that depth. The likelihood of such a small pressure increase triggering a slip event is very small. It is even more unlikely that events would be induced at the significantly greater depths where most of the recorded earthquakes are concentrated, because it is unlikely that such a small pressure pulse would propagate downwards any appreciable distance.

Therefore, in response to the specific question of the likelihood of the CO_2 injection causing a magnitude 3.0 (or larger) event, this preliminary analysis suggests that no such induced or triggered events would be expected. However, it is possible that a fault, too small to be detected by the existing seismic data, yet sufficiently large to cause a magnitude 3.0 event, could exist in close proximity to the injection point where the pressure increase could cause slippage. However, the existence of such a fault would be detectable in the data planned for collection from the well prior to injection. It should be noted that natural earthquake events of up to 3.7 in magnitude have occurred in this area and would be expected to occur again regardless of the proposed CO_2 injection.

To reduce the uncertainties discussed above, the following recommendations are made: (1) installing a seismic monitoring network to record natural and possible induced seismic activity before, during, and after CO_2 injection; (2) collecting well log data and core samples from the wells to assess the in-situ stress state and fracturing near the wells; (3) using this information to refine operating procedures to minimize the risk of significant induced seismicity and develop a protocol for mitigation should it occur; (4) conducting geomechanical analyses and developing a probabilistic seismic hazard analysis (PSHA) during and after injection; (5) as the project progresses, relocating microearthquakes in the Northern California Seismic Network catalogue, calculating focal mechanisms where possible, and improving characterization of the Kirby Hills Fault; and (6) evaluating PSHA results for the Montezuma Hills area.

5.4. Down-Select Report for Northern California Pilot Project

Available geologic and nontechnical data were selected to identify two top-ranked candidate sites for its Phase III field characterization projects: a preferred site and a backup location. The report (Appendix 18) provides a summary of the data and criteria that were used to support down-selection to the King Island site, with the Kimberlina site as a back-up. This report served to the DOE to determine if there is sufficient evidence including favorable geology to support a decision to proceed with the installation of the test borings. Additional information on access and permitting is also provided.

The major technical objective of its site selection process is to find a site which would allow sample and data collection from as many of the key storage and sealing formations of the Sacramento-San Joaquin Basin as possible, the same formations which were targets for injection at the Phase II and Phase III candidate sites. A set of geologic and geographic criteria and nontechnical/logistical criteria was developed in order to rank potential characterization well sites (Table 3) In addition, the site was evaluated to assure that the well plan would be able to meet the scientific objectives of the characterization well project.

Table 3. Characterization well site selection criteria

Category	Criteria Description
Geologic and Geographic Criteria	Well-defined stratigraphy or structure that should minimize CO_2 leakage
	No impact on low-salinity (<10,000 mg/L TDS) aquifers; minor impact on a deep, high-salinity aquifer beneath a confining seal formations
	Location is unlikely to cause public nuisance (noise, traffic, dust, night work, etc.) and does not disturb environmentally protected or other sensitive areas
	Well will intersect formations identified as potential major storage resources for the region
	Area is in sufficiently close proximity to large volume CO_2 sources
	Sufficient preliminary geologic data (hydrogeologic data, well logs, seismic surveys, rock and fluid properties) available to inform site down-select process yet not so much as to make characterization well unnecessary to fill knowledge gaps
	Major faults in area are known and can be assessed for their potential as leakage pathways
	Depth of storage formations are greater than 800 m (~2,600 feet) to keep CO_2 in dense supercritical state
	Potential for CO_2 utilization at site improve likelihood of early CCS development opportunities
Non-technical/ Logistical	Surface owner grants project access
	Subsurface (mineral rights or well) owner grants project access and accepts well liability
	Pre-existing roads and easy access for heavy equipment
	Pre-existing well pad or well to eliminate or minimize surface disturbance and easy access for heavy equipment
	Ease of permitting process

WESTCARB has been performing site characterization work in California in collaboration with the California State Geologic Survey, with various industry partners with interest in CCS development, and in preparing for its original Phase II pilot injection and Phase III large volume storage test phases. The knowledge gained in these endeavors (see above, under section 6.2) was reviewed and used as a starting point for the characterization well down-selection.

Four sites were considered: King Island, Thornton, Kimberlina and Montezuma Hills. All sites met the geologic/geographic criteria, however the geology at King Island and available data offer some advantages over the other sites. The King Island site (Figure 6) meets the scientific objectives better than the other three sites considered. Furthermore, King Island is the only site that completely fulfills the nontechnical/logistical criteria. Kimberlina is a close second based on these criteria and was chosen as a back-up on that basis. King Island meets the criteria, related to liability, permitting, site access and other non-technical factors necessary to assure successful completion of the project. In the case of the other sites selected, as is described in more detail below, these non-technical factors were the criteria eliminated the sites from further consideration.

5.5. King Island Characterization Well

[Refer to Appendix 18 for the full discussion.]

The King Island site is located a few miles west of U.S. interstate 5, providing ready access to California’s freeway corridors serving the San Francisco Bay, Sacramento, and Stockton metropolitan areas (Figure 6). The site is close to significant CO2 point sources, including the nearby Lodi energy center (NGCC power plant), and to industrial sources such as Contra Costa County oil refineries. There were no access limitations associated with the site. WESTCARB was able to use an existing natural gas production well as a re-entry point to drill a deeper well, thus eliminating the need for new surface construction or disturbance, which left more funds for the scientific program, as well as streamlining permitting with the California Division of Oil, Gas and Geothermal Resources (DOGGR), CEQUA, and NEPA. A permit was issued by DOGRR on May 17, 2011, to re-enter the King Island gas well, and an environmental questionnaire was submitted to DOE on September 22, 2011.

WESTCARB partner and mineral rights and well owner (Princeton Natural Gas, LLC) procured the drilling permit at its own expense and assumed liability for the well. The owner also agreed to assume ownership and responsibility for the well after completion of the WESTCARB project. The surface landowner gave permission to access the well pad via unimproved, private roads.

The King Island site is located west of the Interstate 5 and south of Kettleman Lane (State Highway 12). The nearest communities are Stockton (pop. 290,000), about eight miles (13 kilometers) to the southeast, and Lodi (pop. 63,000), about five miles (eight kilometres) to the northeast. The immediate vicinity is rural.

The Mokelumne River Formation consists of a series of interbedded sands and shales deposited in a deltaic system. The Mokelumne is the producing formation at King Island. The lower Capay Shale was deposited in an outer neritic environment, and the upper Capay was deposited in an inner-neritic to brackish water environment, implying a partial shoaling of the basin during the Eocene. The Domengine Sand consists of alternating layers of marine sand and shale with sand being the dominant lithology. The Markley sand is a poorly consolidated deltaic deposit containing interbedded sand and shale. The Eocene sediments are unconformably overlain by approximately 2000 to 2300 feet (610–701 meters) of Miocene and Pliocene undifferentiated nonmarine strata.

Structural and stratigraphic information for King Island is provided by two wells in the King Island gas field and two in the nearby East Island gas field, which provide logging data and a 3D seismic survey of the King Island field (Figure 8) The King Island field is in a northeast-southwest trending structure with a seal provided by a mudstone-filled gorge cut. King Island Field has produced 10.3 bcf of gas, with an EUR of about 11 bcf. Natural gas was produced primarily from the top of the Mokelumne River Formation. Additional sequestration potential may be present in the overlying Domengine sandstone and the underlying Starkey sandstones.

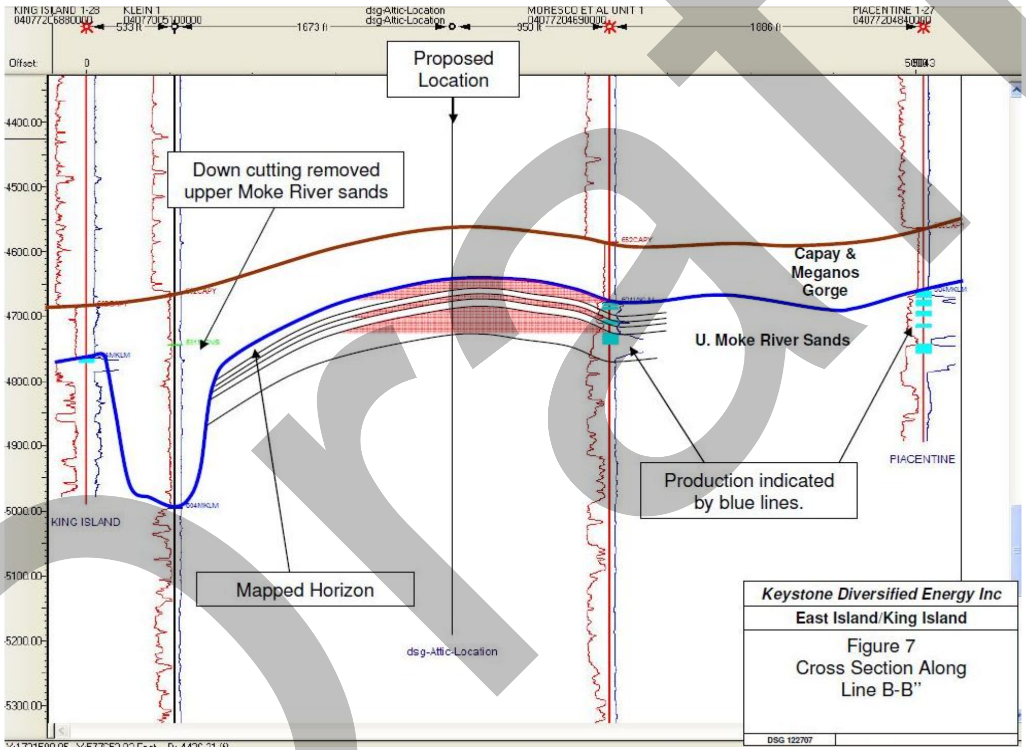

Figure 8. Cross-section of the East Island–King Island gas fields showing the inferred tops from resistivity logs of several gas wells within these fields. The King Island Citizen Green #1 well is indicated as a vertical well, but in order to avoid surface disturbance and to take advantage of an existing well pad, the well was actually deviated at 30°

The King Island characterization well retrieved core samples, and subsequent analysis of deep and shallow hydrocarbon and aqueous gas and liquid phases will help establish whether flow paths exist from the deep subsurface to shallower formations. Shale cap rock and storage sandstones will be included in the coring program. The samples were transported to laboratory test facilities at LBNL, where CO_2 injection tests will provide data on CO_2-rock-fluid interactions at the core scale to provide data for geohydrologic simulations of CO_2 fate and transport and to inform development of new monitoring techniques. At Sandia National Laboratory, shale samples will be tested to improve understanding of the geomechanical behavior of cap rocks. Other samples will be analyzed at commercial laboratories to acquire specific data to inform simulation activities. Part of the research objective of the King Island studies will be to improve understanding of the scalability of laboratory and field logging data.

In addition, earth scientists at LBNL will use the sophisticated numerical codes TOUGH2 and TOUGHREACT for modeling the movement of fluids in geologic formations. Simulation of the CO_2 injection and storage based on detailed site-specific hydrogeological models will be performed. The well constrained stratigraphy and structure from nearby wells and seismic surveys, multiple stacked sands, including gas-bearing and saline zones, and the acquisition of a robust set of petrophysical and geochemical data from the characterization well logs and samples will allow for a significant simulation effort. A geologically realistic mathematical model of the multiphase, multi-component fluid flow produced by CO_2 injection is indispensable for determining the viability of a potential storage site because capacity and trapping ability are both strongly impacted by the coupling between buoyancy flow, geologic heterogeneity, and history-dependent multi-phase flow effects, which is impossible to calculate by simpler means. Modeling may also be used to (1) optimize CO_2 injection by assessing the impact of various rates, volumes, and depths; (2) choose monitoring sensitivity and range by providing the expected formation response to CO_2 injection; and (3) assess the state of understanding by comparing model predictions to field observations.

Drilling Operations

The King Island site is at an elevation of 6 feet (2 meters) below mean sea level. The site is located within the Sacramento River drainage basin, which joins the San Joaquin River (which drains the southern part of the Central Valley) to form the Sacramento–San Joaquin River Delta system. The project site is located in a low-lying area protected by levees that have been installed along the river banks to prevent the property from flooding during winter and spring when peak precipitation and surface runoff occur.

The King Island well was deviated in order to take advantage of an existing well pad from an operational but no longer productive gas well, the Source Energy Corporation’s “King Island” 1-28 well (Figure 9). Because the site is in a relatively remote crop farming area, operations caused no disruption to residences or businesses. All facilities for fueling, waste storage tanks, power generators, etc., were brought by trailer to the site for temporary use during the project and fit within the footprint of the existing well pad.

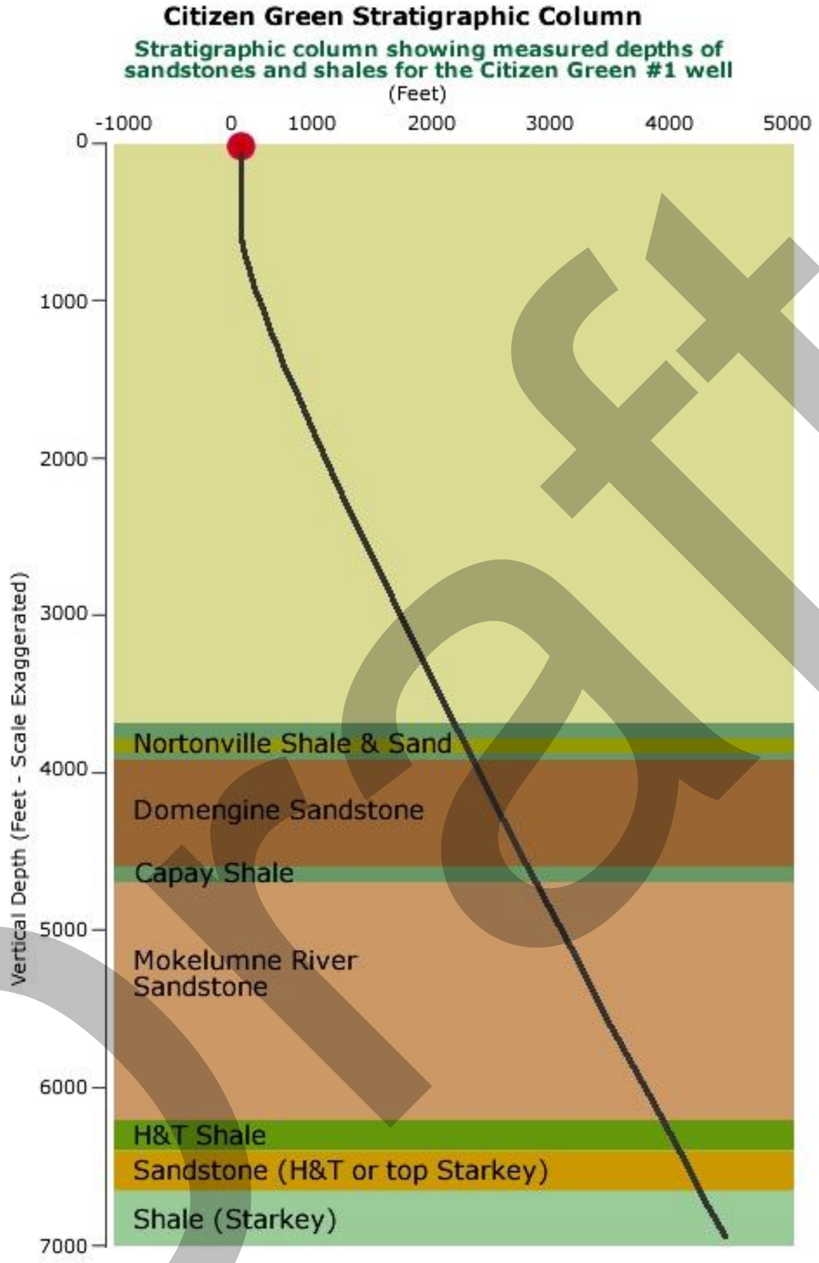

Figure 9. A schematic stratigraphic cross-section at the King Island Citizen Green #1 well indicating the deviated penetration of the borehole.

Sandia Technologies, Inc. was contracted to conduct field operations for the well. Plug-back activities at the former gas well commenced on August 30 and were completed on September 12, 2011. The start of drilling was delayed and drill pipe and other equipment were delivered between November 30 and December 2. Drilling began on December 3 (Figure 10), including the start of directional drilling once the bit passed the surface casing.

Figure 10. Citizen Green Well 1 drill rig at King Island.

Alaska Saline Sedimentary Basin CO 1

Because of the "sticky" shales encountered in the Central Valley, it was necessary to wipe the drill stem at regular intervals to prevent the drill stem from becoming stuck in the borehole.. Cores were taken between 4201 and 4249 feet; 19 feet (6.3 meters) of core was recovered from the Nortonville Sandstone.

On December 15, cores were drilled from 5246 feet to 5306 feet (measured depth), with 57.5 feet (19.2 meters) recovered from the upper part of the Mokelumne Sandstone. The hole was completed to target depth (7570 feet, measured depth) on December 19. On December 20, Schlumberger Carbon Services began open hole wireline logging (Platform Express multi-tool string) and logged from 516 feet to 7562 feet. Schlumberger completed a second logging run using the CMR-HNGS (Combinable Magnetic Resonance-Natural Gamma Ray Spectroscopy) tool on December 21. A MSIB/ECS (Multi-component Shear Sonic Log/Neutron Induced Spectroscopy Log) tool between 7562 feet and 3600 feet. On December 23, a sidewall coring tool was lowered into the well and 50 sidewall cores were drilled, of which 43 were recovered. Following Schlumberger's logging activities, the well was prepared for casing on December 25. Casing and active operations were completed on December 26. The rig and other materials were removed by December 28.

6.0 CENTRALIA GEOLOGIC FORMATION CO2 STORAGE ASSESSMENT

The goals of this task was to evaluate the potential CO_2 injectivity and storage potential of deep Puget Sound, Washington state, coal seams and other geologic formations near TransAlta Centralia Generation's coal-fired power plant, develop a conceptual plan for a pilot test, and identify engineering techniques needed to achieve large-scale geologic sequestration in Puget Sound coals.

A preliminary evaluation of the CO_2 storage potential of deep coal seams and saline aquifers in the Centralia-Chehalis basin of west-central Washington was performed by Advanced Resources International, Inc. (Appendix 19). The study assessed the feasibility of a potential CO_2 injection and storage test near TransAlta's 1,404 MW coal-fired power plant, near Centralia, Washington. The study determined that deep coals and interbedded saline aquifer sandstones within an identified target area may have 90 to 345 million tonnes of storage capacity, sufficient for 22 to 86 years of the Centralia power plant emissions (assuming 50% capture rate).

Data from the Centralia coal mine provided by study partner TransAlta, as well as coalbed methane pilot production testing in the region, allow detailed evaluation of the coal seam storage potential. Data for sandstone saline aquifers at Centralia were more limited—mainly lithologic and petrographic data, as well as analog data on underground gas storage and natural gas production fields in the region—permitting only a more generalized view of their storage potential.

CO_2 captured at the Centralia power plant could be injected into nearby deeply buried coal seams, the mining of which ceased in 2006. Thick, well-developed, subbituminous rank coal seams in the Eocene Skookumchuck Formation are capable of storing about 20 m^3/tonne of CO_2 at typical depths of 500-1,650 feet (150-500 meters). Coalbed methane testing in the region, though not commercially successful to date, has recorded encouraging levels of permeability (1-7 mD) and methane content (5-15 m^3/t). CBM testing experience indicates that land costs are low ($1/acre).

Thick sandstone saline aquifers also occur in the Eocene Cowlitz, Northcraft, and Skookumchuck Formations. The vast majority of these are of poor reservoir quality, comprising poorly sorted volcanic-derived sediments that have been hydrothermally altered with secondary chlorite, zeolite, and quartz mineralization. However, certain Skookumchuck sandstones interbedded with the coals have good reservoir quality, with porosity as high as 30% and permeability of up to 3 darcys. Anticlines near Centralia could provide structural traps. Comparable reservoirs and traps occur at the Jackson Prairie storage field 20 kilometers south of Centralia, which holds 650 million m^3 (23 Bcf) of natural gas. However, the lateral and vertical distribution of saline aquifer sandstones at Centralia is uncertain given sparse available well log control and additional testing is required to gather key data. Our initial estimate is that sandstone aquifers interbedded with the coal seams could store roughly 38 to 292 million tonnes, adding 9 to 73 years of storage capacity (at 50% capture).

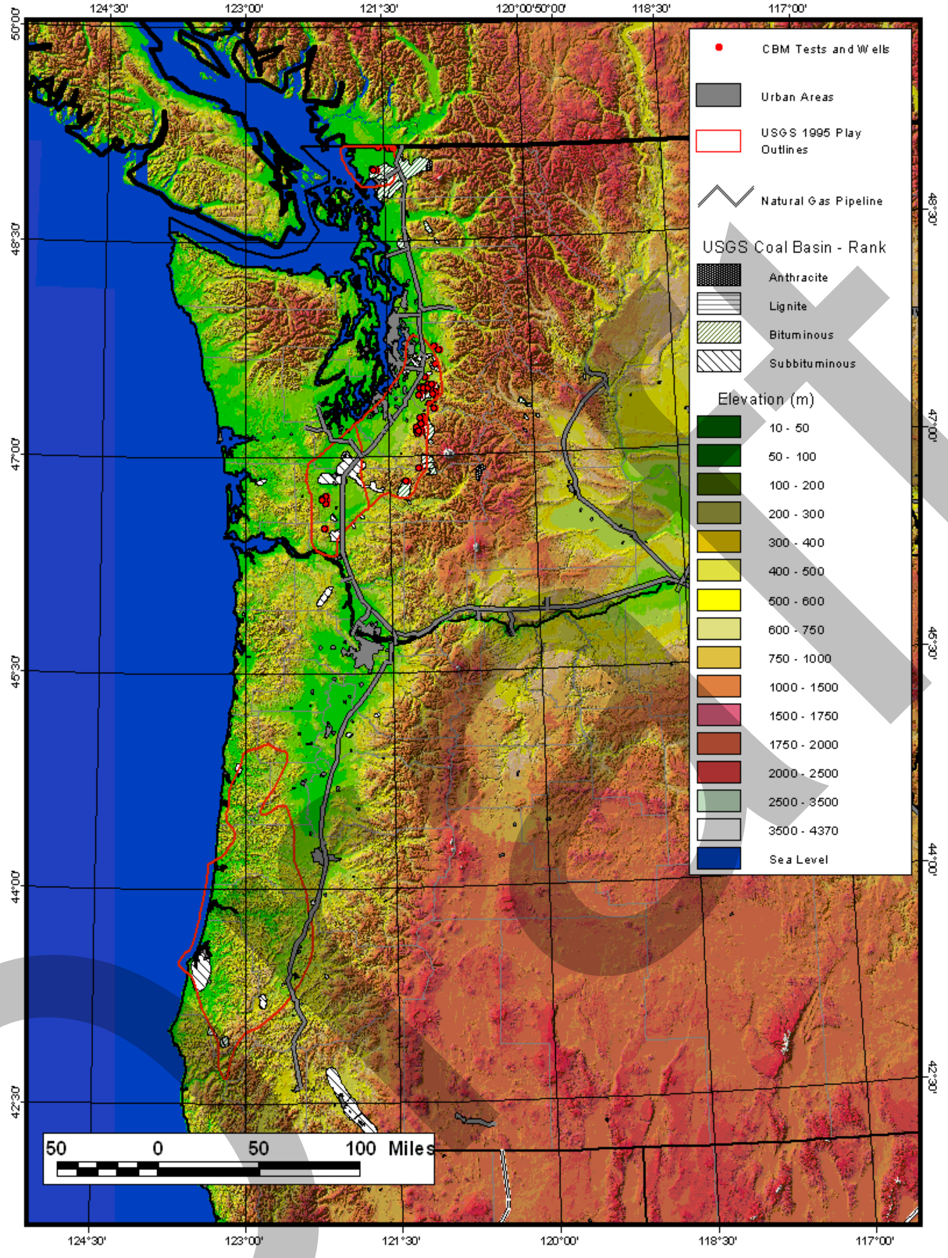

Figure 11. Location of the Centralia site, south of the Puget Sound, Washington

Geologic mapping indicates that approximately 52 million tons of CO_2 could be stored in coal seams adjacent to the power station, equivalent to about 13 years of current emissions (50% capture). Scoping reservoir simulation indicates that 0.16-km^2 (40-acre) injector spacing using vertical frac wells would be the most efficient and cost-effective design for CO_2 storage, minimizing breakthrough, swelling, and fracture gradient risks. This capacity could be augmented by saline aquifers or deep coals elsewhere in the Centralia-Chehalis or greater Puget Sound region.

Certain geologic characteristics at Centralia appear to be unfavorable for a CO_2 injection project. The Centralia region is strongly folded and faulted, including some potentially active faults. Fault compartmentalization may hinder effective CO_2 injection and storage and increase the number of injection wells required. The individual coal deposits are of relatively small size and partly mined out. The coals and sandstones are intruded by igneous dikes and sills. These challenges have hindered the commercial production of coalbed methane throughout the Pacific Northwest.

Centralia's interbedded coals and sandstones with limited individual capacity make the site a candidate for the stacked storage strategy, being pursued by SECARB in the Appalachian region for example, where multiple lower-quality zones are targeted for enhanced storage with reduced risk of leakage. Given the routine permitting experience of CBM and gas storage operations in Washington to date, a CO_2 injection test at Centralia should be low cost and straightforward to permit and implement. Success would provide a rare opportunity to advance CO_2 capture and geologic storage in the challenging Pacific Northwest region. A joint coal seam and saline aquifer test program, involving three to five coreholes, would be the next step to measure coal seam and saline aquifer reservoir properties at Centralia and better define their CO_2 storage characteristics and capacities.

7.0 METHODOLOGY FOR CARBON CREDITS FROM FIRE MANAGEMENT ON FORESTED LANDS

The goal of this task is to establish a methodology, which has broad credibility among scientists, for determining carbon credits for improved fuels management to qualify fuels management projects for carbon offset market recognition and validation. This methodology included measurement, monitoring, and verification (MMV) protocols for a range of fuel reduction activities to establish net emissions reductions benefits that could be credited to each fuel's management activity.

7.1. Emissions and Potential Emission Reductions From Hazardous Fuel Treatments in the WESTCARB Region

[Refer to Appendix 20 for the full discussion.]

Emissions from fire were identified in WESTCARB Phase I as the single largest source of GHG emissions from land use. Thus, the focus of this research was to determine if GHG emissions from wildfire could be reduced and provide a potential opportunity for landowners to generate a new type of carbon mitigation or "offset" activity. For such activities to yield GHG offsets, rigorous MMV methodologies and reporting protocols must be developed to meet the standards of voluntary and regulated markets for high-quality GHG reductions. Fire suppression and hazardous fuel accumulation are concerns primarily in low- to mid-elevation mixed conifer forests that prehistorically experienced frequent and low severity fires; analysis and findings were therefore focused on these ecosystems.

Purpose

The aim of this research was to determine whether a methodology could be developed for use by developers of potential carbon projects to quantify their baseline emissions, project emissions with activities to reduce hazardous fuels, and estimate the associated project carbon benefit.

Project Methodology

A conceptual framework was developed to determine the net impact hazardous fuel treatment activities have on the total quantity of greenhouse gases in the atmosphere? This framework incorporated the critical elements of fuel treatments and wildfire as they relate to net CO_2 emissions:

- Annual Fire Risk
- Emissions as a Result of Treatment
- Emissions as a Result of Fire
- Removals from forest Growth / Regrowth
- Retreatment
- Shadow Effect

The following framework was used to estimate losses and gains in stored carbon with and without treatments (with and without "project") and fire:

- **Gain** from *decreased* intensity or spread of fire due to fuel treatment within the treatment and shadow area * annual fire probability
- **Loss** from biomass removed during treatment
- **Gain /Loss** from substitution of fuels for energy generation
- **Gain** from long term storage as wood products from removed biomass during fuels treatment
- **Loss** from decomposition of additional dead wood stocks created through fuels treatment
- **Gain /Loss** from growth differences between with and without treatment and with and without fire
- **Loss** from fires occurring in with project case (with treatment) * annual fire probability
- **Loss** from retreating stands through time

A positive net result indicates increased carbon storage as a result of the with-treatment project, while a negative net result indicates a net loss in carbon storage and increased emissions as a result of the with-treatment project.

The individual elements of this framework were quantified to determine their overall impact on net emissions/removal, and on-the-ground projects were implemented to test the overall validity of the framework.

Project Outcomes

Fire represents a significantly more complex opportunity than traditional land use greenhouse gas reduction activities such as afforestation, changes in forest management, and forest protection. This is because a fuel reduction project compares emissions that would have occurred from fires without any treatment on the landscape, which necessarily requires a complex fire baseline modeling effort, against emissions that did occur through fuel treatment. For this purpose it was necessary to examine the risk of a fire burning through a particular location or fireshed in a given year and the emissions that would occur if such a fire did occur.

The reality is that fire risk in any given location on the landscape considered in this report is relatively low (< 0.76% per year), and consequently amortized baseline emissions are low. This reality must be balanced with the emissions that occur when a catastrophic fire does occur. While emissions from fire in the baseline scenario are relatively low, emissions from fuel treatment in the project scenario are not insignificant in that they occur across a relatively broad area in order to intersect with an unknown future fire location.

Substantial emissions occur in the event of a wildfire but significant greenhouse gas emissions still occur on treated sites. In addition regrowth of a healthy forest means that sites have to be retreated with accompanying emissions on a regular schedule (likely <20 years). The impact of growth is complex but in the absence of wildfire growth modeling for these projects show that the treated stands as a whole will store less carbon than the untreated stands—the opposite is true in the event of a wildfire but such a fire is a low probability event.

Consolidating across the conceptual framework the following conclusions are reached:

- Fire risk is very low (<0.76%/yr)
- Treatment emissions are relatively high and are incurred across the entire treated area
- Treatment never reduces fire emissions by more than 40% and on average across five sites only reduced emissions by 6%
- In the absence of fire, treatment reduces sequestration
- Retreatment will have to occur with accompanied emissions
- A positive impact of treatment beyond the treated area is not guaranteed and is unlikely to ever be large enough to impact net greenhouse gas emissions

So low fire probability is combined with high emissions and low sequestration in the absence of a fire and relatively few emissions reductions in the event of fire.

Conclusions

Reducing emissions from fire could be an important contribution to reducing CO_2 emissions overall, yet the inherent reduction of carbon stocks in hazardous fuels treatments, combined with the low annual probability of fire on a given acre of land prevent the development of a workable carbon offset methodology for such treatments. It may be possible that specific treatments, removing a minimum amount of small diameter ladder fuels in certain forest ecosystems can yield an overall emission reduction. Furthermore, low-emissions technologies to be developed in the future may yield increased emission reductions. In the case of the standard fuels treatments for mixed conifer forests in northern California and southern Oregon, which served as the field test for this research, treatments led to increased net emissions over the 60-year modeling period. However, reducing the risk of fire is a critical activity for many other reasons, including enhancing forest health, maintaining wildlife habitat, and reducing risk to life and property, and so hazardous fuel treatments must go ahead and should be planned to minimize net emissions.

In today's world where actions to curb atmospheric greenhouse gas concentrations are growing more urgent, an accurate accounting is important of all emission sources (and sinks) at national, regional and local scales. The work completed here allows a better understanding of the relative emissions that arise from hazardous fuel treatments and wildfires in low to mid elevation mixed conifer forests. While our results show that, in the absence of wildfire, fuels treatments did not lead to net emission reductions at these demonstration sites, it is important for planners to understand relative greenhouse gas emissions in order to be able to design treatments in a way that minimizes emissions while maximizing non-greenhouse gas benefits.

7.2. Wildfire Fuel Treatments as an Offset

[Refer to Appendix 21 the full discussion.]

Introduction

State and federal policies to suppress wildfires on forestlands in the United States have caused many federally owned forested landscapes to hold more biomass, both living and dead, than they would under a natural fire regime. This greater fuel load increases the likelihood of an uncharacteristically severe wildfire, which would emit an abnormally large amount of CO_2.

Fuel treatment projects are actions to reduce the risk of wildfire on a given landscape by removing biomass from specific forest stands to limit a fire's spread and intensity. There is hope that these projects could also reduce CO_2 emissions—primarily through the avoidance of CO_2 emissions from uncharacteristically severe wildfire—and could therefore be eligible to sell carbon offsets to help overcome funding barriers to implementation.

Purpose

The study presents findings from a landscape-scale case study in southern central Oregon that modeled the impact of fuel treatments on wildfire risk and associated CO_2 emissions; it then provides an assessment of the project type's ability to generate quality carbon offsets.

Project Outcomes and Conclusions

The case study indicates that it is possible to model both the baseline and project scenarios in a way that enables an accounting for the carbon benefit (or cost) of the fuel treatment project. It also indicates that:

- Fuel treatment projects may provide net gains in carbon emissions because the biomass removed from the landscape acts as a debit on the project that must be overcome before the project can accrue carbon offsets.
- Extrapolation of the case study results on fuel treatments, wildfire risk, and avoided CO_2 emissions indicates that this class of projects is more likely to be carbon-neutral than to provide significant emissions benefits.

Analysis of this project type indicates that even if the project provides quality offsets, the adoption of the project type may be limited due to the following project design requirements:

- The risk of reversal is high, which requires significant contributions of some of the offsets to buffer pools to insure against this risk.
- The need to continue to implement fuel treatment practices periodically on the landscapes for an additional 100 years after a project is completed can be a disincentive when recruiting project participants.
- The cost of third party verification will be high due to the need for verifiers to have specialized experience in wildfire ecology, forestry, and probabilistic simulation models.
- The cost of monitoring and verification will be high due to the long span of time that both activities are periodically required to occur (project life plus 100 years).

In order to provide certainty that the emissions event would have happened, fuel treatment projects should be considered as a subset of the improved forest management project type; in effect, a fuel treatment project is a commitment to manage the risks of wildfire on a forested landscape. This allows the project lifetime to be defined so as to include an uncharacteristically severe wildfire occurrence in the baseline case with near certainty.

Recommendations

Fuel treatment projects are likely to be near carbon-neutral and therefore do not make good offset projects. However, fuel treatment projects could be critical to long-term climate strategies, because changes in climate will likely increase the risk of uncharacteristically severe wildfires. In addition, there is potential to use the biomass removed by fuel treatment practices to create energy or biochar, both of which could benefit the climate and rural economies.

Federal policymakers should provide clarity about the appropriate role for private financing on public lands, because additionality concerns for projects on public lands is such an important issue for this project type. It is also recommends that studies be conducted to properly define how the CO_2 emission benefits (or carbon neutrality or even a carbon cost) from the fuel treatment projects are linked with either the biochar or energy creation project activities. It is the overall net reduction of CO_2 emissions to the atmosphere—both from the forestland as a result of treatment and from the power plant or other end use as a result of utilization—that will define the potential of the combined activity to provide a climate benefit. Projects will need to be carefully constructed so that the offsets are of high quality.

In conclusion, although fuel treatment projects face significant barriers to providing quality offsets, they continue to have the potential to play an important role in both climate change mitigation and climate change adaptation.

Benefits to California

Results of WESTCARB fuel treatment case study and evaluation will inform voluntary efforts, such as those by California Climate Action Registry members interested in offsetting GHG emissions through forestry. WESTCARB will also inform regulatory developments, such as the process now underway by the California Air Resources Board (ARB) to design a GHG regulatory program under the California Global Warming Solutions Act of 2006 (California Assembly Bill 32). Projects demonstrated to be cost-effective, verifiable, environmentally beneficial, and attractive to both regulated entities and landowners/carbon credit suppliers may become eligible for trading under the market-based compliance program Air Resources Board adopts.

8.0 LAKE COUNTY (OREGON) TERRESTRIAL PILOT PROJECT

The goal of this task was to verify the feasibility of fuels-treatment-based terrestrial sequestration by conducting a pilot project in a representative West Coast forest. A secondary goal is to estimate the potential for afforestation-based terrestrial sequestration using “plantation” tree species (e.g., hybrid poplars).

8.1. Lake County Fuels Management Project, Oregon

[Refer to Appendix 22 for the full discussion.]

Introduction

Earlier analyses by Winrock showed wildland fire to be a substantial source of greenhouse gas (GHG) emissions throughout the region. Actions to reduce hazardous fuel loads, so as to reduce the probability, areal extent, or severity of wildfires, could result in lower net GHG emissions when compared to a baseline scenario without such treatments. Fuel reduction may also contribute to carbon sequestration by enhancing forest health or growth rates in post-treatment stands. Finally, for treatments where fuel removal to a biomass energy facility is feasible, additional GHG benefits may be created by substituting the biomass for fossil fuel rather than leaving the biomass in the forest to decompose.

Hazardous fuel reduction/biomass energy pilot activities were implemented in the two WESTCARB terrestrial pilot locations, Shasta County, California, and Lake County, Oregon. These projects provide real-world data on carbon impacts of treatments, costs, and project-specific inputs to a related WESTCARB task, in which Winrock International and the WESTCARB Fire Panel are working to investigate whether the development of a rigorous methodology to estimate GHG benefits of activities to reduce emissions from wildland fires is feasible.

Purpose

The study provides results from the WESTCARB Phase II hazardous fuel reduction pilot activities in Lake County, Oregon, and on the revised 2010 long-range Strategy for the Lakeview Federal Stewardship Unit, a related activity done in conjunction with the WESTCARB research efforts.

Project Objectives

The specific objectives of the Phase II Lake County fuel reduction pilots were to investigate the feasibility of fuels-treatment-based terrestrial sequestration by conducting pilot projects in a representative West Coast forest; compile information on site conditions, fuel treatment prescriptions, and costs; and inform and field test the WESTCARB fire GHG emissions methodology. Fuels treatments were implemented on two project areas: Bull Stewardship and Collins-Hot Rocks.

Methodology for Measuring Impacts of Hazardous Fuels Treatments

Pre- and post-treatment measurements were made on two fuels treatment projects in Lake County, Oregon. These projects involved removal of non-commercial biomass and saw timber with the overall objective of reducing fuel loading and risk of catastrophic wildfire. The actual fuels treatments were not initiated under WESTCARB support, but they provided an opportunity to conduct on-the-ground measurements of actual hazardous fuel reduction efforts.

The fuel reduction activities were located in the southwest corner of the county. One project area, Bull Stewardship, was on the Fremont-Winema National Forest, and the other, Collins-Hot Rocks, was on privately owned land.

A total of 38 plots were established in the Bull Stewardship and 22 in the Collins Companies Hot Rocks lands. Pre- and post-treatment measurements on these plots addressed live trees greater than 5 cm diameter at breast, canopy density, standing dead wood, understory vegetation, forest floor litter and duff, and lying dead wood. These represent the forest carbon pools that are likely to be affected by fire, treatment, or both, and so are critical to the accounting of hazardous fuel reduction treatment impacts and potential wildfire impacts on forest carbon.

These measurements were used to determine the carbon stocks before and after treatment and before and after a potential wildfire, for each project area. Growth modeling was conducted with the Forest Vegetation Simulator for both with and without treatment stands. Emissions from a potential fire were modeled in both with- and without-fuels treatment scenarios using both the Fuel Characteristic Classification System and the Forest Vegetation Simulator fire and Fuels Extension (FVS-FFE). FVS was also used to project growth on burned stands, incorporating the impacts of fire on the future stand.

Because it was not possible to send harvested biomass that did not go into sawtimber to a biomass energy plant and it was instead piled for burning, the CO_2, CH_4, and N_2O emissions from burning this biomass were calculated. Board feet of timber harvested was converted to metric tons of carbon, with retirement rates applied.

Project Outcomes Bull Stewardship

Including carbon stored in long term wood products and emissions from pile burning, for treated stands without wildfire, a total of 73.2 tons of carbon per acre are stored, with 60.4 t C/acre still stored in the same stands following a wildfire. Incorporating the risk of fire of 0.6% to calculate net emissions or removals, the fuels treatment on the Bull Stewardship project resulted in immediate net emissions of 36.7 t CO_2e/acre (10.0 tons of carbon per acre).

In the absence of a wildfire, the fuels treatments and commercial harvest result in short term emissions of 59.4 t CO_2/acre and emissions of 36.5 t CO_2/acre over 60 years.

Project Outcomes Collins-Hot Rocks

Including carbon stored in long term wood products and emissions from pile burning, for treated stands without wildfire, a total of 34.1 tons of carbon per acre are stored, with 25.1 t C/acre still stored in the same stands following a wildfire. Incorporating the risk of fire of 0.6% to calculate net emissions or removals, the fuels treatment on the Collins-Hot Rocks project resulted in an effective immediate net carbon emission of 76.3 t CO_2e/acre (20.8 tons of carbon per acre).

In the absence of a wildfire, the fuels treatments and commercial harvest result in short term emissions of 108 t CO_2/acre and emissions of 113 t CO_2/arec over 60 years.

9.0 SHASTA COUNTY (CALIFORNIA) TERRESTRIAL PILOT PROJECT

The goal of this task is to verify the feasibility of three types of terrestrial sequestration by conducting a set of pilot projects in a representative West Coast forest and range area. The project types are fuels treatment for improved fire management, afforestation of rangelands, and forest conservation management.

9.1. Rangelands Suitable for Terrestrial Carbon Sequestration in Shasta County

[Refer to Appendix 23 for the full discussion.]

Objectives

This report sought to provide a concise summary of analyses to date on the opportunity to sequester carbon through afforestation of rangelands in Shasta County, including forest suitability, carbon potential, and cost considerations. The report also provides an interim summary of initial outreach efforts to Shasta County landowners.

Project Outcomes

Forest suitability modeling of Shasta County rangelands was conducted based on biophysical factors of soil water availability, mean annual air temperature, annual average precipitation, slope, and elevation. The results of suitability modeling—after excluding wooded rangelands with canopy cover greater than 40% and grassy rangelands dominated by wet meadows—indicate that about 600,000 acres (243,000 hectares), or about 80% of Shasta County rangelands, would be potential candidates suitable for afforestation

9.2. Shasta Afforestation Project, California

[Refer to Appendix 24 for the full discussion.]

Based on analyses conducted in WESTCARB Phase I and related work for the California Energy Commission, afforestation[10] represents the largest single terrestrial carbon sequestration opportunity for Shasta County, for California, and across the WESTCARB region. Protocols, policies and programs to encourage afforestation may make a substantial contribution toward the GHG emission reduction goals of California and other Western states. Meanwhile, afforestation may offer landowners near-term opportunities to participate in rapidly evolving GHG reporting registries,

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[10] The uses of the terms "afforestation" and "reforestation" differ across the US and internationally. In the US and under the USDOE revised 1605(b) guidelines for greenhouse gas reporting, "afforestation" is the establishment of new forests on lands that have not been forested for some considerable length of time, and is in essence a land-use change; "reforestation" is the re-establishment of forest cover, naturally or artificially, on lands that have recently been harvested or otherwise cleared of trees. In contrast, California state agencies and the California Climate Action Registry protocols generally use the term "reforestation" to mean the establishment of new forests on lands that have not been recently forested. Regardless of terminology, the practice being tested under WESTCARB is a land-use change activity that would qualify for carbon reporting in the State of California: *the establishment and subsequent maintenance of native tree cover on lands that were previously forested, but have had less than 10% tree canopy cover*

offset markets and other carbon "credit" sale opportunities under voluntary and regulated markets. WESTCARB Phase II included pilot afforestation projects to evaluate the actual potential to implement these projects.

Purpose

The purpose of this task is to provide a final update on the WESTCARB Phase II afforestation pilot projects in Shasta County, California. The report summarizes pilot locations, site preparation and planting methods, species, post-planting maintenance, costs, landowner interests and concerns, carbon measurement and monitoring plans, projected tree growth and levels of carbon sequestration. WESTCARB conducted afforestation pilots through cost-shared agreements with private landowners.

Project Objectives

The specific objectives of the Phase II Shasta County afforestation pilots are:

- Refine the Phase I economic analysis for afforestation with improved cost data;
- Gain on-the-ground experience to explore the feasibility, success and survival of afforestation projects;
- Refine carbon estimates for afforestation, using baseline measurements, proxy measurements in relevant species groups, and industry data;
- Gain experience with site preparation, seedling sourcing, planting techniques, post-planting maintenance treatments, and other considerations necessary to inform the efforts of land managers, landowners and businesses in replicating and expanding afforestation projects for climate change mitigation in California and the WESTCARB region.

Project Outcomes

Twelve landowner agreements for WESTCARB afforestation pilot projects were signed and implemented, totaling 476 acres (197 hectares; Table 4). Projects range in size from 7 to 98 acres (2.8 to 40 hectares) and average 40 acres (16 hectares). Project baselines consisted of a variety of brush species, mostly in dense stands. Baseline carbon stocks ranged from zero, for a project that had recently burned in a wildfire, to 34 tonnes of carbon per acre, on a project with dense old-growth Manzanita. Projects were planted to ponderosa pine, mixed conifer stands, or native oaks. After 100 years, projections of net carbon stocks over 100 years on conifer plantings ranged from 53 t C/acre to 111 t C/acre. The native oak planting had projected net carbon stocks of 24 t C/acre after 100 years. Survival of planted conifer seedlings was high, despite limited rainfall in the year of planting. Project costs ranged from $354/acre to $1,880/acre.

Table 4. WESTCARB Shasta County afforestation pilot project summaries

Project	Acres	Cost/ac	Baseline C stocks (t/ac)	Species	Trees/ac planted	Projected et project C stocks after 100 years (t/ac)
Red River Forests Partnership	98	$832	21	Ponderosa pine	300	73
Brooks Walker	7	$1,265	3	Ponderosa pine & red fir	300	100
Hendrix-Phillips Tree Farm	20	$1,223	24	Ponderosa pine	300	67
Goose Valley Ranch	60	$1,033	20	Ponderosa pine, Douglas fir, incense cedar	290	80
Lammers	50	$858	15	Ponderosa pine & Douglas fir	249	74
Frase	43	$600	0	Ponderosa pine	282	85
Kloeppel	51	$899	10	Ponderosa pine & Douglas fir	314	198
Sivadas	46	$778	44	Ponderosa pine	197	43
Eilers	20	$354	0	Ponderosa pine (18 acres)	208	64
				Ponderosa pine & blue oak (2 acres)	258	53
Wilson	14	$1,300	31	Ponderosa pine	274	60
Lakey	60	$482	0	Ponderosa pine	177	69
BLM	7	$1,880	0	Oak	143	24

Conclusions

Landowners have a strong interest in afforestation projects, and are willing to provide cost-share for projects intended to increase carbon sequestration. There is a wide range of project costs and projected net project carbon stocks, depending on the baseline condition of the land, the accessibility of the project, the quality of the site, and the resulting tree growth. Projects with high carbon stocks in the baseline do not result in positive net carbon stocks for 30 to 40 years after planting, and therefore may not be feasible on a strictly financial basis. However, sites with low carbon stocks in the baseline result in net positive results within the first 10 years, and sequester large amounts of carbon over the project lifetime. Those areas with high site quality result in large net increases in carbon stocks, although even in areas with poor site quality and limited rainfall, seedling survival was high, and projected carbon stocks can be significant.

Recommendations

WESTCARB states should continue to support efforts to explore the potential of afforestation to contribute to state GHG reduction goals. Many different afforestation project designs are conceivable, and can be replicated broadly elsewhere in California and the WESTCARB region. Afforestation can make a significant contribution to carbon sequestration, climate change mitigation and adaptation, and should be considered as part of the broad portfolio of strategies under consideration by the State of California (Climate Action Team and AB32) and analogous policy processes in other WESTCARB states.

Ongoing outreach and education is necessary to keep landowners informed about the opportunities to conduct afforestation for carbon sequestration, evolving carbon markets and climate change policies, and requirements for participation.

Benefits to California

Findings from the WESTCARB afforestation pilots have informed both voluntary efforts, such as those by Climate Action Reserve members interested in offsetting GHG emissions through forestry, and regulatory developments, such as the process now underway by the California Air Resources Board to design a GHG regulatory program under the California Global Warming Solutions Act of 2006 (AB32). The AB32 Market Advisory Committee, charged by Executive Order S-20-06 with advising the Air Resources Board on the design of a market-based compliance program under AB32, has recommended that such a program include offset projects provided such projects meet a series of stringent criteria (“real, additional, independently verifiable, permanent, enforceable, predictable, and transparent”), as well as meeting standards for rigorous accounting methods and environmental integrity (Market Advisory Committee 2007). Although debate remains over the role of offsets in GHG emission reduction programs, what sort of offset project types should be eligible, and the role of forestry within offset programs, afforestation projects like those being demonstrated under WESTCARB are perhaps the most likely to meet the Market Advisory Committee's quality criteria. Projects demonstrated to meet these criteria are likely to be attractive to landowners/carbon credit suppliers, to entities (companies, individuals, financial sector investors) purchasing offsets on the voluntary market, and to regulated entities seeking flexible compliance mechanisms to achieve GHG reductions.

9.3. Baseline Greenhouse Gas Emissions for Forests and Rangelands in California

[Refer to Appendix 25 for the full discussion.]

Objectives

This report's goal is to quantify the baseline of changes in carbon stocks on forest and range lands in California for the decade of the 1990s. The focus here is on carbon but first approximation estimates are also given for non-CO_2 GHGs where appropriate. Baselines provide an estimate of the emissions and removals of greenhouse gases due to changes in the use and management of land. In addition they are useful for identifying where, within the landscape of California, major opportunities could exist for enhancing carbon stocks and/or reducing carbon sources to potentially mitigate greenhouse gas emissions. The 2002 California Energy Commission report estimated the emissions and removals of GHGs from all economic sectors of the State for the period 1990–1999, generally at one-year intervals. However, the sections of the Energy Commission's 2002 report[11] on the forest and rangeland sectors were incomplete and did not include all the changes taking place on these lands. In 2004, Winrock published a report on baseline emissions from forests, rangelands, and agriculture from the same time period, however, in this earlier report data for only three out of the five regions were available for assessment. In this report all five regions are included and enhancements have been made in how the carbon sequestration of forest and rangeland areas with no measureable changes in canopy cover is accounted.

Outcomes

In this report, methods for estimating baseline carbon emissions and removals from forests and rangelands are presented with corresponding results. However, given the nature of the databases used in this analysis, the time periods encompassed by the baselines vary. Across the five regions of California the assessment periods varied with different periods for each region of four to six years between 1994 and 2002.

To develop the baselines, three types of data were used: (1) the area of the forests and rangelands at the start and end of the time interval, (2) the area and magnitude of change in canopy cover during the time interval, and (3) the carbon stocks in each land-use type for each time. Areas were derived from the California Land Cover Mapping and Monitoring Program (LCMMP). Carbon estimates for various forests and rangeland types with corresponding canopy cover were derived from Forest Inventory and Analysis (FIA) data and California Department of Forestry's Fire and Resource Assessment Program (FRAP) staff.

Conclusions

The analysis revealed that forests and rangelands were responsible for a net removal of carbon dioxide from the atmosphere of 24.95 $MMTCO_2e$/year (Appendix 25, Table S-1). Non-CO_2 GHG emissions from forest and range lands were estimated to be 0.16 $MMTCO_2e$/year, or equivalent to

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[11] California Energy Commission, 2002, Inventory of California greenhouse gas emissions and sinks: 1990-1999. Publication #600-02-001F

about 0.76% of the removals by these systems. The overall net result was a removal of 23.01 MMTCO$_2$e/year by forests and 1.94 MMTCO$_2$e/year by rangelands.

The baseline was estimated by combining two approaches. The areas of satellite-detectable change in forests and rangelands, with a measured change in canopy coverage, were available through the California LCMMP. Carbon estimates for various forests and rangeland types with corresponding canopy closures were derived principally from FIA data. The analysis of change, measured from satellite images, only identifies a measurable change in canopy coverage of forests and rangelands that occurred in the time interval, and does not include those forests with a closed canopy that continue accumulating biomass carbon that is undetectable from a satellite. For these reasons, measurable decreases in canopy cover and the resulting decreases in carbon stocks (emissions of carbon) were tracked separately from the measurable increases in canopy cover and resulting increases in carbon stocks. For decreases in carbon stocks, both the gross and net changes, which varied by the cause of the change (e.g., fire, harvest, development), were estimated. Then the likely magnitude of the increase in carbon stocks resulting from the non-measured change in canopy and assumed increase in carbon stocks using U.S. Forest Service data was estimated. In other words, the baseline includes all changes in carbon stocks, from measured and unmeasured changes in canopy coverage.

The previous version of this assessment used a single carbon sequestration rate per forest type across all three regions to estimate the sequestration in forests with no measurable change in canopy cover. In addition, this rate was calculated from a data set for net emissions. In this study, a sequestration rate from FIA data for each forest and rangeland type in each of the five regions was calculated.

A change in canopy cover was measured on 4,622 km2 of forests and rangelands across California. This is approximately 1.8% of the total area of forests and rangeland in the regions. For 83% of the changed area, the cause of change was identified and verified. For forests, a removal of 27.10 MMTCO2e/yr and an emission of 4.09 MMTCO2e/year were estimated. The greatest emissions were found in the North Sierra region with its dry conditions and resultant fires, as well as timber harvesting. The greatest removal was found in the forests of the North Coast with its dominance by fast-growing redwoods and Douglas-fir. Rangelands were a net sink of carbon with a removal of 2.57 MMTCO2e/year exceeding an emission of 0.63 MMTCO2e/year.

Fire and harvest were the dominant causes of emissions on forestlands; these causes were responsible for 1.83 MMTCO$_2$e/year and 1.42 MMTCO$_2$e/year respectively. On rangeland, harvest was less important, accounting for just 5% of the total emissions as opposed to 54% for fire on rangelands. Development is a minor cause of carbon emissions through land use change in both forest- and range-land in California. However, much of the unverified change could include development that tends to occur in smaller patches than those recorded under the pattern of verified changes.

The counties with the largest decrease in carbon stocks (largest emissions) were located in areas affected by fire especially in North Sierra and parts of Cascade Northeast. The largest increases in carbon stocks (detectable and undetectable canopy change) are in the high volume fast-growing conifer forests of the North Coast and Cascades Northeast. Despite a high fire incidence the lower carbon stocks of the forests in the southern regions leads to emissions levels that are not greatly elevated.

The estimated total removals of 27.10 MMTCO₂e/year and emissions of 4.09 MMTCO₂e/year (net 23.01 MMTCO₂e/year) for the forest sector differ markedly from the reported removal of 17.3 MMTCO₂e/year in the California Energy Commission's report[12]. The conclusion follows that despite the relatively high uncertainty, the finer detail, and inclusion of areas with measured changes in canopy, and thus carbon stocks, this estimate should be considered to be representative of the real changes occurring on forest and range lands during the period of 1994/1995-2002.

The estimated removal also differs from the previous Winrock assessment of 10.96

MMTCO₂e/year and emissions of 3.76 MMTCO₂e/year, based on only three regions of California.

The difference between the previous estimate and the one produced in this report is accounted for by the inclusion of the final two regions (South Coast and South Sierra) and the use of an improved method for calculating sequestration in the forests with no canopy cover change.

9.4. Fuels Management Pilot in Shasta County, California

[Refer to Appendix 26 for the full discussion.]

Introduction

This task provides results from the WESTCARB Phase II hazardous fuel reduction pilot activities in Shasta County, California. Earlier analyses by Winrock showed wildland fire to be a substantial source of GHG emissions throughout the region. Actions to reduce hazardous fuel loads, so as to reduce the probability, areal extent, or severity of wildfires, could result in lower net GHG emissions when compared to a baseline scenario without such treatments. Fuel reduction may also contribute to carbon sequestration by enhancing forest health or growth rates in post-treatment stands. Finally, for treatments where fuel removal to a biomass energy facility is feasible, additional GHG benefits may be created by substituting the biomass for fossil fuel rather than leaving the biomass in the forest to decompose.

Hazardous fuel reduction/biomass energy pilot activities were implemented in the two WESTCARB terrestrial pilot locations, Shasta County, California and Lake County, Oregon. These projects provide real-world data on carbon impacts of treatments, costs, and project-specific inputs to a related WESTCARB task, in which Winrock International and the WESTCARB Fire Panel are working to investigate whether the development of a rigorous methodology to estimate GHG benefits of activities to reduce emissions from wildland fires is feasible.

Project Objectives

The specific objectives of the Phase II Shasta County fuel reduction pilots are to investigate the feasibility of fuels-treatment-based terrestrial sequestration by conducting pilot projects in a representative West Coast forest; compile information on site conditions, fuel treatment prescriptions, and costs; and inform and field test the WESTCARB fire GHG emissions methodology.

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[12] Ibid.

Methodology for Measuring Impacts of Hazardous Fuels Treatments

Pre- and post-treatment measurements were made on three fuels treatment projects in Shasta County, California: Berry Timber, Davis, and HH Biomass. The fuel reduction activities were located in the southeast corner of the county; all three projects were located on privately owned land. These projects involved removal of non-commercial biomass and sawtimber with the overall objective of reducing fuel loading and risk of catastrophic wildfire. Treatments also included chipping and removal of biomass fuel to a biomass energy plant. The actual fuels treatments were not initiated under WESTCARB support, but they provided an opportunity to conduct on-the-ground measurements of actual hazardous fuel reduction efforts.

Data were collected in a total of 35 plots (15 on Davis, 9 on HH, and 11 on Berry Timber). Pre- and post-treatment measurements on these plots addressed live trees greater than 5 cm diameter at breast height, canopy density, standing and lying dead wood, understory vegetation, forest floor litter and duff. These represent the forest carbon pools that are likely to be affected by fire, treatment, or both, and so are critical to the accounting of hazardous fuel reduction treatment impacts and potential wildfire impacts on forest carbon. These measurements were used to determine the carbon stocks before and after treatment and before and after a potential wildfire, for each project area.

Growth modeling was conducted with the Forest Vegetation Simulator for both with and without treatment stands. Emissions from a potential fire were modeled in both with- and without-fuels treatment scenarios using both the Fuel Characteristic Classification System and the Forest Vegetation Simulator fire and Fuels Extension (FVS-FFE). FVS was also used to project growth on burned stands, incorporating the impacts of fire on the future stand. The substitution of harvested biomass for existing energy sources was taken into account where fuels were extracted to a biomass energy plant. Board feet of timber harvested was converted to metric tons of carbon, with retirement rates applied.

Project Outcomes

Berry Timber

Treated stands without wildfire have total stocks of 51.2 tons of carbon per acre, with 44.2 t C/acre in the same stands following a wildfire, including carbon stored in long-term wood products and energy offsets. Incorporating the risk of fire of 0.64% to calculate net emissions or removals, the fuels treatment on the Berry Timber project resulted in an effective immediate net carbon emission of 69.2 t CO_2e/acre (18.9 tons of carbon per acre). In the absence of a wildfire, the fuels treatments and commercial harvest result in short term emissions of 83.2 t CO_2/acre and emissions of 116.2 t CO_2/acre over 60 years.

For the treatment to yield benefits to the atmosphere, the emissions from treatments will need to be offset by reductions in emissions from a potential wildfire hitting the area. In order for the treatment to have an impact, such a fire would have to occur before fuels have returned to hazardous conditions, at which point it will be necessary to re-treat the forest. According to the FVS-modeled results, if a wildfire were to occur in the year of treatment, after 10 years the net emissions from treatment would be 31.5 t CO_2/acre. Davis Including carbon stored in long term wood products and energy offsets, treated stands without wildfire have total stocks of 47.9 tons of carbon per acre compared to stocks of 38.7 t C/acre in treated stands following a wildfire.

Incorporating the risk of fire of 0.64% to calculate net emissions or sequestration , the fuels treatment on the Davis project resulted in a net carbon emission in year one of 11.0 t CO_2e/acre (3.0 t C/acre). In the absence of a wildfire, the fuels treatments and commercial harvest result in short term emissions of 39.2 t CO_2/ac re and emissions of 60.1 t CO_2/acre over 60 years.

For the treatment to yield benefits to the atmosphere, the emissions from treatments will need to be offset by reductions in emissions from a potential wildfire hitting the area. In order for the treatment to have an impact, such a fire would have to occur before fuels have returned to hazardous conditions, at which point it will be necessary to re-treat the forest. According to the FVS-modeled results, if a wildfire were to occur in the year of treatment, after 10 years the net emissions from treatment would be 20.2 t CO_2/acre. HH biomass including carbon stored in long- term wood products and energy offsets, treated stands without wildfire have total stocks of 55 tons of carbon per acre compared to a stock of 45.3 t C/acre in treated stands following a wildfire. Incorporating the risk of fire of 0.64% to calculate net emissions or sequestration, the fuels treatment on the HH Biomass project resulted in a net carbon emission in year one of 32.3 t CO_2- e/acre (8.8 t C/acre). In the absence of a wildfire, the fuels treatments and commercial harvest result in short term emissions of 83.6 t CO_2/acre and emissions of 90.5 t CO_2/acre over 60 years.

For the treatment to yield benefits to the atmosphere, the emissions from treatments will need to be offset by reductions in emissions from a potential wildfire hitting the area. In order for the treatment to have an impact, such a fire would have to occur before fuels have returned to hazardous conditions, at which point it will be necessary to re-treat the forest. According to the FVS-modeled results, if a wildfire were to occur in the year of treatment, after 10 years the net emissions from treatment would be 41.4 t CO_2/acre.

Conclusions and Recommendations

In all three projects, the treatments resulted in overall carbon emissions. This result clearly has negative implications for the future potential of fuels treatments as a carbon projects offset category. Within the treated areas, all three projects had significant net emissions when considering treatment and the risk of a potential wildfire. Davis experienced the lowest emissions, but the treatment on Davis did not decrease fire intensity. If a fire were to occur in the year of treatment, all projects would still experience net emissions, though the impact of treatment emissions would be approximately halved in all cases. All three of the pilots led to a projected decrease in crown fire potential, which decreases fire severity and size. While treatments lead to net carbon emissions in both the short and long term in all three projects, there are, of course, additional benefits to fuels treatments, such as increased ability to successfully fight fires and decreased cost of fire fighting; reduced loss of life and property; and reduced potential damage to wildlife habitat.

The results from this study in combination with the paired study in Lake County and the allied study in Mendocino National Forest underlie the unsuitability of fuels treatment as a potential greenhouse gas offset generating activity. Instead, a shift could be made to policies minimizing GHG emissions from wildfires and from fuel treatments while minimizing wildfire risks to lives, homes, wildlife habitat, and livelihoods in the WESTCARB region.

10.0 CARBON OFFSET MARKET RECOGNITION OF TERRESTRIAL PILOT PROJECTS

This task was to develop acceptable methods and procedures for reporting carbon benefits from improved fire management of forested lands, to solicit eligibility reviews of the Shasta County (California) pilot project activities by the California Climate Action Registry (CCAR) and the Lake County (Oregon) pilot project activities by The Climate Trust, and to develop public outreach material for forestry professionals and landowners.

10.1. Bascom Pacific Forest Project, California

[Refer to Appendix 27 for the full discussion.]

This project was initiated with the intent to achieve the following:

- Demonstrate how baselines and project activities associated with the conservation-based management of a commercially productive forestland site in northern California would be interpreted and projected on this site if a CO2 emissions reduction project were undertaken in accordance with the California Climate Action Registry Forest Project Protocol (Version 2.1) (which, together with the associated general reporting and verification protocols are referred to herein as the "Forest Protocols");
- Identify specific management activities that would create carbon reductions on this site;
- Evaluate the costs and benefits of the Forest Protocols with respect to undertaking a forest management project for the purpose of registering forest carbon stock changes with the Climate Action Reserve ("Reserve").

Purpose

The initial conditions on the Bascom Pacific project site (hereafter Bascom Pacific Forest) were defined as the amount of forest carbon stocks on site prior to the start of project activities. Initial conditions were established by directly sampling carbon stocks. This was done by performing both a conventional timber inventory, as is typically used in commercial timber applications, and a lying dead wood inventory. Methodologies for both the conventional commercial timber inventory and the lying dead wood inventory are provided below. Conventional inventory measurements are summarized by stand, whereas lying dead wood measurements are summarized by Public Land Survey System section. Summary information from each inventory includes conversions of data to carbon values.

Project Objectives

The direct sampling efforts on the Bascom Pacific Forest were designed to generate inventory data that achieve the following:

- Provide current estimates of the standing timber volume and biomass.
- Provide current estimates of biomass in lying dead wood.
- Support timber and habitat management activities.

- In the case of the 2006 inventory, support projections of future timber resources and carbon stocks using the CACTOS growth model (Wensel *et al*. 1986; http://www.cnr.berkeley.edu/~wensel/cactos/cactoss.htm).
- In the case of the 2008 inventory update, monitor project activities and resulting changes to carbon stocks.

Project Outcomes

Once initial conditions for the Bascom Pacific Forest were established, changes to future carbon stocks were modeled pursuant to the requirements of the Forest Protocols to evaluate the difference between projected carbon stocks under two distinct management scenarios: *baseline activities* and *project activities*. The baseline management scenario under version 2.1 of the Forest Protocols is based on how the forest would be managed if the landowner were to realize timber harvest volumes to the greatest extent feasible and practicable as allowed under applicable forest management laws, in this case the California Forest Practice Act/Rules. The project activity scenario for the Bascom Pacific Forest is based on management that follows the conservation easement on the property and is intended to sequester and store more carbon stocks over time than the baseline activity scenario. Those project activity carbon stocks that are stored above and beyond baseline activity stocks are considered *additional* carbon stocks, representing net gains due to sequestration and avoided depletion in reference to the "business as usual" baseline. Based on the baseline and project activities modeled, this study shows that over one million tons of additional metric tons of CO_2, or 118 metric tons of CO_2 per acre, would be generated by the end of the 100-year project lifetime.

Conclusions

Over the life of the project, 447,877 board feet (MBF) of timber are harvested under the baseline activity scenario, whereas 417,563 MBF are harvested under the project activity scenario (Appendix 27, Tables 14 and 15). The amount of timber harvested in any given period of time varies considerably under the baseline activity scenario, with significant pulses during the periods in which clearcutting occurs, more modest harvest volumes when intermediate thinning takes place, and no volume harvested in some periods as standing timber volume is allowed to accumulate on clearcut sites. Although the baseline activity scenario exhibits an average harvest rate of about 4,475 MBF per year, as much as 7,413 MBF per year are harvested per year during the initial clearcut phase and up to 14,820 MBF per year in the second clearcut phase, but only between about 1,000 and 3,000 MBF per year during intermediate thinnings and 0 MBF during fallow years. The wood products carbon pool reflects these changes by accumulating rapidly during clearcutting phases, and more slowly during intermediate thinning phases. But during periods in which no harvesting occurs, decay of existing wood products leads to a slight decrease in the overall stocks in this pool. At the end of the project lifetime, the baseline activity scenario has a total of 88,775 tonnes of carbon in the wood products pool.

Combining the wood products pool with the standing live tree, standing dead tree and lying dead wood pools increases the amount of carbon stored under both the baseline activity and project activity scenarios (Figure 12). When the baseline values are averaged over the project lifetime, inclusion of wood products increases the baseline average by 179,064 tons of CO_2. Incorporating wood products also increases the cumulative emissions reductions at the end of the project lifetime by 132,208 tons of CO_2. However, cumulative emissions reductions including wood products remains lower than emissions reductions without wood products until 2066, at which point emissions reductions including wood products is greater through the remainder of the project lifetime.

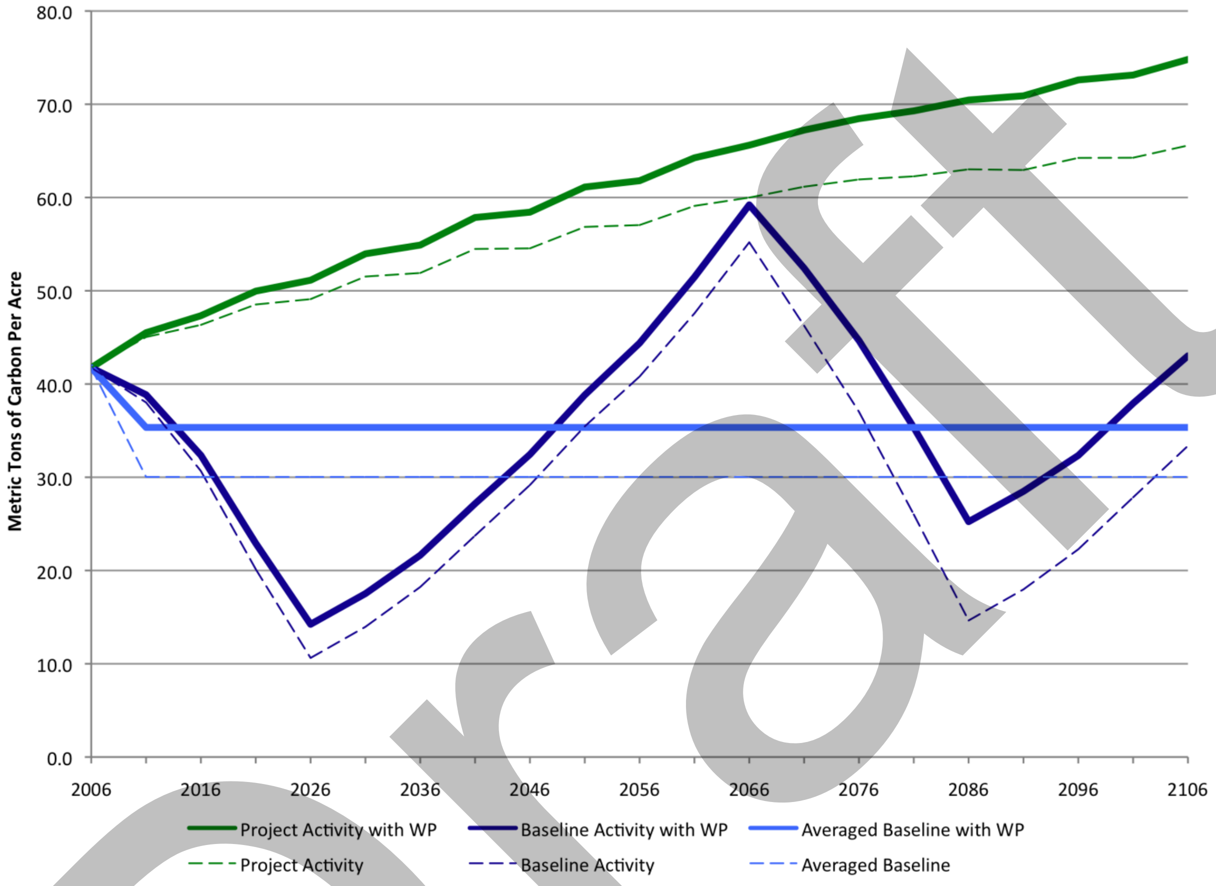

Figure 12. Baseline and project activity carbon stocks, both with and without wood products pool stocks, over the 100-year project lifetime on a per acre basis

[The averaged baseline activity value is also shown. All scenarios have the same initial carbon stocks at the project start date in 2006. The averaged baseline curve begins at this same starting value, but achieves the average value by the end of the first five-year reporting period by being reduced annually in equal increments.]

Overall, the results of the application of version 2.1 of the Forest Protocols appear to provide practical but rigorous accounting of emissions reductions to internationally acceptable standards. Nonetheless, there are a number of areas where changes are recommended to provide for more efficient and accurate application, many of which have been incorporated into version 3.0. In considering the costs and returns of a project such as Bascom Pacific, under the assumptions used in a pro forma analysis, the potential financial returns from an emissions reduction project are believed to provide an incentive for landowner participation, while fostering long-term forest conservation and net gains from long-term reduction of CO_2 emissions.

Recommendations

The initial conditions inventory, when properly specified, can be cost effectively undertaken concurrent with a conventional timber inventory but does add expense. The greater expense is due to the generally higher statistical confidence required in sampling[13] and the inclusion of additional inventory elements such as standing and down dead biomass. Further, the requirement for permanent marking of plot centers is a costly variance from the standard timber inventory practice of temporary flagging. Version 3.0 of the Forest Protocols eliminates the requirement for permanent monumenting, while still requiring temporary flagging so that verifiers can locate plot centers. In addition to the specific requirements of different project types under the Protocols, inventory costs vary with the size and heterogeneity of the property, not unlike timber inventories. Larger more homogenous properties will cost less to inventory than the mid-size, relatively diverse Bascom Pacific property.

Benefits to California

During the course of this project, the Reserve initiated a stakeholder process to review, update and revise the Forest Protocols. The experience the authors gained in preparing this report helped inform the development of the revised Protocols, which are now published as version 3.0 (and subsequently updated to version 3.1). In addition, the Bascom Pacific Forest analysis provides an example for future improved forest management projects, so that project developers can have a sense of what to expect when undertaking such an endeavor and so that policymakers and the public can better understand the potential for real, lasting and verifiable emissions reductions to be achieved through changes in forest management.

10.2. LaTour State Forest, California

[Refer to Appendix 28 for the full discussion.]

This project provides two case studies of improved forest management and reforestation projects using version 3.0 of the CCAR forest protocol. Public and private lands are considered as separate scenarios. The baselines, project activity and Certified Reserve Tonnes (CRT) additionality was calculated for 100-year time periods. An economic analysis is provided for each scenario. A fire risk modeling analysis was also conducted.

Discussion and Conclusions

Harvest scheduling for the improved forest management project type can be complex, even for smaller properties. This is due to trying to optimize additionality by simulating the baseline close to the Forest Inventory and Analysis mean or starting inventory, depending on starting point. If you are conducting an economic analysis, then a flexible optimizing harvest schedule is even more desirable. Therefore, using an optimizing harvest schedule for improved forest management project types, such as a linear or dynamic program, is recommended.

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[13] Lower sampling confidence intervals (i.e., greater than +/-5% at the 90% confidence interval)

The inclusion of harvested wood products in the baseline accounted for reductions in harvest over the 100-year projection period. The secondary effects calculation applied an additional penalty of 20% of the reduced harvest to account for market leakage. The risk assessment analysis produced what appear to be reasonable results, but will have to be monitored over time to match long-term results by geographic region.

The contribution of wood products was relatively small or even negative for the scenarios presented. This might have been different if there had been more harvesting, especially over a larger area with a mix of age classes where harvests could be offset with on-site growth and not cause a reduction in CRTs. Improvements in stand growth could also change the contribution of the harvested wood products pool. Both the baseline and project activity were projected using growth calibrations from the native lightly managed stands. Where group selections or clearcuts occur that create rapidly growing thrifty stands, wood products contributions could greatly increase. This would be captured over time with inventories and would ultimately be reflected in CRTs. Therefore, the CRT projections for these scenarios are conservative. The application of the reforestation project type was found to be appropriate for both private and public lands, but not economically viable without subsidy. The improved forest management project type was not found to be appropriate for these projects as public lands, as the baseline could not be shown to differ from the project activity.

Improved forest management project types on private lands had economic returns (NPV) of $217 and $649 per acre ($536 and $1,603 per hectare) for the two demonstration project areas assuming a price of $9.00 a tonne CO_2e. At $20 a tonne CO_2e the NPVs were $585 and $1,568 per acre ($1,445 and $3,873 per hectare). The higher value resulted from the starting inventory being substantially above the mean for the assessment area, which resulted in CRTs being immediately created.

The use of CVal rapidly produces an economic analysis of a project based on carbon income and project costs. This software provides an excellent example of the type of analytic tools needed to build rational ecosystem services markets.

The analysis of the effects of a fuel reduction project showed that the project appeared beneficial to carbon management. More work is needed in this area as it is the application of stochastic landscape disturbances to project specific areas. Quantification necessarily involves estimates of disturbance and weather probabilities from historical records and local knowledge and estimates of fire severity, for both treated and untreated conditions.

10.3. Carbon Market Validation for Biochar

[Refer to Appendix 29 for the full discussion.]

The nascent carbon offset market offers a venue for directing funds to innovative terrestrial sequestration project concepts. However, such innovative projects must be validated against a set of criteria that are commonly used to determine the appropriateness and viability of the project concept in the carbon offset market.

Heating organic material without oxygen in a process called pyrolysis thermo-chemically transforms biomass into a stable char residue that resists decomposition, while also producing oil and gas. This residue is called biochar when it is incorporated into soils as an agricultural amendment.

Biochar could provide a major contribution to the global effort to reduce GHG emissions; some estimates suggest it could mitigate as much as one-eighth of global GHG emissions. Given the substantial timber resources in the region, many of the WESTCARB states (Alaska, Arizona, California, Nevada, Oregon, and Washington) are suitable candidates to host biochar projects.

Biochar production reduces GHG emissions through the following pathways:

1. *Sequestering carbon in biochar*. Photosynthesis sequesters carbon in biomass as it grows. When this biomass decomposes, the carbon is released back to the atmosphere. If the biomass is instead converted through pyrolysis into biochar, the carbon originally sequestered in the biomass will be stored for a much longer time because much of the carbon in the biochar will not decompose for hundreds or thousands of years. Biochar can slow the basic carbon cycle to sequester carbon for long periods of time, because it is significantly more inert than the original feedstock that created it.
2. *Displacing fossil fuel energy with renewable energy*. Pyrolysis also produces oils and gases that can be combusted to generate renewable energy. When biomass instead of fossil fuels create energy—and it is harvested in a manner that does not increase land-use emissions— it can avoid CO_2 emissions.
3. *Diverting waste from generating methane*. Many biomass feedstocks that could be pyrolyzed currently decompose in the absence of oxygen under water or in landfills. Rice residues, green waste, and manure, for example, are commonly left to decompose in rice paddies, landfills, or lagoons. This anaerobic decomposition releases methane Pyrolysis of these feedstocks prevents this anaerobic decomposition and avoids these CH_4 emissions.

Through these pathways, biochar has the potential to provide a material contribution to efforts to reduce the build-up of greenhouse gases in the atmosphere. Globally, it is estimated that, at its maximum sustainable potential, biochar could annually reduce 1.8 Gt of CO_2e, or 12% of the world's GHG emissions. In the United States, pyrolyzing 40% of unused agricultural and forestry residues could reduce 230 million tonnes of CO_2e, or around 8% of the annual GHG reductions needed to reduce domestic GHG emissions by 50% by 2050.

Purpose

Biochar's potential will only be realized if biochar projects prove to be financially viable. One important step towards profitability is to enable biochar projects to monetize their climate benefits. Biochar projects could do this by selling GHG offsets to regulated emitters under a cap-and-trade system. The Offset Quality Initiative discussed nine criteria that must be met for projects to qualify as offsets under such a system. The study reported on how these nine criteria apply to biochar projects in general and to a specific case study in Philomath, Oregon.

Project Outcomes and Conclusions

This report finds that for a project to qualify as a high quality offset supplier, it should contain the qualities described in Table 5.

Table 5. Essential carbon market investment criteria for biochar projects

Project component	Desirable quality	Carbon market rationale
Feedstock	Projects are fed by waste biomass that would otherwise be burnt or left to decompose. Feedstocks grown specifically for the biochar project are produced on marginal or degraded land.	*Leakage*. Waste feedstocks (or feedstocks grown on marginal/degraded land) do not cause land-use change.
	Feedstocks do not potentially contain heavy metals. Feedstocks do not consist of municipal solid waste, sewage sludge, or tires.	*No net harm*. Heavy metals could potentially be concentrated through pyrolysis and contaminate soils, damaging the environment and human health.
Pyrolysis process	Pyrolysis will generate at least 25,000 metric tons of biochar over ten years. Bigger projects (100,000 metric tons of biochar or more) are the most desirable.	*Verification*. Because many verification costs are fixed regardless of the size of the project, verification costs are a smaller portion of the overall cost of large projects. Economies of scale favor large projects. Projects that produce less than 25,000 metric tons of biochar over their life will not be considered for carbon market investment unless a small-scale methodology and aggregation system is developed to reduce transaction costs.
Use of biochar	The biochar producer can account for, track and monitor where all the biochar is incorporated into soils. Vertical integration, where the producer of the char is also the user of the char, is the most desirable.	*Monitoring and Permanence*. De Gryze et al. (2010) suggest the most credible method to quantify biochar projects is to measure the quantity of biochar remaining in the soil 1, 5, 10, 20 and 50 years after it is incorporated with the soil. Vertical integration makes this monitoring economically feasible. If projects are not vertically integrated, they must at least be able to easily track and account for where all the biochar is integrated into soils.

Using these investment criteria as a guide, this report evaluates a pilot-scale biochar project in Philomath, Oregon. The project, conducted at a log yard that currently produces 6,000 metric tons of waste woody biomass per year, met all but the following two investment criteria:

- The project is too small. The pilot project is projected to produce eight tonnes of biochar per year, while it is estimated that biochar offset projects will need to produce at least 25,000 metric tons of biochar over their lifetime, or around 2,500 tonnes per year.
- The project plans to sell biochar to many entities, making it difficult to account for where all the biochar will be incorporated into soils.

Given the quantity of waste biomass and land available to the log yard, however, it is feasible for the pilot project to scale into an attractive offset project. However, biochar's economic and agronomic benefits are not yet sufficiently proven to justify this scale of investment. Study of the pilot project is a first attempt to make this justification.

Recommendations

As the biochar industry matures and starts producing at scale, projects are likely to be eligible to sell their climate benefits as GHG offsets to regulated emitters under a cap-and-trade program. This makes biochar a promising project type for pilot-scale investment and carbon market protocol development. A protocol will help enable the biochar industry to scale up and focus on maximizing the potential climate benefits of biomass utilization.

10.4. Public outreach material for forestry professionals and landowners.

This task was to develop carbon storage/credit outreach materials for forestry professionals, forest products industry associations, and public land managers. An interactive website was created for dissemination of terrestrial pilot results and terrestrial storage data. Winrock provided data for the carbon atlas, beginning in 2006, which focused primarily on the initial regional characterization efforts. A set a six outreach materials can be seen in Appendix 30.

A Carbon Emission Project was established using remaining funds under the subcontract with Winrock, to produce a half-hour television program about the effect of carbon emissions on the growth and development in Shasta County. Utilizing different perspectives, the program focuses on explaining the issues to the general public. The program is broken into three parts: an explanation of CO_2 emissions, the problems that the emissions cause, and a discussion about possible solutions for CO_2 reduction. The program concludes with a discussion of carbon sequestration and established re-vegetation programs. Participants include Shasta County RTPA, WSRCD, KIXE TV, Winrock International, and The American Carbon Registry, and also municipalities, industries, landowners, and utility providers to the list of participants. The video was completed in March 2012 (see Appendix 31).

11.0 CONCLUSIONS

Phase II of the WESTCARB undertook an extensive geological and terrestrial characterization of CO_2 sequestration potential throughout its region, contributed information on regulatory and policy issues, and increased awareness about CCS The principal achievements of the project are identified as follows:

Storage estimates in several WESTCARB regions have been refined, providing the following:

- Coal-bed storage in Alaska's major sedimentary basins has been estimated to be approximately 50 Gt. The storage potential in its deeper saline formations is less clear due to a number of limiting factors.
- Onshore and offshore sedimentary basins in Washington and Oregon may have between 115 Mt and 450 Mt storage potential, with the highest potential being in the Puget Sound area of Washington.
- A revised assessment of the CO_2 sequestration potential in California's oil and gas fields indicates 6,455 million tons.

WESTCARB undertook an analysis of CCS technology evolution and adoption in the western USA.

- It identified challenges facing successful CCS deployment.
-
- In addition to geological and terrestrial storage, this analysis integrated policy, economic, financial, and public acceptance issues.
-
- This analysis constitutes a holistic perspective on CCS in this region.

WESTCARB played a major role in:

- The development of National Geologic Storage Atlas
- Developing a centralized GIS source and sink database; major point sources and geologic sinks identified and characterized; work on updating and adding additional geologic information continues
- Contributing to the development of a methodology for storage resource estimation, and carried out estimates for major sinks
- Developing a GIS-based methodology for matching "point" emission sources with injection sites, and establishing optimum pipeline routes. Illustrated methodology through development of marginal cost curves for California

In California, WESTCARB

- Demonstrated site characterization methodologies for a large volume injection in the Central Valley of California
- Development of geologic models
- Prepared reservoir simulations for project planning

In an effort to reach out and inform to entities throughout the region about CCS, WESTCARB:

- Increased awareness of geologic sequestration through the Region through many presentations to state agencies, professional organizations, industry trade groups, community leaders, general public, and policymakers
- Developed a unique educational outreach tool enabling web-based "real-time" monitoring of pilot field activities

In addition, WESTCARB played a major role in informing California policy on CCS by:

- Providing input for California's Energy Policy Report
- Providing technical input for the California Carbon Capture and Storage Review Panel, created to advise the California Energy Commission, the California Public Utilities Commission, the Air Resources Board, the Department of Conservation and other state agencies on CCS policy.

Contributions to terrestrial sequestration research by WESTCARB include:

- Developed marginal cost curves for sequestration through forest management actions
- Results of work in LaTour state forest informed forestry implementation rules for California's AB 32 – Global Warming Solutions Act
- Established pilot projects in Shasta County California to demonstrate sequestration through afforestation activities
- These pilots attracted high levels of participation by landowners and stakeholders, providing significant impact on public awareness of terrestrial sequestration
- Shasta pilots were featured along with PCOR terrestrial activities in an award winning documentary.
- Provided important insight into fire hazard management and CO_2 emissions.
- Documented the impact of urbanization on sequestration potential in the historically forested area around the Puget Sound.
- Developed outreach material for land and forestry owners to enhance carbon storage and credits.
- Major sponsorship of the television documentary, *The Climate of Opportunity*, aired in the spring of 2012.

APPENDED REPORTS

1. Alaska geologic CO_2 storage – scoping evaluation of deep coal seam and saline aquifer storage potential.
2. Alaska geologic carbon sequestration potential estimate: screening saline basins and refining coal estimates.
3. CO_2 resource assessment – oil and gas fields of California.
4. Preliminary assessment of the potential for CO_2 sequestration in geologic settings in Nevada, *and* Assessment for the potential for CO_2 sequestration by reactions with mafic rocks and enhanced oil recovery in Nevada.
5. Storage estimates – Washington and Oregon onshore and offshore sedimentary basins.
6. Opportunity assessment for establishing hybrid poplars in California, Oregon and Washington, *and* Summary of the carbon storage potential for fast growing species (hybrid poplar) in Oregon.
7. 1Regional characterization for the Arizona: potential of riparian areas for carbon sequestration.
8. Baseline greenhouse gas emissions and removals for forest and rangelands in Arizona.
9. Project Idea Note: afforestation/restoration of riparian areas along Santa Cruz River, Arizona USA.
10. Characterization of the greenhouse gas emissions associated with conversion of forest to residential Development the Puget Sound, Washington.
11. Community perceptions of carbon sequestration – insights from California.
12. Environmental non-governmental organizations' perceptions of geologic sequestration.
13. The role of social factors in shaping public perception of CCS: results of multi-state focus group interviews in the US.
14. Regional Technology Implementation Plan.
15. Certification framework: leakage risk assessment for CO_2 injection at the Montezuma Hills site, Solano County, California.
16. Seismicity characterization and monitoring at WESTCARB's proposed Montezuma Hills geologic sequestration site.
17. Potential for induced seismicity related to the Northern California CO_2 reduction projection pilot test, Solano County, California.
18. Down-Select Report for Task 7: The King Island Characterization Well at King Island, San Joaquin County, California.
19. Centralia (Washington) geologic formation CO_2 storage assessment.
20. Emissions and potential emission reductions from hazardous fuel treatments in the WESTCARB region (including 4 appendices).
21. An analysis of wildfire fuel treatments as a carbon offset project type.
22. Final Report on WESTCARB fuels management pilot activities in Lake County, Oregon.
23. Summary of the rangelands suitable for terrestrial carbon sequestration in Shasta County.
24. WESTCARB afforestation pilot projects in Shasta County, California.

25. Baseline greenhouse gas emissions for forests and rangelands in California.
26. Final Report on WESTCARB fuels management pilot activities in Shasta County, California.
27. Demonstration of conservation-based forest management to sequester carbon on the Bascom Pacific Forest.
28. Demonstration of the Climate Action Reserve Forestry protocols at the LaTour Demonstration State Forest.
29. Carbon Market Investment Criteria for Biochar projects.
30. Reforestation Outreach Materials (six items).
31. The Climate of Opportunity, video flyer.

ALASKA GEOLOGIC CO2 STORAGE SCOPING STUDY

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DOE Contract No.: DE-FC26-05NT42593
Contract Period: October 1, 2005 - May 11, 2011

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Abstract

As part of the West Coast Regional Carbon Sequestration Partnership (WESTCARB), Advanced Resources International, Inc. evaluated at a preliminary basin level the CO_2 storage potential of deep coal seams and saline aquifer sandstones in Alaska. Based on scoping review of petroleum well logs, reservoir data, maps, and geologic reports originally compiled by the Alaska DNR, MMS, USGS, and industry for petroleum exploration purposes, we estimate Alaska has approximately 120 Gt of CO_2 storage potential in deep coal seams (Table A) and perhaps 16,700 Gt in saline aquifer sandstones (Table B).

Alaska has large coal resources concentrated mainly in the onshore North Slope and Cook Inlet regions. North Slope coals occur in the Lower Cretaceous Nanushuk and Upper Cretaceous Colville Groups as well as the Tertiary Sagavanirktok Group. Coal rank ranges from lignite A to high-volatile A bituminous. Based on thickness, rank, and aerial distribution, deep coals in the North Slope are estimated to have about 98 Gt of CO_2 storage capacity. However, because coalbed methane (CBM) testing has not yet occurred in the North Slope, critical reservoir properties (i.e., permeability) are unknown.

In southern Alaska, the Cook Inlet's Miocene Tyonek Formation contains approximately 30-50 m of sub-bituminous rank coal at favorable CO_2 storage depths of 800-1200 m. A 4-well vertical coalbed methane pilot conducted by Evergreen Resources flowed fairly high water rates, indicating at least modest coal seam permeability (1-10 mD). The Tyonek is estimated to have about 21 Gt of CO_2 storage capacity, as well as 136 Tcf of CBM potential. Using a 3:1 ratio of CH_4/CO_2 storage, we estimate Alaska's deeply buried coals may be capable of storing approximately 120 Gt of CO_2. Although smaller than the North Slope, the onshore Cook Inlet basin would be the better location from an operational viewpoint for a CO_2 injection test to confirm the actual storage capacity of Alaska's deep coal deposits.

Alaska's saline aquifer sandstone formations have far greater CO_2 storage capacity than its deep coals (albeit without the potential economic benefit of enhanced methane recovery). We mapped and analyzed the thickness, lateral and depth distribution, and reservoir quality of sandstone formations in eight of Alaska's largest sedimentary basins, both onshore and offshore (note : Cook Inlet was excluded from the study). The Chukchi Sea and North Slope regions stand out as having particularly large CO_2 capacity, estimated at about 5,000 Gt each. In particular, the Cretaceous Nanushuk Formation in the Colville basin (North Slope) and Chukchi Sea region is a widespread and attractive potential storage unit.

The next five basins (North Aleutian/Bristol Bay, St. George, Navarin, Beaufort Sea, and Gulf of Alaska) each have on the order of 1,000 Gt of CO_2 storage potential, though each basin has its unique geologic setting as well as challenges. The eighth basin (Norton) is rather small and has thinner, more limited sandstone targets. All of these basins, particularly the Beaufort, are located in operationally difficult areas challenged

by persistent and mobile ice flows. Next steps for evaluating Alaska's saline aquifer storage potential could include detailed basin studies of the more promising areas. In particular the North Slope and Chukchi Sea, where petroleum exploration activity recently has increased, may offer opportunities for joint industry testing.

Table A : Preliminary Estimate of Deep Coal Seam CO_2 Storage Potential in Alaska

	Identified & Undiscovered Coal Resources	Mean Ash Content	Mean Moisture Content	Identified & Undiscovered Coal Resources	Mean Volatile Matter	Gas Content	CBM Resources	CO_2 Storage Capacity	CO_2 Storage Capacity	
Region	(Btons)	(%)	(%)	(Btons, daf)	(%)	(scf/ton daf)	(Tcf)	(scf/ton) (daf)	(Tcf)	(Gt)
North Slope	4,020	10.3	12.5	3,103	30.1	200	621	400	1,241	65
Nenana	17	9.9	24.7	11	35.9	100	1	200	2	0
Cook Inlet	1,292	10	20	905	35.0	150	136	400	362	19
Total	5,329			4,019			758		1,605	84

Table B : Preliminary Estimate of Sandstone Saline Aquifer CO_2 Storage Potential in Alaska

Saline Aquifer Basin	Prospective Area	Avg Depth	Reservoir Pressure	Sandstone Thickness	Rock Volume	Avg Porosity	Pore Volume	CO_2 Storage Saturation	Density	Capacity
	(km^2)	(m)	(psi)	(m)	(km^3)	(%)	(km^3)	(%)	kg/m^3	Gt
Chukchi Sea	100,000	2,000	2,855	600	60,000	25%	15,000	50%	700	5,250
North Slope / Colville	75,000	2,000	2,855	750	56,250	25%	14,063	50%	700	4,920
North Aleutian / Bristol Bay	20,000	1,700	2,429	1,100	22,000	23%	5,060	50%	700	1,770
St. George	5,000	1,800	2,571	2,500	12,500	31%	3,875	50%	700	1,360
Navarin	80,000	1,800	2,571	325	26,000	15%	3,900	50%	600	1,170
Beaufort Sea	30,000	2,300	3,281	500	15,000	20%	3,000	50%	700	1,050
Gulf of Alaska	40,000	2,000	2,855	500	20,000	15%	3,000	50%	600	900
Norton	19,500	2,400	3,423	300	5,850	15%	878	50%	600	260
TOTAL	**369,500**									16,700

1.0 Introduction

Background

This study was performed for WESTCARB by Advanced Resources International, Inc. (ARI), a consulting firm based that focuses on geologic CO_2 storage technologies and unconventional oil and gas resource development.

The purpose of the study is to evaluate at a scoping level the geologic CO_2 storage potential of sedimentary strata in Alaska. One region was excluded from the study. The saline aquifer and enhanced oil recovery storage potential of the Cook Inlet region was evaluated separately by the Alaska Division of Natural Resources. However, ARI did evaluate the deep coal seam storage potential in the Cook Inlet region.

WESTCARB Project

The West Coast Regional Carbon Sequestration Partnership is one of seven research partnerships established in 2003 and co-funded by the U.S. Department of Energy (DOE) to characterize regional carbon sequestration opportunities and to develop action plans for pilot-scale validation tests. WESTCARB is evaluating opportunities in a six-state region (California, Oregon, Washington, Nevada, Arizona, and Alaska) for removing carbon dioxide (CO_2) from the atmosphere by enhancing natural processes and by capturing it at industrial facilities before it is emitted; both will help slow the atmospheric buildup of this greenhouse gas and its associated climatic effects.

A key part of the project is identifying subsurface locations to store the captured CO_2. These geologic sinks are expected to include deep formations (such as oil and gas reservoirs as well as saline aquifers) that are essentially leak-proof. These potential sinks will then be matched with major anthropogenic CO_2 sources, such as large utilities and industrial emitters.

DOE's intention is to combine WESTCARB's findings with those of the other six partnerships to create a national “carbon atlas” to better understand how sequestration technology can help the United States reduce the carbon intensity of its economy and mitigate climate changes. On the basis of the source and geologic characterization, WESTCARB will prioritize geologic sequestration opportunities within the region and will propose pilot-scale projects that combine industrial CO_2 capture, CO_2 transport via pipeline, and injection into geologic formations for storage or enhanced oil and gas recovery.

Methodology

No previous state-wide estimate of Alaska's CO_2 storage potential has been performed. To conduct this study, ARI reviewed published and unpublished geologic and reservoir information on Alaska's sedimentary basins. We constructed basin-level maps of coal and sandstone thickness, evaluated representative well logs to gather porosity and permeability data, and developed a first-order volumetric estimate of the CO_2 storage potential. Given the large size and apparent CO_2 storage capacity of Alaska's sedimentary basins, this relatively small effort should be viewed as the starting point for more rigorous future evaluations.

Data Control

ARI gathered geologic data gathering for most of the onshore and offshore sedimentary basins in Alaska and synthesized this data set into a GIS system (ArcView format). The data base comprises well logs, seismic reflection data, and basin studies which were originally conducted for the purposes of conventional oil and gas exploration. However, in many cases these data also are useful for CO_2 storage analysis. We also compiled surface geology, detailed topography and bathymetry data, cities, towns, and oil and gas pipeline infrastructure locations. Due to budget limitations, not all of this extensive data set could be fully analyzed, as ARI focused its analysis on the geologic storage potential of the higher-potential basins in Alaska. However, the files provide a good basis for future more detailed studies. **Figure 1** shows the data set in its entirety.

2.0 Deep Coal Seam CO_2 Storage Potential in Alaska

Alaska contains major coal deposits that range from shallow outcrop to over 2,000 m deep. Three major geologic provinces account for vast majority of Alaska's coal resources (**Figure 2**) : 1) Southern Alaska – Cook Inlet region; 2) Northern Alaska - North Slope Region; and 3) Central Alaska – Nenana Region. Most of Alaska's coal is sub-bituminous in rank, but extensive high-volatile bituminous rank deposits exist in the western North Slope and Central Alaska. Coal mining has been limited to date mainly due to the remoteness and climate.

To estimate CO_2 storage capacity, it is necessary first to estimate coal and CBM resources. ARI estimates Alaska's CBM resources to be approximately 776 Tcf of gas in place, larger than the estimated 600 Tcf resources in the Lower-48 States.

2.1 Coal and CBM Resources

In contrast to the Lower 48 States, where coalbed methane (CBM) development is advanced and several enhanced CO_2-CBM pilots have been tested, CBM testing in Alaska is still at the very earliest conceptual stage. Basic information on coal thickness, quality, depth, and rank are available. However, few reservoir data (such as gas content or permeability) exist for deep coals in Alaska.

Initial CBM well testing has occurred in the onshore Cook Inlet region in southern Alaska, but other areas of the state remain essentially untested. The Alaska Department of Natural Resources (DNR) and the U.S. Geological Survey (USGS) have conducted initial evaluations of coal and coalbed methane resources in certain regions of Alaska, providing a basis for our preliminary estimate of CO_2 storage capacity.

Coal Resources. Although coal mining activity has been limited, Alaska contains major coal deposits that range from shallow outcrop to over 2,000 m deep. Three major geologic provinces account for approximately 90% of Alaska's coal resources (**Map 1**) : 1) Southern Alaska – Cook Inlet Region; 2) Northern Alaska - North Slope Region; and 3) Central Alaska – Nenana Region. Most of the coal resource estimates date back to the early 1980's. They tend to be biased towards shallow mineable coal deposits and frequently do not consider coals encountered in deep oil & gas wells that are prime targets for CBM development and CO_2 storage.

- The **Southern Alaska – Cook Inlet** region has Tertiary (Miocene) coal resources in the Tyonek Formation. Demonstrated resources are estimated at 2.9 to 12 billion tons, with another 970 to 1,600 billion tons of undiscovered (but reasonably reliable) resources. The coal deposits total about 80-150 feet thick and in many onshore areas occur at favorable storage depths of 2,600 to 3,700 feet. Coal rank is sub-bituminous to high-volatile bituminous C. The coals are estimated to have sourced about 7.7 Tcf out the Cook Inlet's total 8.3 Tcf of conventional natural gas reserves. The Alaska DNR has estimated 245 Tcf of CBM resources in the Cook Inlet, while the USGS has placed resources at 140 Tcf of gas in place.

- The ***North Slope*** region has coals in the Lower Cretaceous Nanushuk and Upper Cretaceous Colville Groups as well as in the Tertiary Sagavanirktok Group. Coal underlies an area of approximately 83,000 km^2. Coal rank ranges from lignite A to high-volatile A bituminous, with a mean rank of high-volatile C bituminous. Identified resources are 120 billion short tons, with a further 3,870 billion tons of undiscovered but likely coal resources. Although the largest in Alaska, these deposits are not currently mined due to their depth and remoteness.
- The ***Central Alaska – Nenana*** region has Tertiary coals estimated at 6.4 to 7.7 billion tons of identified resources, with an additional 10 billion tons of undiscovered resources. Coal thickness is approximately 50 to 66 feet and occurs at depths ranging from surface to around 3,000 feet. Coal rank ranges from lignite to sub-bituminous, mainly sub-bituminous C. Although smaller than the North Slope and Cook Inlet, the Nenana basin is the only coal province in Alaska that is currently being mined. The region is not continuously underlain by coal, but instead comprises numerous small structural basins (synclines) that are separated by anticlinal highs. Coal occurs in the Tertiary Usibelli Group.

CBM Resources. The first published estimate of CBM resources in Alaska was the Alaska DNR's 1,000 Tcf of gas in place.[1,2] In 2004, the USGS national coal resource evaluation also examined CBM in Alaska, characterizing it as "exceedingly large," but did not actually quantify CBM resources.[3]

In 2006, the USGS assessed CBM resources in the North Slope region only, estimating a total 19 Tcf in place.[4] Although the USGS did not display their methodology in this report, standard volumetric calculation would imply an average gas content of only 6 scf/ton (dry, ash-free basis) was used in the estimate. That would seem to be much lower than reasonable gas content given the rank and depth of North Slope coal seams. (Typical gas contents in the Lower-48 States vary from 30 to 600 scf/ton, d.a.f.)

ARI developed an independent preliminary estimate of CBM resources (**Table 1**). We started with the USGS coal resource estimate, adjusting to ash- and moisture-free basis because these components do not adsorb gas. We further inferred an average methane content based on the average coal rank in each region, indicated by the mean volatile matter content (higher rank coals have higher gas storage capacity). Gas content was assumed to range from 100 scf/ton in the relatively low-rank and shallow Nenana region, to 200 scf/ton in the higher-rank and deeper North Slope region.

Using this methodology, we preliminarily estimate CBM resources in Alaska to be approximately 758 Tcf, somewhat less than the initial 1,000 Tcf Alaska DNR estimate. We further estimated that geologically high-graded CBM resources in the Cook Inlet, the only area in Alaska to have experienced CBM well testing to date, could be approximately 27.1 Tcf.

Table 1 : Estimated coalbed methane resources in Alaska.

Region	Identified & Undiscovered Coal Resources (Btons)	Mean Ash Content (%)	Mean Moisture Content (%)	Identified & Undiscovered Coal Resources (Btons, daf)	Mean Volatile Matter (%)	Methane Content (scf/ton, daf)	Total CBM Resources (Tcf)	High-Graded CBM Resources (Tcf)
North Slope	*4,020*	*10.3*	*12.5*	*3,103*	*30.1*	*USGS 6*	*18*	
North Slope	**4,020**	**10.3**	**12.5**	**3,103**	**30.1**	**ARI 200**	**621**	
Nenana	**17**	**9.9**	**24.7**	**11**	**35.9**	**ARI 100**	**1**	
Cook Inlet	**1,292**	**10.0**	**20.0**	**905**	**35.0**	**ARI 150**	**136**	**27.1**
ARI Total	**5,329**			**4,019**		**ARI**	**758**	

2.2 CO$_2$ Storage Potential

ARI performed a highly preliminary estimate of the CO$_2$ storage potential. As previously for the CBM resource assessment, ARI used the USGS estimates of coal resources as a starting point (**Table 1**). The CO$_2$ sorption capacity of Alaskan coals has not yet been measured in the laboratory. Therefore, we used sorption analyses for similar-rank coals to estimate CO$_2$ storage capacity in each of the three Alaskan coal regions.

The ratio of CO$_2$/CH$_4$ adsorption capacity ranges from about 2:1 to over 10:1, depending on coal rank, maceral composition, and other factors.[5] Based on the somewhat low coal rank in Alaska (lower than San Juan but higher than Powder River basin), we assumed that the CO$_2$ storage capacity was three times that for methane, ranging from about 300 to 600 scf/ton (d.a.f.). However, this number is highly approximate and needs to be updated with actual laboratory CO$_2$ adsorption measurements.

ARI estimates that Alaska has on the order of 120 Gt (2,273 Tcf) of CO$_2$ storage capacity in deep coal seams, mainly in the North Slope and Cook Inlet regions. However, it is likely that only a portion of this total storage target would be considered favorable for CO$_2$ sequestration, due to variations in permeability, seam geometry, surface access, faulting, and other site-specific but currently undetermined conditions.

Table 2 : Estimated CO_2 storage capacity in deep Alaska coal deposits

Region	Identified & Undiscovered Coal Resources (Btons)	Mean Ash Content (%)	Mean Moisture Content (%)	Identified & Undiscovered Coal Resources (Btons, daf)	Mean Volatile Matter (%)	Methane Content (scf/ton, daf)	Total CBM Resources (Tcf)	CO2 Storage Potential	
								(Tcf)	(Gt)
North Slope	***4,020***	***10.3***	***12.5***	***3,103***	***30.1***	***USGS 6***	***18***		
North Slope	**4,020**	**10.3**	**12.5**	**3,103**	**30.1**	**ARI 200**	**621**	**1,862**	**98**
Nenana	**17**	**9.9**	**24.7**	**11**	**35.9**	**ARI 100**	**1**	**3**	**0**
Cook Inlet	**1,292**	**10.0**	**20.0**	**905**	**35.0**	**ARI 150**	**136**	**407**	**21**
ARI Total	**5,329**			**4,019**		**ARI**	**758**	**2,273**	**120**

The following sections discuss in greater detail the coal deposits, CBM resources, and CO_2 storage potential of the three main Alaska coal regions.

2.3 Cook Inlet

Geology. The Cook Inlet region of southern Alaska is a tectonically active, convergent plate margin (**Figure 3**). Subduction of the Pacific Ocean plate northward beneath Alaska since latest Triassic generated a classic island arc system with deep ocean trench, accretionary prism (Chugash Terrane), forearc basin (including the Cook Inlet area) with Mesozoic and Cenozoic marine and nonmarine strata, and an andesitic volcanic arc.[6]

The Cook Inlet basin covers an area of approximately 36,000 km^2 and contains up to 10 km of marine Mesozoic sedimentary rocks and 8 km of Tertiary nonmarine sedimentary rocks. Cook Inlet is a NE-SW trending forearc basin associated with the Aleutian Island Arc subduction system. The basin fill has been folded and faulted by continuing subduction, creating conventional structural traps. [7]

The Oligocene to Pliocene Kenai Group is the major coal-bearing sequence in the Cook Inlet region (**Figure 4**). The base of this unit is the Hemlock Conglomerate, comprising fine- to coarse-grained sandstones, siltstone (tuffaceous in part), sporadic coal seams, and conglomerate. Sandstones within this unit have good porosity and permeability (average 17% and 80 mD) and provide the dominant conventional hydrocarbon reservoir of the Cook Inlet Basin.

Overlying the Hemlock Conglomerate are the Tyonek, Beluga, and Sterling formations, thick sequences of alluvial sandstones, siltstones, mudstones, carbonaceous shales, and coals with a combined thickness of up to 7 km. Sandstones are commonly massive or lenticular channel deposits, consisting of quartz, feldspar, lithic fragments, and volcaniclastic debris. Similarities in lithology among the three formations, as well as rapid lateral facies changes and the lack of diagnostic fossils, have made it difficult to determine precise and consistent stratigraphic contacts.

The Miocene Tyonek and Beluga Formations host the major coal deposits in the Cook Inlet basin, although the Chickaloon Formation has locally thick coals in the Matanuska Valley.[8] The Kenai Group is interpreted to be an alluvial fan deposit comprising meandering stream systems, with coal seams developed in swamp or marsh settings on the floodplains.[9]

Gas Infrastructure. The Cook Inlet has a liquefied natural gas (LNG) facility (Kenai-Nikiski plant) for exporting natural gas produced in the basin to Asian markets (**Figure 5**). Operated by ConocoPhillips (70%) and Marathon (30%), the plant has annual production of about 1.2 million t. Most of Kenai's production is exported to Japan. Kenai is the oldest LNG plant in operation, having started production in 1969.

Current estimates of the conventional gas reserves remaining in the Cook Inlet Basin vary from 1 to 2 Tcf, which are not sufficient for long-term LNG exports. Thus, the CBM resources of the Cook Inlet have taken on renewed interest, especially following the recent Australian model of converting CBM to LNG for export.[10] Commercial CBM production from the Cook Inlet need not await the construction of a pipeline to the Lower-48 States, but could be handled out of the existing Kenai LNG facility.

Coal Resources. Demonstrated coal resources in the Miocene Tyonek Formation are estimated at 2.9 to 12 billion tons, with another 970 to 1,600 billion tons of undiscovered resources. The Cook Inlet coals can total up to 1,000 feet or more in places, making this one of the thickest known coal deposits (**Figure 6**).[11] The coal seams often occur at optimal CBM and CO_2 storage reservoir depths of 1000 to 4000 feet. Coal rank is sub-bituminous to high-volatile bituminous C. Vitrinite reflectance at the Pioneer lease reached R_o = 0.6%. The coals are estimated to have sourced about 7.7 Tcf out the Cook Inlet's total 8.3 Tcf of conventional natural gas reserves.

CBM Resources. The onshore Cook Inlet region near Anchorage appears particularly prospective for CBM development, with thick sub-bituminous rank coals onshore with gas contents of 100-200 scf/ton. Only one CBM production pilot has been tested to date, the 4-well Evergreen Resources pilot northwest of Anchorage. This pilot did not succeed commercially but provided useful geologic and reservoir information.

ARI estimates that the onshore Cook Inlet region has about 136 Tcf of accessible CBM resources in place (**Table 1**). This estimate does not include offshore potential, which has not been developed elsewhere due to high costs. ARI's estimate is similar to a recently published USGS estimate (using similar but independent methodology) of 140 Tcf.[12]

ARI further estimated that 20% or 27.1 Tcf of this total would located in high-quality areas with favorable permeability, hydrology, and other reservoir properties. Applying a standard 50% recovery factor, ARI estimates there could be 13.6 Tcf of technically recoverable CBM resources in the onshore Cook Inlet region.

CBM Testing. The onshore Cook Inlet is the only region in Alaska that has experienced CBM well testing to date. No CBM testing has occurred yet in the North Slope region. CBM projects have included one Alaska DNR gas content corehole, a number of confidential coreholes drilled by Unocal (now Chevron), and Evergreen Resources' (now Pioneer Resources) production pilots. There has also been an offshore coal seam well recompletion test conducted by XTO Energy.

Currently, only one company (Fowler Oil and Gas) is actively pursuing CBM exploration in the Cook Inlet area. Considering the size of the Cook Inlet basin coal deposit, available data on coalbed methane reservoir properties remain limited.

- **Alaska DNR.** In 1994 the state agency DNR drilled Alaska's first gas content corehole (AK-94-1), located in the Matanuska-Susitna Valley (**Figure 7**), about 50 km north of Anchorage. Approximately 40 feet of coal was cored and desorbed using standard US Bureau of Mines analytical procedures. Gas content was encouragingly high and increased regularly with depth, ranging from 63 scf/ton (d.a.f.) at a depth of 500 feet (R_o = 0.47%), to 245 scf/ton at a depth of 1,300 feet (R_o = 0.58%). Gas composition was mainly methane (98-99%), with minor CO_2 and N_2. Overall, reservoir properties tested in this corehole were favorable for CBM development and CO_2 storage (**Figure 8**).

- **Unocal.** During the late 1990's, Unocal drilled several coreholes to test gas content in the same portion of the upper Cook Inlet (Matanuska-Susitna Valley), but decided not to attempt production wells. Data from these coreholes remain confidential.

- **Evergreen.** During 2002-2004, Evergreen Resources (now Pioneer Resources) tested a 294,890-acre lease in this area (coincidentally called the Pioneer Unit; **Figure 7**). Evergreen had already developed a successful CBM project in the Raton basin, Colorado. The company's first Alaska land acquisition was in 2001, when they acquired a 100% WI in 64,000 gross acres, including $1 MM paid to Ocean Energy and Unocal for 48,000 acres.

  Coal seams in this area are in the Oligocene-Miocene Tyonek Formation, part of the Matanuska coal field. Coals total 80-150 ft thick, are high-volatile bituminous in rank (R_o=0.6%), and occur at depths of 2,600 to 3,700 feet. There are some structures, including the Pittman anticline, bounded by two active reverse faults.

  During 4Q-2002, Evergreen drilled two separate 4-well CBM pilot production patterns (total 8 vertical wells). The company mobilized crews and equipment from the Raton basin. This undoubtedly added costs to the project but was necessary given the lack of suitable local capability. An air-percussion rig was used to drill to total depth in only three days (**Figure 9**).

ARI reviewed unpublished well records for the Evergreen test in detail. **Figure 10** shows the coal thickness that was perforated. Individual coal seams are fairly thin (3 - 6 feet). A total 34 to 39 feet of coal was completed in the wells. Coal seam depths ranged from 1700-2300 feet, which is generally considered favorable for CO_2 storage in this reservoir type. During the second quarter of 2003, Evergreen hydraulically stimulated all four wells of first pilot and one well of the second pilot. Four zones were frac'd in each well (**Figure 11**).

Although drilling permits were granted for two water-disposal wells, Evergreen abandoned the project in 2004 following long-term production testing, saying it was "probably not capable of commercial production." It is worth noting that the $1.80/Mcf wellhead gas price was among the lowest in the USA at the time. There was also considerable environmental opposition to the project.

- **Stormcat Energy.** This small natural gas operator acquired leases near the Evergreen project in the onshore Cook Inlet. Stormcat entered the play in 2004 by acquiring two leases totaling 18,359 acres at auction from the Alaska Mental Health Trust. Stormcat paid approximately $200,000 for 100% working interest in the leases, which run for a period of 5 years. However, Stormcat – which also has operations in the Powder River basin and the Fayetteville Shale -- entered bankruptcy in 2008 and has not drilled any CBM wells in Alaska.

- **XTO Energy.** In late 2003 this large independent gas producer tested a shallow uphole CBM zone in one or two of the company's shut-in wells at C platform, offshore Cook Inlet, where they operated conventional oil production (**Figure 12**). This was one of only very few offshore CBM well tests ever conducted. Gas production was needed to replace 700 Mcfd of gas from Unocal's Baker platform, which had been shut down. Results have not been released and it is not clear whether the test was successful or not.

- **Fowler Oil and Gas.** This small local independent operator currently holds about 25,000 CBM-prospective acres in the Matanuska Valley, the same general area as the Alaska DNR and Evergreen CBM projects. Fowler hold a permit to drill one well in the environmentally sensitive Mat-Su Valley. As of February 2009, the well site had been constructed but drilling is waiting on further funding.

  The Fowler leases reportedly are underlain by about 18 coal seams, each 6-10 feet thick. ARI estimates gas content to be in the 100-250 scf/ton range as measured in the nearby Alaska DNR corehole, although Fowler has estimated higher gas contents up to 500 scf/ton.

  Fowler plans to minimize environmental controversy encountered by Evergreen by using horizontal rather than vertical frac wells and has engaged Scientific Drilling as a potential drilling contractor. Scientific is planning on a 5-seam completion. Fowler also plans to use a downhole water diverter to directly re-inject water into a disposal zone without lifting it to the surface. (This method is being tested by Marathon Oil and Continental in the Powder River basin.)

After a 7-month application period to the Alaska Oil & Gas Conservation Commission, Fowler finally was granted a permit in May 2008 to drill a single "mother" well, from which multiple lateral wells could be kicked off. The permit is valid (and confidential) for two years. As of report time, Fowler had not yet spud the well.

- **Marathon Oil.** Alaska's tight gas resources are beginning to attract interest but still have not been thoroughly assessed. The first conference on Alaska tight gas resources was held during April 2008 in Anchorage.[13] And the Alaska DNR has just begun a major research effort to characterize tight gas sandstone formations in the Cook Inlet region. Potential TGS target include the Eocene West Foreland Formation, which underlies the Miocene Tyonek coals in the Cook Inlet basin, is a complex fluvial to alluvial fan clastic deposit that may have TGS potential.[14]

  Marathon already has been completing tight gas and nearby coal formations in Alaska for about 7 years.[15] Not surprisingly, Marathon finds the Alaskan operating environment more challenging for TGS development than the Lower-48 states. Marathon's main concerns for Alaska include relatively low gas prices, higher costs, geographic challenges, and the immature state of the service industry infrastructure.

  Marathon's Kenai gas field has a thick clastic Tertiary gas-bearing section (**Figure 13**). The primary TGS target is the Beluga Sandstone in the offshore Cook Inlet. They typically encounter 10-20 gas sands within a 1700-foot thick stratigraphic interval. Individual sandstones range from 5-30 feet thick, with 0.01 to 3.0 mD of permeability (<0.1 mD generally is the cutoff for tight sands). Numerous coal seams also are present in the section.[16] Prior to hydraulic stimulation, Marathon's wells produced at 0.5 to 1.0 MMcfd initially (pure methane, no condensate); some sands did not contribute at all.

CO_2 Storage Potential. Using the USGS coal resource estimate and an average estimated CO_2 adsorption content of 450 scf/ton (d.a.f.), three times the average 150 scf/ton methane content, ARI estimated CO_2 storage potential in the onshore Cook Inlet region to be approximately 21 Gt (**Table 2**). This preliminary estimate could be improved with new laboratory and well test data on the sorption characteristics of Cook Inlet coal.

Conclusions. The onshore Cook Inlet appears to have Alaska's best potential for coalbed methane development as well as near-term CO_2 storage. Coal seams are thick, laterally extensive, and present at target depths of about 1 km. Early, albeit quite limited CBM testing has taken place. The existing natural gas infrastructure of Kenai LNG facility and gas pipelines, as well as drilling and well services, could help support CO_2 storage testing and operations in this region.

A future more detailed study could evaluate the large data set that exists in the Cook Inlet (**Figure 14**). There are several dozen well penetrations that could help define coal seam thickness, geometry, rank, and gas kicks, but their interpretation was beyond the scope of this preliminary scoping study. This evaluation could be followed by a possible CO_2 injection test in a well of opportunity, such as the planned and already permitted Fowler Oil & Gas well in the Matanuska-Susitna Valley.

2.4 North Slope

Geology. Coal underlies an area of approximately 83,000 km^2 in the onshore North Slope region (**Figure 15**). Coal occurs mainly in the Lower Cretaceous Nanushuk and Upper Cretaceous Colville Groups as well as in the Tertiary Sagavanirktok Group, representing deltaic and fluvial depositional environments.[17]

The Nanushuk Group is about 3 km thick and comprises a regressive marine to non-marine sequence. The lower Nanushuk Group comprises the marine-deposited Tuktu, Kukpowruk, and Grandstand Formations (**Figure 16**). Overlying these are the nonmarine Chandler, Corwin, and Ninuluk Formations.

Roughly 150 individual coal seams individually ranging up to 6 m thick occur in the middle and upper parts of the Nanushuk Group. Total coal thickness exceeds 400 feet in the thickest areas, within the western part of the Alaska National Petroleum Reserve.

Overlying the Nanushuk Group is the 1.5-km thick Upper Cretaceous Colville Group, which also contains extensive coal deposits. The Colville Group comprises (from bottom to top) the marine Seabee and Schrader Bluff Formations, and the coal-bearing, nonmarine Prince Creek Formation. However, the Colville Group coals are thinner, higher in ash content, and lower in rank (lignite) than those of the Nanushuk Group and thus have been less well studied.

Nanushuk coal rank is significantly higher than for the younger Miocene-age sub-bituminous coal deposits of the Cook Inlet basin. Nanushuk coal ranges from lignite A to high-volatile A bituminous, with a mean rank of high-volatile C bituminous. Identified resources are 120 billion short tons plus a further 3,870 billion tons of undiscovered (but fairly high probability) coal resources. Although the largest in Alaska, North Slope deposits are not currently mined due to their depth and remoteness.

Unconformably overlying the Cretaceous Nanushuk Formation are the Cretaceous-Tertiary Jago River and Sagavanirktok Formations. The Jago River Formation dates to Late Cretaceous to Paleocene, while the Sagavanirktok Formation is Paleocene to Pliocene and may be as young as Pleistocene.

The 2.3-km thick Sagavanirktok Formation, which intertongues with the Canning Formation of the Colville Group, comprises a coarsening-upward sequence of mainly sandstones, with siltstones, mudstones, conglomerates, carbonaceous shales, and coals (**Figure 17**).[18] Within the Sagavanirktok Formation are two coal zones, a lower 260-m thick unit with 12 coal seams and an upper 110-m thick unit with 7 coal seams. Individual coal beds range up to 7 m thick. Coal beds are distributed over an area of 15,000 km^2. The lower coal zone was deposited in an alluvial-delta plain setting, while the upper coal zone reflects lower delta-plain and back-barrier mires.

CBM Resources. There are no desorbed gas content data for the Alaska North Slope region, nor have laboratory sorption isotherms been measured. Based on mostly bituminous coal rank and average burial depths of approximately 2000 feet, ARI assumed a preliminary gas content of 200 scf/ton (d.a.f.). This generates a volumetric estimate of 621 Tcf of CBM gas in place (**Table 1**), a very significant deposit roughly equivalent in size to total Lower-48 State CBM resources.

Based on this assumed gas content and the USGS coal resource estimate, ARI estimates volumetrically there are approximately 621 Tcf of coalbed methane resources in the North Slope (**Table 1**). These CBM resources have not yet been well tested, are located far from existing natural gas infrastructure, and thus represent a long-term target for natural gas supplies.

CO_2 Storage Potential. Using the USGS coal resource estimate and an average estimated CO_2 adsorption content of 600 scf/ton (d.a.f.), three times the average 200 scf/ton methane content, ARI estimated CO_2 storage potential in the onshore North Slope region to be approximately 98 Gt (**Table 2**). This highly preliminary estimate could be improved with new laboratory and well test data on the sorption characteristics of North Slope coal.

Conclusions. Although the onshore North Slope region has a massive coal resource with significant CO_2 storage capacity, data on CBM reservoir properties are practically non-existent. The Cook Inlet region, with somewhat smaller but still sizeable resources, still appears to be Alaska's best near-term area for CBM development and CO_2 storage. Future work to locate and interpret individual coal corehole and oil and gas well logs in the western North Slope region, as well as sorption isotherm lab testing would be a low-cost but high-return approach to refine our preliminary estimate of CO_2 storage potential.

2.5 Central Alaska (Nenana)

Geology. The Nenana coal field in central Alaska is the state's smallest coal province yet also its most thoroughly studied, because it has experienced the most extensive coal mining. The Nenana coal province is located in the northern foothills of the Alaska Range (**Figure 18**). The region is not continuously underlain by coal, but rather comprises numerous small structural basins (synclines) that are separated by anticlinal highs where coal is not present, stretching over an area 15 km from north-south and 160 km long east-to-west.

Coal occurs mainly in the Tertiary Usibelli Group, a nonmarine sedimentary sequence. The Usibelli Group comprises (from bottom to top) the coal-bearing Healy Creek, noncoaly Sanctuary, coal-bearing Suntrana and Lignite Creek Formations and the noncoaly Grubstake Formation (**Figure 19**).[19] It is overlain unconformably by the Nenana Gravel. Up to 30 coal beds occur in the Usibelli Group, typically 0.7 m thick and reaching a maximum 9 m thick.

Coal in the Central Alaska-Nenana coal province ranges from lignite to subbituminous, most commonly subbituminous C. Coal in the Healy Creek and Lignite Creek coalfields ranges from 3,410 to 5,120 kcal/kg (mean 4,320 kcal/kg). Ash content ranges from 5 to 34% (mean 9.9%) and moisture content 15-33% (mean 24.7%).[20]

Coal Resources. The Central Alaska – Nenana region (**Figure 19**) has Tertiary coals estimated at 6.4 to 7.7 billion tons of identified resources, with an additional 10 billion tons of undiscovered resources.[21] Coal thickness is approximately 50 to 66 feet and occurs at depths ranging from surface to around 3,000 feet. Coal rank ranges from lignite to sub-bituminous, mainly sub-bituminous C. Although smaller than the North Slope and Cook Inlet, the Nenana basin is the only coal province in Alaska that is currently being mined.

CBM Resources and CO_2 Storage Potential. Based on the relatively low rank and shallow coals in the Central Alaska Nenana coal field, ARI estimated methane content to be in the range of 100 scf/ton. This is less than estimated for the deeper and/or higher rank North Slope (200 scf/ton) and Cook Inlet (150 scf/ton) areas and results in a volumetric calculation of only 1 Tcf of CBM resource in place (**Table 1**). Assuming CO_2 storage capacity of 300 scf/ton (triple the CH_4 content), total CO_2 storage could be well under 1 Gt (**Table 2**). The small potential of the Central Alaska Nenana coal field would appear to warrant low priority for future analytical and testing work.

2.6 Development Potential

Alaska CBM deposits still are at a very early stage of testing and there is very little reservoir data for evaluating CO_2 storage potential and costs. There are many reservoir risks including low permeability, undersaturation, lack of isolation from aquifers, as well as other risks. It is useful to look for commercial analogs in similar geologic settings, two of which appear broadly similar to Cook Inlet and the North Slope, though neither is a perfect analog.

One possible analog is the Powder River basin in Wyoming, which currently produces more than 1 Bcfd from about 30,000 vertical wells. However, the Powder River is considered a unique setting, in that CBM wells are uniquely shallow (300-1000 feet), very thick (50-100 foot individual seams), very low rank sub-bituminous to lignite (R_o = 0.3%), have low gas content (<50 scf/ton), but also extremely high permeability (~1 darcy). Powder River CBM wells are completed open-hole and unstimulated, an unusual method for the industry. Water production rates are high initially (500-1000 bwpd). Although per-well reserves are modest (<0.5 Bcf), capital costs are low ($0.25 million currently) and the basin is economic to develop at wellhead prices above $5/Mcf.

A second analog for Alaska CBM resources is the Washakie sub-basin within the Greater Green River basin of Wyoming,[22] where Anadarko and other operators currently are developing a 2 Tcf field. The eastern "Atlantic Rim" portion of the Washakie basin has multiple-seams that are moderately thick, ranging from 12 to 30 m within a 200-m thick stratigraphic section. Typically, about half (15 m) of the coal is completed and stimulated. Individual coal seams show lateral variation in thickness. Coal rank is comparable to that of the Cook Inlet and portions of the North Slope (R_o = 0.5%). Permeability is in the range of 10-30 mD, which is rather high but conceivable for Alaska. The coals are over-pressured with pressure gradients of 0.48-0.67 psi/foot and commonly are drilled with mud weights ranging from 10.3-12.3 pounds per gallon.

Washakie basin vertical frac wells spaced 160 acres and drilled to 600-m depth cost approximately $1 million all-inclusive, including drilling, completion, frac, pumping equipment, gathering system, and amortized costs for a water disposal well. ARI's analysis indicates these wells recover an average 1.3 Bcf/well in the better areas, while less favorable areas recover 0.5 Bcf/well. The produced gas has a heating value of 990-1,000 Btu/ft^3, with <0.5% CO_2.

Water production in the Washakie CBM development is fairly high (1,200 barrels/day) during initial dewatering, then declines to below 500 Bwpd after about four years. Produced water quality ranges from 1,000-1,450 ppm TDS, mainly sodium bicarbonate. Most of the produced water is injected into the underlying Deep Creek sandstone at depths of 3,000 to 4,000 ft or Nugget sandstone at a depth of 9,600 ft at rates of 5,000 to 10,000 Bwpd per well.

In summary, while by no means a perfect commercial analog, the eastern Washakie and the Powder River basins together appear reasonably similar to Cook Inlet and North Slope CBM resources in terms of coal thickness, geometry, structural geology, rank, and hydrology. It would appear that Alaska CBM resources, and by inference their CO_2 storage, have development potential.

Drilling and completion costs for CBM and CO_2 injection wells in Alaska are uncertain but likely to be 20-100% higher than in the Lower-48 USA. The Alaska DNR has estimated the costs of drilling CBM test wells in several remote parts of the state, including the North Slope, central Alaska, and the northeastern Aleutian Islands (but not Cook Inlet).[23] These were full-sized, cased wells including a complete program of gas content and permeability testing. However, the wells were not to be stimulated or produced, so no frac, equipment, or water-disposal costs were included. The number of wells per site ranged from 2 to 4, thus rig mobilization costs were steep. Overall well costs were estimated to range from $0.25 to $1.0 million per well.

For the typical 3000-foot deep, 5-frac well in southern Alaska, ARI estimates capital costs for drilling, completion, stimulation, and equipment to run approximately $1.0

million per well, with an additional $0.5 million/well for gathering pipelines ($1.5 million/well all-in costs). There may be another $0.1 million/well for road construction, seismic, and other non-drilling costs. We further assume that gas treating and compression would be leased and appear as an operating expense.

CBM production and CO_2 injection operating costs will depend primarily on well depth, water production and disposal, power costs, and remoteness. Alaska operating costs probably will remain higher than L-48 costs due to climate and relative remoteness. No data on produced-water quality is available. Based on Evergreen's plan to re-inject, we assume that this would be necessary.

2.7 Gas Shale Resources

Gas shale reservoirs are the fastest growing natural gas supply source in the USA, as the large resource base becomes geologically better understood and advancements in well drilling and stimulation result in improving recovery. Gas shale production in 2008 averaged over 6 Bcfd, about 10% of US gas production, while major producer EnCana projects close to 15 Bcfd of gas shale production in the US by 2015.[24]

Although some of the other regional partnerships are evaluating gas shales for CO_2 storage, this study did not consider the CO_2 storage potential of gas shales in Alaska. First, budget constraints limited the study scope to conventional and CBM reservoir types. Second, there essentially are no public data on gas shale reservoir properties in the state. ARI's research did not uncover any documented gas shale targets in Alaska that could be included in this preliminary CO_2 storage evaluation. However, future more detailed evaluations should consider gas shale potential.

The only known gas shale exploration taking place in Alaska is by the mining company Teck Cominco, supported by ARI on the evaluation and testing of gas shale deposits near its Red Dog zinc mine in remote western Alaska.[25] Apart from this commercially confidential test, Alaska's gas shale resources remain poorly characterized.

3.0 Saline Aquifer Storage Potential

As is commonly the case for most geologic provinces, saline aquifer formations account for the bulk of Alaska’s geologic CO_2 storage potential. However, unlike storage in deep coal or depleted oil and gas fields, saline aquifer storage would not benefit from potential enhanced hydrocarbon recovery. Most of Alaska’s saline aquifer storage potential is located far from anthropogenic CO_2 sources and should be viewed as some of the country’s longest-term storage potential. Although unlikely to be utilized anytime soon, it is still useful to attempt to quantify the undoubtedly vast storage potential of Alaska’s thick and laterally widespread saline aquifers.

There are four main storage mechanisms for CO_2 operate in saline aquifer rocks.[26] These are:

- **Structural and Stratigraphic Trapping.** Migration of CO_2 in response to its buoyancy and/or pressure gradients within the reservoir is prevented by low permeability barriers (caprocks) such as shale.

- **Residual saturation trapping.** Capillary forces and adsorption onto the surfaces of mineral grains within the rock matrix trap some of the injected CO_2 along its migration path.

- **Dissolution Trapping.** Injected CO_2 dissolves and becomes trapped within the reservoir brine.

- **Geochemical Trapping.** Dissolved CO_2 reacts with pore fluids and minerals in the rock matrix of the reservoir, slowly forming reaction products as solid carbonate minerals over hundreds to thousands of years.

For the purposes of a first-order capacity estimate, we calculated structural and stratigraphic trapping in the estimated pore space. Residual saturation and dissolution trapping were not considered, due to lack of reservoir data at this early stage. Geochemical trapping was considered to be too slow to be significant over the time frame of an injection project (20-40 years) but would be significant over a much longer period.

All of the CO_2 storage estimates computed in this report, particularly for the poorly understood saline aquifer formations, should be viewed as highly scoping in nature. Further more detailed basin evaluation should be performed to confirm and refine these estimates.

3.1 North Slope Region (Colville Basin and Adjacent Chukchi/Beaufort Seas)

Introduction. The North Slope region contains several large sedimentary basins and is one of Alaska's most important potential CO_2 storage areas. **Figure 20** shows the major sedimentary basins in the North Slope region with CO_2 storage potential. These include the onshore North Slope and Colville basins and the offshore Nuwuk and Kaktovik basins. (The Chukchi and Beaufort Sea areas are discussed in separate sections.)

Figure 21 shows well, seismic and other data that ARI gathered into an ArcView GIS project for the CO_2 storage evaluation. Due to budget constraints, only a small sampling of the data could be interpreted for the current study. However, future analysis could build on our data compilation.

The onshore North Slope is dominated by the Colville basin, which hosts the prolific Prudhoe Bay and nearby oil fields. The Colville basin is relatively well studied, with extensive petroleum industry drilling and research conducted by the Alaska DNR and USGS.

The Colville Basin is the major sedimentary depositional feature on the North Slope and one of the largest basins in the USA (**Figure 22**). It is bounded on the south by the Brooks Range Thrust and on the north by the Barrow Arch, which generally parallels the Arctic Sea coastline.[27] Sedimentary rocks in the Brooks Range have been uplifted and structurally deformed, thus are not considered to be primary targets for CO_2 storage (**Figure 23**). Also not considered was the CO_2 storage potential of the National Petroleum Reserve Alaska (NPRA), which is located on the northern, shallower flank of the Colville basin, nor the Arctic National Wildlife Reserve (ANWR), which is located to the east.

A great thickness of Tertiary and Cretaceous clastic sediments derived from the ancestral Brooks Range was deposited in the North Slope foreland basin of northern Alaska. Uplift and erosion in the foothills of the Brooks Range has exposed these deposits. The rock units are dominantly nonmarine to near-shore shallow-marine shelf sediments deposited in fluvial, delta-plain, delta-front, prodelta, and shallow-shelf environments. Slope and basinal sediments deposited as turbidites and other sediment gravity flows correlative with the non-marine sediments also occur.

Figure 24 shows a schematic stratigraphic correlation section of the Brookian Sequence across the North Slope, while **Figure 25** shows a regional seismic cross section.[28] The sedimentary sequence comprises the Cretaceous Torok, Nanuskuk, Seabea, Tuluvak, and Shrader Bluff Formations as well as the Late Cretaceous to Paleocene Prince Creek and Paleocene-Ecocene Sagavanirktok Formations. The best targets for CO_2 storage appear to be thick and deep sandstones within the Torok and particularly the Nanushuk Formations.

Potential CO_2 Storage Reservoirs. Potential CO_2 storage reservoirs in the Colville basin include the following formations, presented from oldest to youngest.

- **Torok** (Cretaceous) : The oldest clastic unit in the North Slope Colville basin is the Torok Formation, a thick sequence of mainly nonresistant, fine-grained sedimentary rocks. The Torok forms the base of the folded sedimentary sequence that creates most of the northern foothills belt. The formation thickens from a minimum 1 km in the Arctic Coastal Plain in the north to about 6 km in the southern fold belt region. Age ranges from Aptian to Cenomanian.

  The Torok comprises mainly dark-gray to black silty shale, mudstone, and clay shale with interbedded thin-bedded siltstone and lesser amounts of greenish-gray, thin-bedded siltstone and finegrained sandstone.[29] Fine- to medium-grained sandstone also is common in the lower part of the formation. Channelized, thin-bedded fine-grained sandstone and debris-flow deposits are locally present in the lower part of the formation. Oil-stained sandstones up to 100 m thick are present, indicating good porosity and permeability development in past history.

  The Torok is the lower portion of the Nanushuk-Torok clastic wedge, with mudstone facies deposited in marine slope and basin-floor settings and sandstone facies deposited as turbidites in lower slope and basin-floor settings. The Torok is often deformed by chevron folding and faulting, because as a relatively thick and competent layer, it acts as a detachment surface for décollement folding of the overlying Nanushuk Formation.

- **Nanushuk** (Cretaceous) : This unit contains thick sandstones of Albian to Cenomanian age in the south-central North Slope, mainly non-marine and shallow marine deposits (**Figure 26**).[30] The Nanushuk typically is an erosionally resistant sandstone that forms prominent landscapes on the North Slope (**Figure 27**). Deep well data are sparse but outcrop samples have good permeability and porosity. **Figure 28** shows a transect from the marine shelf to the alluvial plain, illustrating the southward-thickening wedge of Nanushuk clastic deposits.

  Formation thickness of the Nanushuk ranges from about 250 m in the northeast, to about 1.5 km in the outcrop belt of the central Colville basin, to over 6 km in the western Colville basin. Subsurface data show that the Nanushuk pinches out along a shelf margin trending southward from the Colville River delta. Nonmarine sediments decline in importance from south to north.

  A total of 24 lithofacies in 10 facies associations have been mapped in the Nanushuk Formation (**Figure 29**). In order from base to top, facies range from alluvial floodbasin succession above crevasse splay sandstones, to trough cross-bedded sandstone, to pebble conglomerate with lenticular sandstone. Shoreface association is the most abundant association in marine strata of the Nanushuk.

Distributary mouth bar, distributary channel, and tidal inlet associations are common over relatively narrow stratigraphic thickness in the lower part of the formation. Nonmarine strata along south side of the outcrop belt include abundant tabular fluvial bodies, channel-fills, and alluvial floodbasin successions. Nonmarine sand and conglomerate bodies in outcrop are typically separated by poorly exposed fine-grained floodbasin successions (overbank facies associations), which might act as inter-formation seals for CO_2 trapping. (For example, back-barrier mudstone has been mapped immediately above shoreface sands.)

Figure 30 shows a measured outcrop section of the Nanushuk Formation, in the Kanayut River area, North Slope basin. The section measures a total 620 m thick, of which sandstone accounts for approximately 80% or 500 m. More typically, total Nanushuk formation thickness is approximately 10,000 feet (3 km; **Figure 31**).

The deltaic complexes in the south-central North Slope portion of the Nanushuk Formation are interpreted as having resembled the modern Po, Rhone, and Danube River deltas.

- **Seabee** (Cretaceous) : Conformably overlying the Nanushuk Formation, the Seabee (previously termed the Shale Wall Member of the Shrader Bluff Formation) comprises mudstone, silty mudstone, and fissile, organic-matter-rich paper shale, with interbedded bentonite and thin, silicified tuff beds. Thin siltstone and fine-grained sandstone beds are locally present, as are large (1.2-m) concretions.

  The Seabee Formation thickens from about 100 m west of Chandler River to about 400 m along the Nanuskuk River to the east (**Figure 32**). Seismic data shows the unit thickens abruptly eastward across the shelf margin to about 600 m. Its age is Cenomanian to Coniacian.

  The Seabee does not appear to be a primary target for CO_2 storage, given the predominance of mudstone and shale relative to scarce sandstones. However, the Seabee may act as an effective seal to the underlying sandstone-rich Nanushuk and Torok Formations.

- **Tuluvak** (Cretaceous) : Age of this unit is Turonian to Coniacian with thickness of approximately 400 m. The Tuluvak Formation forms the main reservoir at Gubik gas field and is locally oil stained, indicating good porosity and permeability in these areas. The middle part of the Tuluvak Formation is the coarsest and best-exposed, to pebble and boulder conglomerate. Interbedded coals and carbonaceous shales are abundant north of the Colville River. Well-sorted, fine- to medium-grained quartz marine sandstone also occur.

Although it has good reservoir properties in places, the Tuluvak is not particularly thick compared to other formations in the North Slope and thus may be viewed as a secondary CO_2 storage target.

- **Shrader Bluff** (Cretaceous) : Santonian to Maastrichtian in age, the Shrader Bluff Formation consists mainly of marine sandstones and shale which are locally and variably tuffaceous.[31] The formation reaches up to 800 m thick in the Chandler River region, thinning to about 400 m in the Umiat area (**Figure 32**).[32]

  The formation has been divided into three members, in ascending order: the Rogers Creek, Barrow Trail, and Sentinel Hill Members. The members represent a transgressive-regressive-transgressive cycle within the overall regressive succession of the Schrader Bluff and Prince Creek Formations. Subsurface data indicate the Schrader Bluff intertongues basinward (to the northeast) with deeper marine strata of the Canning Formation.

  The Schrader Bluff is bentonite-rich, containing common bentonitic shale, tuffaceous mudstone, and bentonitic fine-grained, fossiliferous sandstone, as well as beds of relatively pure bentonite. The upper part consists mostly of shallow-marine sandstones, incised by nonmarine channel sandstones.

- **Prince Creek** (Late Cretaceous to Paleocene) : This unit consists mainly of light-colored, nonmarine sandstones interbedded with carbonaceous mudstone, coal, and bentonite. Sandstones are very fine- to fine-grained and variably tuffaceous. Sands grains are dominantly quartz and black to gray chert. Thick sections of interbedded bentonite, bentonitic mudstone, carbonaceous shale, and coal also occur. Deposits characteristic of fluvial, meandering-stream environments are interbedded with deposits from marginal marine and intermittent shallow-marine intervals. Formation thickness is poorly controlled but appears to be around 400 m.

- **Sagavanirktok** (Paleocene to Eocene) : This formation unit consists of poorly consolidated siltstone, sandstone, conglomerate, and lignite of Tertiary age roughly 2 km thick. It's shallow depth and relatively poor reservoir qualities would seem to rate it as low potential for large-scale CO_2 storage.

Oil and Gas Potential. The North Slope is the largest oil and gas producing area in Alaska as well as one of the most important in the country. The Ellesmerian sequence includes the reservoirs for the Prudhoe Bay, Lisburne and Endicott fields. The Beaufortian or rift sequence includes the Kuparuk River, Alpine, and Milne Point fields, among others. Finally, the Brookian sequence in the Colville basin includes the Meltwater, Tarn and West Sak oil fields.

The USGS recently conducted an updated study of undiscovered, technically recoverable oil and gas resources in the central North Slope region. The study comprised 24 individual conventional resource plays in the onshore and offshore region between NPRA and ANWR.[33] The mean estimate was determined to be approximately 4 BBO and 33 Tcf.

In addition, the Beaufort and Chukchi Sea areas in the Arctic Ocean north of the North Slope probably contain large undiscovered oil and gas resources. These continental shelf regions share a tectonic rift history with the North Slope region, but are considered to have even larger undiscovered resource potential. The MMS recently evaluated these areas and identified twelve large (>150,000-acre) prospective structures that individually exceed the size of Prudhoe Bay field. MMS estimates undiscovered potential oil and gas resources in the combined Beaufort and Chukchi seas in the Arctic Ocean to be about 24 BBO and 104 Tcf (mean estimate).[34]

Scoping CO_2 Storage Estimate. ARI volumetrically estimated the CO_2 storage potential of saline aquifers in the North Slope Colville basin. Thickness was difficult to estimate, despite the relative abundance of data. The Nanushuk Formation was assumed to be the main target, averaging 2 km thick including a conservative average 1 km of sandstone thickness. The Nanushuk was estimated to cover an area of 75,000 km^2, approximately the entire area of the Colville basin. In addition, the Schrader Bluff Formation was estimated to add an additional 250 m of sandstone over an equivalent area, for a total 750 m net sandstone thickness. Other formations could add additional sandstone thickness but were not considered given their generally lower reservoir quality.

Based on average sandstone thickness (750 m) and porosity (25%) data and the estimated total basin area (75,000 km^2) and the average depth to the sandstone package (2,000 m), we estimate that the CO_2 storage potential of the Colville basin could be on the order of 4,920 Gt.

3.2 Chukchi Sea Area

Introduction. North and offshore of the Colville basin, the Chukchi and Beaufort Seas on Alaska's Arctic continental shelf contain extensive but still poorly defined sedimentary sequences. These areas are covered most of the year by moving ice sheets, making these particularly challenging areas for petroleum (or CO_2 storage) operations.

ARI compiled data location maps for these regions (**Figures 33** and **34**), showing mostly 1970 and 80's-vintage seismic data and the relatively few petroleum exploration wells that have been drilled in these remote and operationally hostile Arctic Ocean areas.

The Minerals Management Service (MMS) conducted early studies during the 1970 and 80's when initial leasing and industry exploratory drilling took place.[35,36] MMS recently (2006) updated its estimate of undiscovered oil and gas resources in the

Chukchi/Beaufort Sea region, but there still is little publicly available geologic information, apart from the older, low-quality seismic reflection data and the key Shell Klondike 1 exploration well log.

Thus, it was not possible to conduct a thorough investigation of the CO_2 storage potential of the Chukchi and Beaufort Sea areas. Fortunately, however, the geology of these regions is considered by researchers in Alaska to be broadly similar to that of the Colville basin. We treated the Chukchi and Beaufort Seas as extensions of the Colville basin for the purpose of estimating CO_2 storage capacity.

Initially explored during the early 1980's, when over 100,000 line miles of seismic data were collected, recent higher oil prices have sparked renewed interest in the petroleum potential of the Chukchi Sea. In its first petroleum license auction since 1991, the MMS recently garnered $3.5 billion in bonuses for new exploration and production leases.[37] However, the Chukchi Sea remains a remote and operationally highly challenging region for petroleum development as well as CO_2 storage.

The 127,000-km^2 Chukchi Sea region encompasses the outer continental shelf of northwestern Alaska (**Figure 35**). The Chukchi Sea actually is not defined as a geologic basin but rather is an MMS administrative area. About 90% of this area is in water shallower than about 200 feet, which until recently has been considered the practical limit for petroleum development in the Arctic.

The Chukchi and Beaufort Sea areas share similar general stratigraphy (**Figure 36**). Sedimentary units in the Chukchi comprise the metamorphosed Franklinian sequence of carbonates and clastics (Cambrian-Early Devonian); the Ellesmerian sequence of mildly deformed marine shelf deposits (Late Devonian-Early Cretaceous); and the Brookian clastic transgressive wedge of deep marine to nonmarine sediments (Early Cretaceous-Holocene). Some units, such as the Ellesmerian, are even thicker than their onshore equivalents in the central Chukchi Sea. Seismic interpretation shows that the regional geology of the Chukchi Sea is an extension of the onshore North Slope and Brooks Ranges (**Figure 37**).

Figure 38 shows a time-structure map of acoustic basement in the Hope basin, Chukchi Sea. Structural elements in the Chukchi are extensions of those present in the onshore North Slope. Faults trend mainly northwest-southeast. The Ellesmerian reflector can be traced from onshore to an estimated depth of 45,000 feet in the Tunalik basin. The basin's southern margin is defined by thrusting associated with the Herald Arch. The Wainwright fault zone defines the northern boundary.

Potential CO_2 Storage Reservoirs. The Chukchi Sea region contains numerous potential saline aquifer reservoirs that could be suitable for CO_2 storage. The most prospective may be the Ellesmerian sequence, including the Endicott, Lisburne, and Sadlerochit Groups and the Kuparuk River Formation, all of which are productive in the Prudhoe Bay oil fields. Major sandstones also occur in the Brookian sequence, including in the Nanushuk Group.

The Shell Klondike 1 well was a critical data point for our estimate of CO_2 storage capacity of the Chukchi Sea region. It was located about 75 miles northwest of Point Lay in the central Chukchi Sea and drilled vertically in 1989 to a total depth of about 12,000 feet (**Figure 33**). The well encountered a clastic sequence, including numerous reservoir-quality sandstones in the Kuparuk, Torok, and Nanushuk Formations as well as the Brookian unit.

Figure 39 shows the stratigraphic log from this key well. Sandstones become better developed and more frequent towards the top of the sequence, especially within the Nanushuk and Brookian sequences. Individual sandstone units range from 50 to 400 feet thick. The upper two sandstone units in the Cretaceous Torok and Nanushuk Formations that were cored and analyzed had good porosity (28%) and permeability (63-259 mD). However, at the Kavik-equivalent Formation level close to 11,300 feet deep, the sandstone had become extremely tight (k = 0.01 mD), although oil shows still were apparent.

Overall, the Klondike 1 well and seismic coverage in the basin suggests that the Chukchi Sea could have significant CO_2 storage potential within saline aquifers. **Figure 40** shows the detailed sandstone analysis for this well, including sandstone depth, thickness, and reservoir quality data.

The well penetrated a total gross sandstone thickness of about 3,405 feet. Three sidewall cores were analyzed, with good porosities (28%) in the two shallower samples and much lower porosity (6%) in the deepest sample. Permeability also was much higher in the shallow samples (63 to 259 mD vs 0 mD). Based on this small data set, the net CO_2-prospective storage depth in the Chukchi Sea would seem to be in the range of roughly 3000-10,000 feet. The Klondike well encountered a net total of 1,880 feet (573 m) of sandstone with good porosity, permeability, and depth characteristics.

Lacking additional well data, ARI assumed that the Klondike sandstone thickness, depth and reservoir quality would be uniform throughout the Chukchi Sea basin, a simplistic but necessary assumption.

Scoping CO_2 Storage Estimate. ARI volumetrically estimated the CO_2 storage potential of saline aquifers in the Chukchi Sea basin based on rounded average sandstone thickness (600 m) and porosity (25%) data from the Klondike well. The density of CO_2 at this depth (2,000 m) and probable low temperature (20º C) likely would be high (700 kg/m^3).[38] Based on the estimated total basin area with at least 2 km of sediment (100,000 km^2) and the average depth to the sandstone package (2,000 m), we estimate that the CO_2 storage potential of the Chukchi Sea basin could be on the order of 5,250 Gt.

3.3 Beaufort Sea Area

The Beaufort Sea geology was introduced previously in the Chukchi Sea section. The Beaufort Sea is covered by a pervasive and mobile ice cover which complicates petroleum (or CO_2 storage) activities. From an operational perspective, the Beaufort Sea likely would be Alaska's most challenging area for CO_2 storage.

The Beaufort differs from the Chukchi in that oceanic rifting took place during early Cretaceous time, marked on its southern edge by the "Hinge Line." The northern portion of the Beaufort Sea (Canada basin) is characterized by thin sedimentary deposits overlying oceanic crust and likely would not be suitable for CO_2 storage. South of this line, however, much of the Beaufort contains a thick Ellesmerian sequence, correlative with productive units in the Prudhoe Bay region, such as the prolific Triassic Ivishak Sandstone.

Thus, the CO_2-prospective portion of the Beaufort Sea is restricted to a long, narrow belt that parallels the modern coastline of northern Alaska (**Figure 41**). Basins in this belt include the Nuwuk and Kaktovik basins as well as the Arctic Platform. The estimated area prospective for CO_2 storage is approximately 30,000 km^2. Based on onshore Arctic Coastal Plain trends, the MMS predicted that the geothermal gradient in the Beaufort Sea subsurface ranges from 27-36ºC/km.

The Ellesmerian is absent or buried deeper than 20,000 feet in the Nuwuk and Kaktovik basins, but fluvial-deltaic sandstones in the Brookian sequence are well developed and considered to have the potential for good reservoir characteristics (**Figure 42**). More deeply buried Brookian turbidites, formed in submarine canyon complexes, are considered lower potential for petroleum and CO_2 development. Brookian sandstone porosities are thought to range from 12-16% in the lower-quality deltaic sandstones to 25-35% in the pro-deltaic sandstones.

Exploration wells in the US Beaufort Sea remain confidential, but the Dome Petroleum Natsek E-56 well log, located about 30 miles east of the US-Canada border in the Canadian portion of the Beaufort Sea, is available (**Figure 43**). This well encountered a 3,200-foot thick gross section of good-quality, fluvial sandstones and conglomerates (porosity >10%) in the Late Cretaceous to Early Eocene section at depths of 6,500-8,700 feet. Siltstones, shales, and coal seams are intercalated with these sandstones. Net sandstone thickness in this section alone is more than 1,600 feet.

Additional marine sandstones were penetrated in the deeper Late Cretaceous section, but appear to have poor reservoir quality (porosity <10%). The sandstone sequences are overlain by thick (5,000 feet) and continuous Early Paleocene marine shales, which would seem to be an effective CO_2 seal. The US Beaufort Sea is likely to have similar sandstone and shale sequences suitable for CO_2 storage.

Scoping CO_2 Storage Estimate. ARI volumetrically estimated the CO_2 storage potential of saline aquifers in the Beaufort Sea basin based largely on the Dome Natsek well log. Average sandstone thickness was estimated to be 500 m, with estimated 20% average porosity. The density of CO_2 at this average depth (2,300 m) and probable moderately low temperature (72º C) likely would be high (700 kg/m^3).[39] Based on the total basin area with at least 2 km of sediment (30,000 km^2, stretching an estimated 600 km east-west by 50 km north-south) and the average depth to the sandstone package (2,300 m), we estimate that the CO_2 storage potential of the Beaufort Sea basin could be on the order of 1,050 Gt.

3.4 Norton Basin

Introduction. The Norton basin is located off the west coast of Alaska, just south and southwest of the Seward Peninsula. It generally corresponds with the Norton Sound in the eastern Bering Sea (**Figure 44**). The Norton basin is elongated in the east-west direction, extending over a total area of about 34,000 km^2. Water depths are fairly shallow, ranging up to 50 m.

Norton Sound actually comprises two distinct sub-basins separated by the northwest-trending Yukon Horst, which has up to 3 km of uplift. The Stuart basin in the east part of Norton Sound has up to 6.5 km of sediments, while the St. Lawrence basin to the west contains up to 5 km of sedimentary deposits. These basins contain up to 24,000 feet of Tertiary marine and non-marine sedimentary rocks.[40] The geothermal gradient is fairly high, stabilized at about 45º C/km in the COST #1 well.[41]

Figure 46 shows a structure map on seismic horizon A in the Norton basin. The Norton basin is structurally fairly complex with numerous mainly northwest-southeast trending faults and folds. It is an extensional basin adjacent to the right-lateral strike-slip Kaltag Fault, which extends offshore southwestward from onshore Alaska and forms the southern margin of the Norton basin. Outcrop samples of sandstones from outcrops surrounding Norton Sound tend to have poor reservoir properties, generally less than 10% porosity and about 1 mD of permeability.[42]

Since 1984 a total of six petroleum exploration wells have been drilled in the Norton basin; all have been plugged and abandoned with no commercial discoveries announced. In 1980 two joint industry COST (Continental Offshore Stratigraphic Test) wells were drilled and logged in the shallow Norton Sound portion of the Norton basin.

The COST #1 well was drilled west of the Yukon Horst in the St. Lawrence sub-basin, which COST #2 penetrated the Stuart sub-basin east of the uplift. Both wells were drilled into the deeper portions of their respective sub-basins and so encountered relatively thick sedimentary sections.

The COST wells both were drilled to metamorphic basement at depths of 12,500 to 14,500 feet, and encountered generally similar clastic marine shelf sequences of Eocene to Pleistocene sediments (**Figure 47**). These Paleogene and Neogene deposits rest unconformably on Precambrian to Paleozoic metasedimentary basement, similar to outcrops in the Seward Peninsula.

The Arco Norton Sound COST No. 1 well was drilled to a total depth of 14,683 feet in 90 feet of water on OCS lease block 197, approximately 54 miles northwest of Nome, Alaska.[43] The well encountered a 900-m thick continental coal-bearing Eocene (?) section and 1600-m thick Oligocene mostly marine sequence. This was followed by 560-m thick Miocene, 400-m thick Pliocene and 350-m thick unconsolidated Pleistocene sediments.

Potential CO_2 Storage Reservoirs. Potential reservoir sandstones in the COST #1 well in the St. Lawrence sub-basin were outer shelf upper slope and turbidite deposits. COST #2 sandstones in the Stuart sub-basin were deposited mainly in alluvial, deltaic, and shallow shelf settings. This relationship probably reflects the Stuart basin's closer proximity to sediment sources.

The Neogene section in the COST wells comprises Miocene and Pliocene diatomites, diatomaceous mudstones, siltstones and sandstones, reflecting inner- to middle-shelf depositional environments (**Figure 48**). The diagenic conversion from Opal-A to Opal-CT appears to occur at a depth of about 3,500 feet in these wells. Thus, most of the diatomaceous section would be low-permeability Opal-A mudstone, probably with poor reservoir characteristics.

Underlying the Neogene are Oligocene turbidites which actually account for most of the sedimentary sequence in the Norton basin and have much better potential reservoir properties. Several regressive/transgressive sequences occurred during the Oligocene, depositing interbedded shallow shelf to deltaic sandstones, siltstones, mudstones, and coals. Nonmarine deltaic sediments are more prevalent in the Stuart sub-basin, again reflecting its closer proximity to sediment sources; COST #2 well penetrated a number of thick coal seams.

Figure 49 is a detailed sandstone thickness log for the COST #1 well showing turbiditic sandstone development between depths of 7,200 to 8,350 feet. Individual sandstones in the Oligocene generally are 5-20 feet thick and relatively clean based on their large SP and gamma log deflections as well as core and petrographic data. Analysis of whole core in sandstones from depths of 7030 to 7046 feet (admittedly a small sampling) in the COST #2 well showed porosities ranging from 8.5 to 20.3%, averaging 15%. Quartz content averaged 40% with significant lithic fragments, feldspar, and clay. Permeability averaged about 100 mD.

Thermal maturity is fairly low in the Norton basin, with the COST #2 well measuring vitrinite reflectance of only 0.54% at a depth of 10,000 feet. Maturity increased to 0.74% at 11,900 feet, with a sharp increase to 1.0% at 12,200 feet indicating a possible erosional unconformity.

The most recent (1995) resource assessment prepared by the MMS for the Norton basin places its potential undiscovered natural gas at about 2.7 Tcf. Of this total, perhaps 29 Bcf has not been developed but is located within 30 miles of Nome and may be producible over 30 years. Development costs for this part of Alaska are high, but one recent (2005) study determined that development could be economically feasible.[44]

Scoping CO_2 Storage Estimate. ARI volumetrically estimated the CO_2 storage potential of saline aquifers in the Norton basin based on relatively thin average high-quality sandstone thickness (300 m) and low-moderate porosity (15%) data from the Norton COST well. The density of CO_2 at this depth (2,400 m) and probable high temperature (100º C) likely would be moderately high (600 kg/m^3).[45] Based on the total basin area with at least 2 km of sediment (19,500 km^2) and the average depth to the sandstone package (2,400 m), we estimate that the CO_2 storage potential of the Norton basin could be on the order of 260 Gt.

3.5 Navarin Basin

Introduction. The Navarin basin is located west of the Norton basin in far western offshore Alaska, close to the disputed US-Russian international boundary (**Figure 44**). Data for the Navarin basin that were gathered by ARI into a GIS project are shown on **Figure 50**.

The Navarin basin covers a total area of approximately 80,000 km^2, as defined by the 2-km basement depth, about equivalent to the state of Maine. The Navarin basin is considered a forearc tectonic setting that formed in the Late Cretaceous-early Tertiary as a response to oblique subduction or transform motion between the Kula and the North American plates.[46]

The Navarin basin contains in excess of 10 km of Tertiary sedimentary rocks and comprises three sub-basins (Navarinsky, Pervenets, and Pinnacle Island) that are separated by basement uplifts (**Figures 51** and **52**). The basin trends northwest-southeast and is fairly symmetrical. Several major northwest-trending faults cut the basin, with the deeper Horizon B reflector reaching depths below 11,000 feet in the basin center.

The Pinnacle Island sub-basin, southernmost of the three depocenters in the Navarin basin, is an asymmetric northwest-trending graben measuring 170 miles long by 45 miles wide and filled with over 10 km of Tertiary sediment. The Pervenets sub-basin is a symmetrical graben 75 miles long by 15 miles wide with up to 10 km of Tertiary sediment. The Navarinsky sub-basin, northernmost of the three, is more circular in shape, extending about 70 by 50 miles and containing at least 10 km of Tertiary deposits.

Seismic data interpretation performed by the MMS and the Arco Navarin COST #1 well, the first deep stratigraphic test in the region, provide the main data sources for the CO_2 storage evaluation. The Navarin COST 1 well was funded by a consortium of 18 oil companies and drilled in 1983 by joint industry operator Arco. Located in 432 feet of water, and centrally located within the Navarin basin, the COST well was drilled vertically to a total depth of 16,400 feet. A total 20 conventional whole cores, each 30-feet long, were cut between depths of 3,637 to 16,342 feet. The well was cased to a depth of 12,834 feet and a thin 20-foot interval from 6,278-6,298 feet was drill-stem tested.

The lower section penetrated by the COST well (13,000-16,400 feet) comprised Late Cretaceous Campanian and Maastrictian sections (**Figure 53**). Unconformably overlying the Mesozoic was a thin Eocene and much thicker Oligocene section from depths of about 5,700 to 13,000 feet. These are conformably overlain by Miocene and Pliocene deposits from about 1,500 to 5,700 foot depth.

The Late Cretaceous section includes an angular unconformity at a depth of about 12,780 feet, below which rocks dip 25-30 degrees and have been intruded by diabase and basalt sills. The Eocene section consists of dark-gray calcareous claystone and sandy mudstone.

The lower Oligocene section comprised poorly sorted gray claystone, mudstone, and sandy mudstone with abundant detrital clay matrix that was deposited in a bathyal environment. The middle to upper Oligocene interval is characterized by sandy mudstone, fine-grained muddy sandstone, and claystone with rare lenses of siltstone and sandy carbonate that reflects marine outer shelf and upper slope environments.

The Miocene interval consists of fine and very fine-grained, poorly to well sorted sandstone and siltstone interbedded with mudstone and claystone, probably deposited in a middle to outer neritic environment. Some of the sandstones are up to 100 feet thick, with 28-33% porosity but fairly low permeability (5 to 233 mD). Finally, the Pliocene interval consists of poorly sorted, silty to sandy mudstone and diatomaceous ooze deposited in a mid-shelf environment.

Potential CO_2 Storage Reservoirs. Apart from the Late Cretaceous coal-bearing section, the fine-grained clastic sediments encountered in the Navarin COST wells all were deposited in a marine environment. Reservoir characteristics are generally poor, with porosity and permeability reduced by compaction, cementation, diagenesis, and authigenesis.[47]

The only significant potential reservoir-quality sandstones occur in the early to middle Miocene to late Oligocene sequence, namely zones C-1 and C-2 at depths of about 5,000-7,000 feet in the COST well. These marine shelf sandstones occur in a regressive sequence with 1,425 feet of net sandstone out of a total 2,120-foot thick section. About 1,070 feet of this sandstone was characterized by SP deflections of at least 10 mV, considered good reservoir quality. These sandstones are described as feldspathic litharenites, dominated by feldspar and lithic fragments with quartz generally accounting for less than 40% of the grains.

Sandstone porosity was determined by core and log analysis to range from 25% to 35%. However, effective porosity determined petrographically, considered by MMS to be more indicative of actual conditions, was much lower at 5-20% with an average of about 15% (**Figure 54).** Permeability also generally was low, mostly under 10 mD although a few samples measured in the range of 20-120 mD.

Static bottomhole temperature analysis in the Navarin COST well indicate a stable temperature of about 100º C at a depth of 8,000 feet. The temperature gradient was about 1.8º F / 100 feet from TD to a depth of about 3,800 feet and higher (2.5º F / 100 feet) above the 3,800-foot depth level.

Thermal maturity is relatively low in the Navarin basin. The COST well encountered vitrinite reflectance of 0.6% at a depth of 10,000 feet. Anomalously high R_o's of up to 4% were encountered at depths below 13,000 feet in this well, probably reflecting local contact metamorphism with Miocene-age sills that intruded the Cretaceous section.

The only successful RFT test in the COST 1 well confirmed over-pressured reservoir conditions below depths of about 9,400 feet. The pressure gradient was calculated at 0.524 psi/foot pressure gradient, significantly higher than hydrostatic 0.45 psi/foot gradient at this location. These abnormal pressures may reflect hydrocarbon generation at depth overlain by effective sealing shales. Of note, sealing caprock was identified in the well at a depth of 8,500 to 9,550 feet, comprising “grey, sticky, plastic, bentonitic shales” that appear to be excellent seals.

A second over-pressured zone was identified between 2,500 and 3,840 foot depth, which may be caused by diagenetic changes in the Miocene siliceous diatomite-rich shales. Although considered potential drilling hazards, these overpressured zones indicate the presence of good sealing cap rocks for effective CO_2 storage in the Navarin basin.

Scoping CO_2 Storage Estimate. ARI volumetrically estimated the CO_2 storage potential of saline aquifers in the Navarin basin based on relatively thin average high-quality sandstone thickness (325 m) and low-moderate porosity (15%) data from the Navarin COST well. The density of CO_2 at this depth (1,800 m) and probable high temperature (100º C) likely would be moderately high (600 kg/m^3). Based on the large total basin area with at least 2 km of sediment (80,000 km^2) and the average depth to the sandstone package (1,800 m), we estimate that the CO_2 storage potential of the Norton basin could be on the order of 1,170 Gt.

3.6 North Aleutian / Bristol Bay Basin

Introduction. Located in southwestern Alaska, the North Aleutian/Bristol Bay basin lies just north of the Aleutian Island Arc (**Figure 55**). The portion of the basin containing at least 2 km of sediment extends over an area of approximately 20,000 km^2 (400 km east-west by 50 km north-south), the vast majority of which is offshore. Data control is relatively sparse, consisting mainly of outcrop studies along the north Aleutian coast and several deep offshore petroleum exploration wells, including notably the NAS COST 1 joint industry stratigraphic test well.

The Bristol Bay basin is not productive for oil and gas and has experienced relatively little drilling activity during the past few decades. However, it is a frontier oil- and gas-prospective basin that tectonically is a back-arc basin in the Aleutian Island Arc subduction system. **Figure 56** shows the regional geology and tectonics of the Bristol Bay basin and Alaska Peninsula.

The Bruin Bay Fault separates unmetamorphosed, oil-prone Mesozoic sedimentary rocks to the southeast from highly metamorphosed and intruded Mesozoic rocks to the northwest. The David River Zone (DRZ) west of Port Moller is a combination dextral strike-slip and uplift that separates the subsiding Bristol Bay basin on the north from the transpressional Black Hills Uplift to the south.

Potential CO_2 Storage Reservoirs. Triassic to Tertiary sedimentary rocks are present in the North Aleutian / Bristol Bay basin (**Figure 57**). The main oil and gas prospective targets are the Eocene Tolstoi, Eocene-Oligocene Stepovak Fm, and Miocene Bear Lake Formations (**Figure 58**). Overall, the Bristol Bay hydrocarbon system is considered somewhat analogous to that of the well-studied productive Cook Inlet basin.[48] Seismic and well log data gathered into an ArcView GIS data base are shown in **Figure 59**.

The Bristol Bay COST 1 well, a joint industry research effort operated by Arco, was drilled in 1983 to a total depth of 17,155 feet (**Figure 60**). The well encountered thick sandstones with good reservoir characteristics, particularly between the depths of 3,000 to 8,000 feet. Individual sandstone units ranged from 10 to 200 feet thick and are separated by siltstones and shales (**Figure 61**).

Overall, sandstone porosity in the COST well averaged about 22.8% while permeability averaged 338 mD (**Figures 62, 63**; not thickness-weighted), both good values for CO_2 storage. The Cenozoic units penetrated in the well are coaly and dominantly gas-prone, possibly with minor liquid-prone coals.[49]

Vitrinite reflectance measured in the NAS COST 1 well in the western Bristol Bay basin showed R_o increasing fairly linearly from a very low 0.15% at a depth of 3,000 feet to a maximum 1.0% near total depth of just over 17,000 feet. This low trend suggests paleo heat flow in this basin has been fairly low.

Despite the lack of oil and gas activity, there are significant mainly sandstone saline aquifer formations in the Bristol Bay basin that could provide CO_2 storage capacity. The main units with reservoir data and CO_2 storage potential include the Tertiary Bear Lake, Stepovak, and Tolstoi Formations, of which the Miocene Bear Lake Formation appears to have the most attractive potential reservoir rocks. Few reservoir data are available for the older Mesozoic sedimentary rocks.

Figure 64 shows a regional stratigraphic cross-section of the Bristol Bay basin, illustrating the thickness and continuity of the Miocene Bear Lake, Stepovak, and Tolstoi Formations. The Bear Lake Formation is the most laterally persistent, while the Stepovak and Tolstoi Formations either were eroded or not deposited on paleo highs. However, all three units have thick sandstone packages with good porosity and permeabiolity, as well as interbedded shales with excellent hydrocarbon sealing capacities.

The Miocene Bear Lake Formation (BLF) is present offshore in most of the Bristol Bay basin and is exposed along the coast near Port Moller on the Alaska Peninsula. It is exposed along the coast of the Alaska Peninsula near Port Moller, where it is approximately 1.2 km thick. The BLF is considered to have the best reservoir potential in the Bristol Bay basin,[50] with Mesozoic rocks and Cretaceous-Tertiary coals and carbonaceous shales the most likely potential hydrocarbon source. Total organic carbon is approximately 5.3%, with hydrocarbon index of 756 and vitrinite reflectance ranging from 0.6% to 0.8%.

The BLF is a transgressive sequence resulting from rapid subsidence on the southeastern margin of the foreland basin, despite a eustatic drop in sea level that took place during its deposition. This subsidence may have been caused by a northward prograding thrust belt or emplacement of intrusive rocks in the arc to the south.

The lower BLF section is characterized by fossiliferous, cross-stratified sandstone and interbedded coal and mudstone deposited in a fluvial setting. The central portion of the BLF is mainly bioturbated sandstone and shale interbedded with wavy- and flaser-bedded sandstone and shale. The upper BLF consists of flaser- and wavy-bedded sandstone and conglomerate, bioturbated sandstone locally rich in marine trace and megafossils, and coarse-grained, bioturbated, channelized sandstone interbedded with discrete horizons rich in marine megafossils.

The Alaska DGSS measured porosity and permeability of sandstones on 11 samples taken at two onshore locations from the Bear Lake Formation. Porosity of samples within the same sandstone package varied from about 4% to 17%, generally averaging around 10%. Permeability was mostly quite low (<0.05 mD), qualifying as tight sandstone. However, two samples from the Sundean location measured significantly higher permeability of around 0.2 mD and one sample from the Left Head location measured about 0.5 mD.

Deep petroleum exploration wells in the offshore central Bristol Bay basin had considerably higher porosity and permeability (**Figure 65**). The Tertiary Bear Lake Formation has the best porosity (25 to 40%) and permeability (10 to 4,000 mD), followed by the Stepovak (5-35%; 0.01-3,000 mD) and Tolstoi (0-25%; 0.02-200 mD) Formations. No water chemical composition data were available, but formation water is assumed to be saline given the age of the units and the mainly offshore location. Overall, the Mesozoic and Tertiary sedimentary rocks in the Bristol Bay basin appear to be excellent potential CO_2 storage reservoirs.

Potential intra-reservoir seals exist in the Bristol Bay basin, considered by the AGGS to be similar to those in the Cook Inlet, mainly interbedded shales. The hydrocarbon seal capacity in the Bear Lake, Tolstoi, and Staniukovich Formation ranges from several hundred to nearly 4,000 feet, indicating excellent potential CO2 sealing capacity in the basin (**Figure 66**). Numerous structural and stratigraphic traps also are present. These seals would appear to be sufficiently thick and laterally widespread for effective CO_2 trapping.

Scoping CO_2 Storage Estimate. ARI volumetrically estimated the CO_2 storage potential of saline aquifers in the North Aleutian / Bristol Bay basin based on average sandstone thickness (1,100 m) and porosity (23%) data from the centrally located North Aleutian COST well. The density of CO_2 at this depth (1,700 m) and probable low temperature (50º C) likely would be high (700 kg/m^3).[51] Based on the total basin area with at least 2 km of sediment (20,000 km^2) and the average depth to the sandstone package (1,700 m), we estimate that the CO_2 storage potential of the North Aleutian / Bristol Bay basin could be on the order of 1,770 Gt.

3.7 St. George Basin

Introduction. Located in southwestern Alaska, the St. George basin is located north of the Aleutian Islands and west of the North Aleutian/Bristol Bay basin (**Figure 67**). The St. George basin is a northwest-trending graben approximately 200 by 25 miles in size with over 40,000 feet of Tertiary sediments overlying Lower Cretaceous Hoodoo to Upper Jurassic Naknek acoustic basement rocks penetrated by the St. George COST #1 well. Tertiary deposition took place during graben formation, probably related to oblique subduction of the Kula plate underneath North America, and continues with active subsidence to the present time.[52]

Two COST wells were drilled in the St. George basin during the early 1980's. In 1976 Arco drilled the COST No. 1 well in 442 feet of water about 20 miles south of the graben to a total depth of 13,771 feet. The well penetrated about 10,000 feet of volcaniclastic Cenozoic sediment overlying basaltic basement rock. Strata encountered in the well were Pliocene (from 1600-3600 feet), Miocene (from 3600-5370 feet), Oligocene (from 5370 to 8410 feet), and Eocene (from 8410 to 10,380 feet).[53]

The sedimentary section in the COST 1 well consisted of interbedded sandstone, siltstone, mudstone, diatomaceous mudstone, and conglomerate reflecting mainly volcanic source terranes. The sediments consist of physically and chemically unstable materials that are easily deformed and altered. Permeabilities are lower than might be expected for the given porosities. Porosity and permeability have been reduced by ductile grain deformation, cementation, and authigenesis.

The COST No. 2 well was drilled within the first set of faults on the south flank of the graben, penetrating over 12,000 feet of volcaniclastic Cenozoic sediment and 2000 feet of the underlying Mesozoic sedimentary rocks.[54]

Potential CO₂ Storage Reservoirs. Thick Tertiary sedimentary rocks with good potential reservoir characteristics are present in the St. George basin. **Figure 68** shows sandstone sequences ranging from 200 to 1650 net feet thick at depths of 1,600 to 11,000 feet in the two St. George COST wells. Porosity ranges from 25-38% with permeability averaging close to 100 mD. On average for the two wells, total reservoir-quality sandstone thickness averages about 2,500 m, with average 31% porosity and fair permeability in the range of 50-100 mD (**Figure 69**).

Figure 70 shows the lithologic log for the COST #2 well, which penetrated over 12,000 feet of volcaniclastic Cenozoic sediment and 2000 feet of the underlying Mesozoic sedimentary rocks. The sandstones encountered in this well generally have good reservoir quality, totaled over 9,000 feet thick, and have 31% average porosity 50-100 mD of permeability.

Scoping CO_2 Storage Estimate. ARI volumetrically estimated the CO_2 storage potential of saline aquifers in the St. George basin based on excellent average sandstone thickness (1,800 m) and porosity (31%) data from the centrally located North Aleutian COST well. The density of CO_2 at this depth (1,700 m) and probable low temperature (50º C) likely would be high (700 kg/m^3).[55] Based on the total basin area with at least 2 km of sediment (20,000 km^2) and the average depth to the sandstone package (1,800 m), we estimate that the CO_2 storage potential of the North Aleutian / Bristol Bay basin could be on the order of 1,770 Gt.

3.8 Gulf of Alaska Region

Introduction. Located along the southern edge of Alaska (**Figure 71**), the continental margin of the northern Gulf of Alaska is tectonically and stratigraphically much more complex and diverse than the other areas of the state discussed earlier in this study. The continental margin of Alaska is an amalgam of allochthonous terranes of various origin that accreted to their present positions during Mesozoic and Tertiary time.

The Gulf of Alaska's continental margin contains a fairly continuous Cenozoic stratigraphic section more than 10 km thick that consists of marine and non-marine clastic rocks. Seismic stratigraphy analysis performed by the MMS has defined several major sequences Y2, Y3, and Section III that average about 12,000, 19,000, and 10,000 feet thick, respectively (**Figures 72-74**). However, much of this section is of poor reservoir quality and likely not to be suitable for CO_2 storage.

Thirteen petroleum exploration wells have been drilled in the offshore Gulf of Alaska region, including six COST wells on the Kodiak Shelf in 1976-77, resulting in no commercial discoveries. Seven of the 13 wells bottomed in Miocene or older sediments. The other six wells did not penetrate deeper than the Plio-Pleistocene section of the Yakataga Formation, which likely is the best potential CO_2 storage unit in this region. ARI's GIS data location map is shown in **Figure 75**.

Potential CO_2 Storage Reservoirs. Tertiary sandstones are the main potential petroleum and CO_2 storage opportunities in the Gulf of Alaska stratigraphic section. Although sandstone or conglomerate occurs in nearly all of the onshore Tertiary units, offshore only the Yakataga and Kulthieth Formations appear likely to contain coarse-grained rocks of sufficient thickness and areal distribution to represent prospective reservoir targets.[56]

- **Yakataga Formation.** This mid-late Miocene, Pliocene, and Pleistocene age unit is the principal clastic target for petroleum exploration (and potentially CO_2 storage) in the Gulf of Alaska. It occurs over an arcuate area stretching approximately 200 miles parallel to the coastline by about 30 miles wide (**Figure 76**), for an area of about 6,000 mi^2 (15,000 km^2). Percentage sandstone declines to the south, from as much as 80% near the coast to less than 10% distally.

  Sandstones and conglomerates in the Yakataga Formation are predominantly glacio-marine in origin and were deposited in inner shelf to upper slope settings. Deposition took place mainly by sediment gravity flow in large submarine channel systems located downslope from tidewater glaciers. This resulted in lenticular sandstone deposits that are generally poorly sorted and mineralogically immature, with poor reservoir characteristics. Yakata sandstones are lithic arkose consisting of about 35% quartz, 40% feldspar (mainly plagioclase), and 25% lithic fragments.

  The total thickness of sandstone in the Yakataga Formation varies from about 250 to 3,800 feet in the Gulf of Alaska. Furthermore, the percentage of sand diminishes rapidly to the south away from the glacial sources. In the Arco OCS Y-0007 exploration well, individual sandstone beds vary widely in thickness, from about 10 feet to over 200 feet (**Figure 77**). Sandstone quality is relatively better in the lower part of the unit. Sandstone and conglomerate reached 15% of the formation in the Middleton Island well, with an average 13% porosity. Overall, porosity declines rapidly with depth, in general from about 30% at 1,500 foot depth to about 15% at 8,000 foot depth (**Figure 78**). Permeability is generally less than 10 mD at depths below 5,000 feet, and nearly absent below about 12,000 feet.

- **Kultheith Formation.** This unit was penetrated by only one of the offshore wells (Y-0211) but seismic mapping indicates it extends over an extensive area (perhaps 200 by 50 miles or approximately 25,000 km^2) in the southeast corner of the Gulf of Alaska, close to the US-Canadian border (**Figure 79**). Kulthieth sandstones were deposited in non-marine to relatively deep marine environments in an oceanic basin along a continental margin. This well encountered 29 individual sandstones ranging from 6 to 153 feet thick (total about 1,500 feet), distributed over a depth range of 8,574 to 11,530 feet (**Figure 80**). These sandstones typically consist of 60-85% quartz, 1.5 to 7% feldspar, 4-14% mica, and 1-30% shale. Porosity declined with depth from about 20% near the top of the section to 10% near the base.

Scoping CO_2 Storage Estimate. ARI volumetrically estimated the CO_2 storage potential of saline aquifers in the Yakagata and Kulthieth Formations of the Gulf of Alaska. We assumed an average sandstone thickness of 500 m and 15% porosity, based on the Y-0007 and Y-0211 wells. The density of CO_2 at this depth (2,000 m) and probable temperature (80º C) likely would be high (700 kg/m^3). Based on the total basin area with at least 2 km of sediment (15,000 km^2 for Yakagata plus 25,000 km^2 for the Kulthieth for a total 40,000 km^2) and the average depth to the sandstone package (2,000 m), we estimate that the CO_2 storage potential of the Gulf of Alaska basin could be on the order of 900 Gt.

5.0 Conclusions and Recommendations

1) Alaska's sedimentary basins have large storage capacity both in deep coal seams and (particularly) in saline aquifer sandstone formations. This is clear from the extensive data base of well logs, core analyses, seismic, maps, and geologic studies that have been prepared for petroleum exploration. However, most of the inputs used in this assessment for calculating storage capacity are uncertain. Thus, the 120 Gt and 16,700 Gt storage estimates should be viewed as highly approximate, though probably better than order-of-magnitude.

2) The potential for CO_2 storage in deep coal seams in Alaska, though probably very large (120 Gt), remains poorly understood. Future work should include laboratory sorption isotherm measurements of Alaska coal seam candidates to determine methane and CO_2 storage capacity and behavior. In-situ well testing of coal seam permeability, hydrology, and stress also are needed, ideally with an industry partner in the CBM-prospective onshore Cook Inlet basin.

3) Alaska's saline aquifer storage capacity demonstrably is large but poorly understood. Future work should include more detailed well log and basin evaluations, particularly of the high-potential North Slope and Chukchi Sea regions. There could be joint industry opportunities for well and core testing in these areas, where exploration interest has been rejuvenated.

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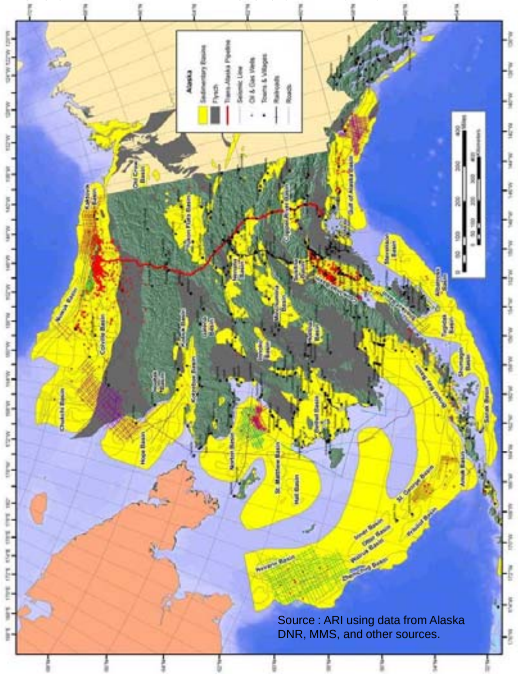
ALASKA GEOLOGIC CO2 STORAGE SCOPING STUDY

Scott Stevens
Advanced Resources International

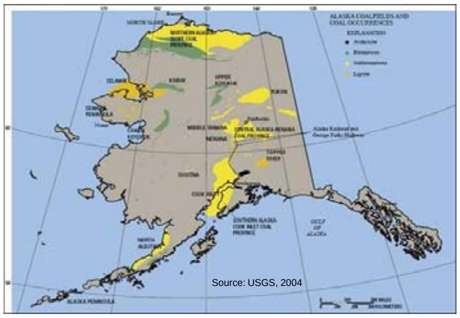
DOE Contract No.: DE-FC26-05NT42593
Contract Period: October 1, 2005 - May 11, 2011

Figure 1 : Location map of sedimentary basins, oil and gas wells, pipeline infrastructure, and geophysical data control in Alaska. Topography and bathymetry also are shown.



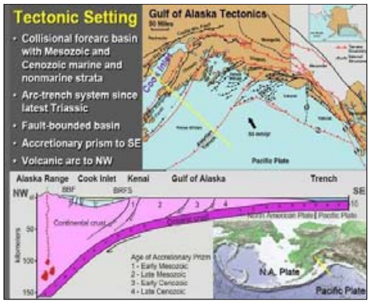
Source : ARI using data from Alaska DNR, MMS, and other sources.

Figure 2 : Alaska has large coal deposits in three regions : the North Slope, Central Alaska, and the Cook Inlet. Most coal is sub-bituminous rank (yellow), but some high-volatile bituminous rank deposits exist (green).



Source: USGS, 2004

Figure 3 : The tectonic setting of southern Alaska is a classic island arc subduction system, comprising deep ocean trench, accretionary prism, forearc basin (Cook Inlet), and volcanic arc.

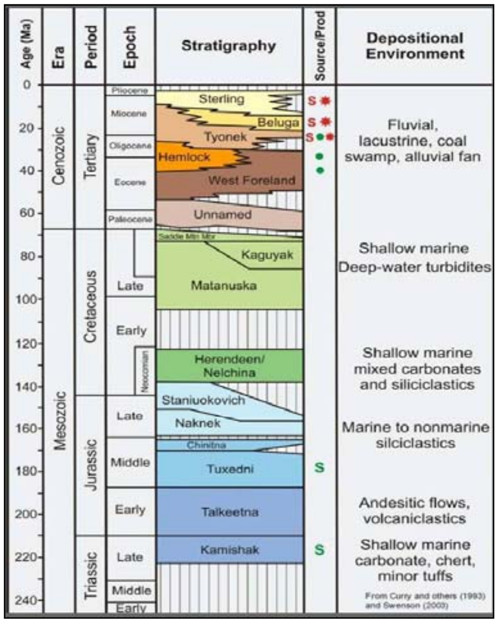


Tectonic Setting

- Collisional forearc basin with Mesozoic and Cenozoic marine and nonmarine strata
- Arc-trench system since latest Triassic
- Fault-bounded basin
- Accretionary prism to SE
- Volcanic arc to NW

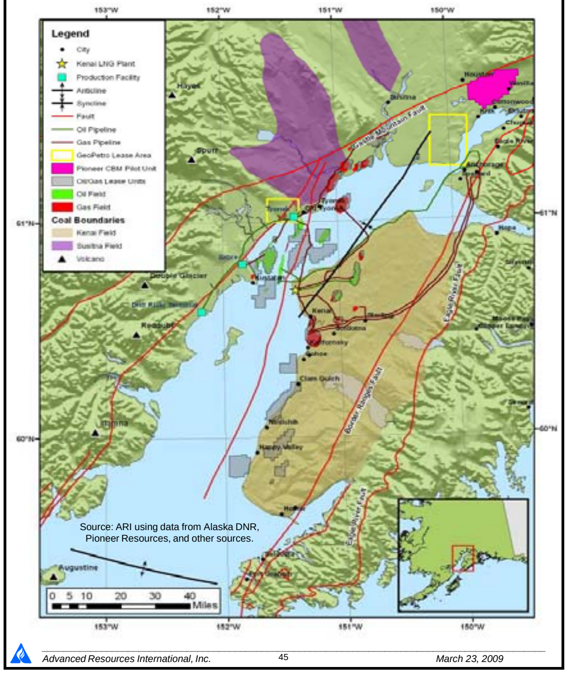
Source: Helmhold, 2008

Figure 4 : Stratigraphy of the Cook Inlet region, southern Alaska. The Cook Inlet basin contains up to 10 km of marine Mesozoic sedimentary rocks and 8 km of Tertiary nonmarine sedimentary rocks. The principal coal deposits occur in the Miocene Tyonek Formation.



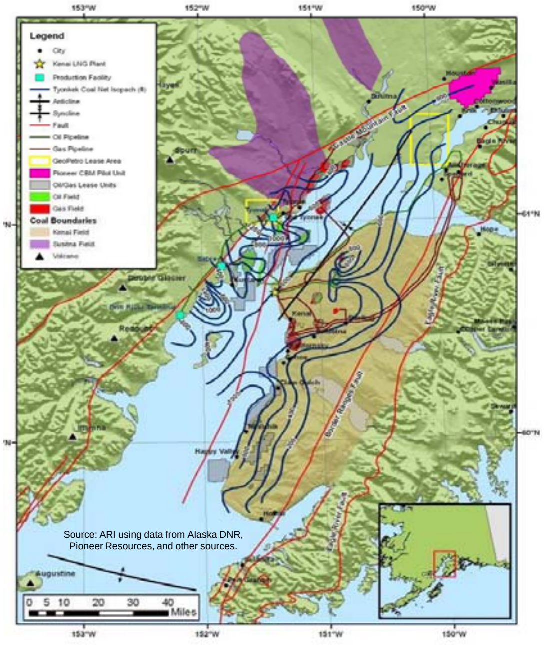
Source: Helmhold, 2008

Figure 5 : Coal resources and coalbed methane exploration leases, conventional oil and gas development, and gas pipeline and LNG infrastructure in the Cook Inlet region, southern Alaska. Pioneer (Evergreen) Resources' CBM test project was located in the onshore Matanuska-Susitna Valley north of Anchorage.



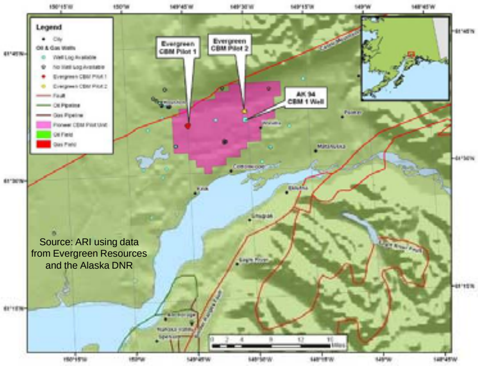
Source: ARI using data from Alaska DNR, Pioneer Resources, and other sources.

Figure 6 : Coal thickness in the Miocene Tyonek Formation in the Cook Inlet region, southern Alaska. Total coal thickness exceeds 1,000 feet in places, making it one of the thickest coal deposits in the world.

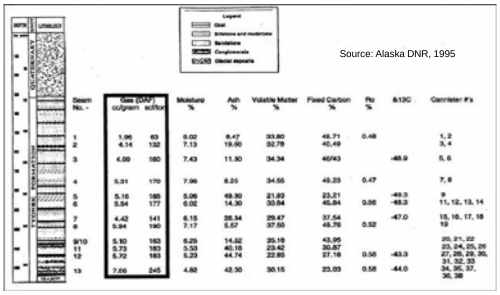


Source: ARI using data from Alaska DNR, Pioneer Resources, and other sources.

Figures 7 (above) and 8 (below) : The Matanuska-Susitna Valley, Cook Inlet basin, showing location of CBM wells. The Alaska DNR corehole measured good coal thickness, quality (R_o=0.58%), gas content (60-245 scf/t).



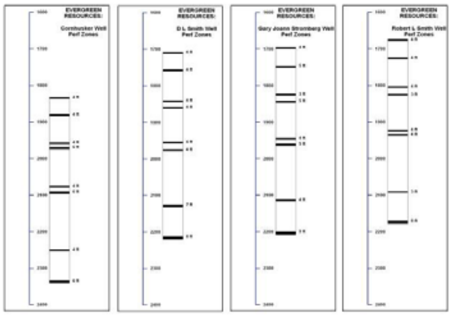
Source: ARI using data from Evergreen Resources and the Alaska DNR



Source: Alaska DNR, 1995

Seam No. -	Gas (DAF) cc/gram	Gas (DAF) scf/ton	Moisture %	Ash %	Volatile Matter %	Fixed Carbon %	Ro %	δ13C	Cannister #'s
1	1.96	63	8.02	8.47	33.80	48.71	0.48		1, 2
2	4.14	132	7.13	19.60	32.78	40.49			3, 4
3	4.99	160	7.43	11.50	34.34	46/43		-48.9	5, 6
4	5.31	170	7.96	8.25	34.56	49.23	0.47		7, 8
5	5.16	166	5.06	49.80	21.93	23.21		-49.3	9
6	5.54	177	6.02	14.30	33.64	45.84	0.56	-48.3	11, 12, 13, 14
7	4.42	141	6.15	26.54	29.47	37.54		-47.0	15, 16, 17, 18
8	5.94	190	7.17	5.57	37.50	49.76	0.52		19
9/10	5.10	163	6.25	14.82	35.18	43.95			20, 21, 22
11	5.73	183	5.53	40.18	23.42	30.87			23, 24, 25, 26
12	5.72	183	5.23	44.74	22.85	27.18	0.56	-43.3	27, 28, 29, 30, 31, 32, 33
13	7.66	245	4.82	42.30	30.15	23.03	0.58	-44.0	34, 35, 36, 37, 38

Figure 10 : Miocene Tyonek coal seams in the Evergreen Resources CBM pilot wells, Cook Inlet basin. Individual coal seams are fairly thin (3 - 6 feet) and a total 34 to 39 feet of coal was completed. Coal seam depths ranged from 1700-2300 feet, which is favorable for CO_2 storage.



Source: ARI using data from the Alaska DNR

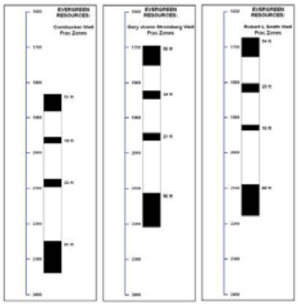


Figure 11 (left) : Evergreen Resources conducted four hydraulic stimulations per well in their Cook Inlet CBM pilot.

Figure 9 (below) : Drilling rig used for the Evergreen Cook Inlet CBM pilot.

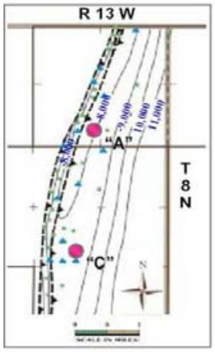


Figure 12 : In late 2003 XTO Energy tested a shallow uphole CBM zone in one or two of their shut-in wells at C platform, offshore Cook Inlet, where they operated conventional oil production. This may be the only offshore CBM well test ever conducted. Results have not been released. The gas was to replace 700 Mcfd of gas from Unocal's Baker platform, which had been shut down.

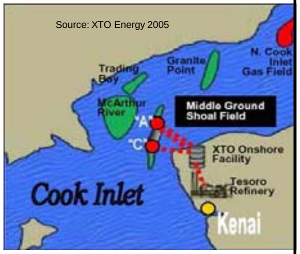
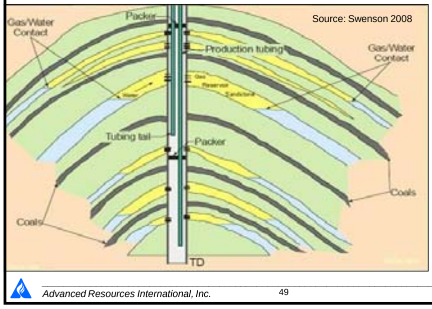
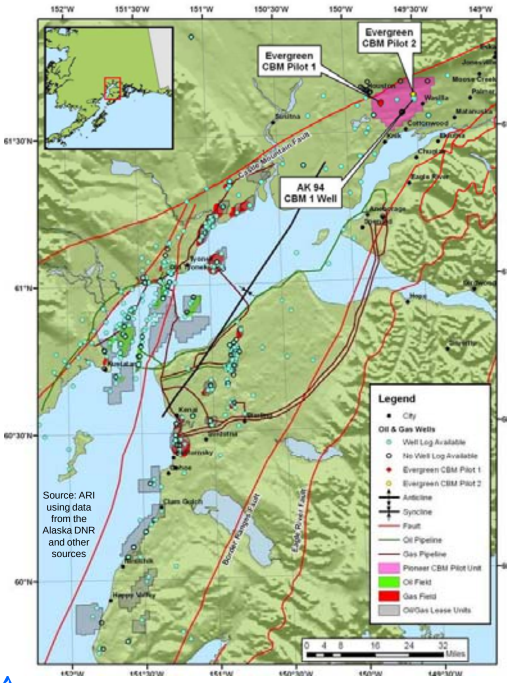

Source: XTO Energy 2005

Figure 13 : Diagrammatic cross-section of Marathon's Kenai gas field, showing a thick sequence of gas-bearing Tertiary sandstones with interbedded coal seams. The extremely thick (>5000-foot) sequence makes hydraulic stimulation challenging. Marathon has used a variety of advanced fracturing methods.

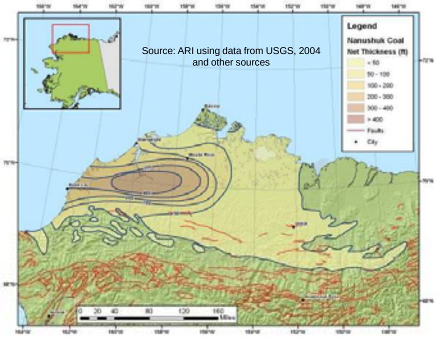

Source: Swenson 2008

- Built-In Dead String and Injection strings.
- Bottom-hole pressure electronic recorders.
- Real-time diagnostics to improve fracturing.
- Automated zonal Isolation.
- Flush of a previous stage used as pad on ensuing stages.

Figure 14 : Cook Inlet data availability is sufficient to support a more detailed evaluation of CO_2 storage potential.



Source: ARI using data from the Alaska DNR and other sources



Source: ARI using data from USGS, 2004 and other sources

Figure 15 : The North Slope region contains Alaska's largest coal deposits.

Over 400 ft of coal is present in the Nanushuk Fm in the western North Slope.

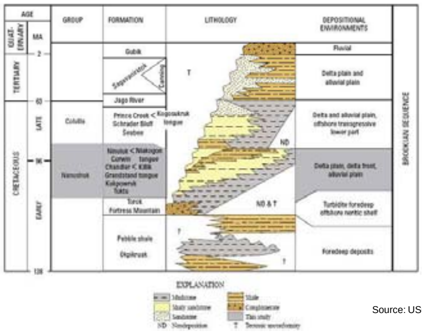
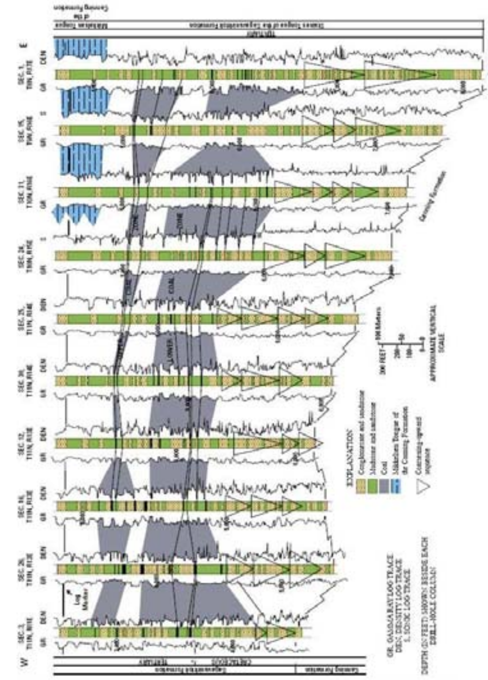


Figure 16 : The mid-Cretaceous Nanushuk Group in the North Slope region contains thick coal deposits with deltaic and alluvial origins.

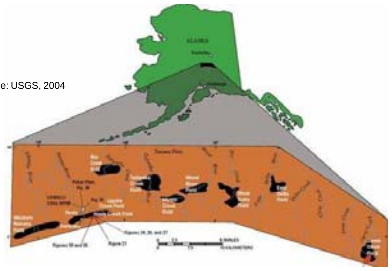
Source: USGS, 2004

Figure 17 : Cross-section showing coals in the Staines Tongue of the Sagavanirktok Formation between the National Petroleum Reserve in Alaska and Arctic National Wildlife Refuge, Alaska.



Source: Roberts et al., 1992

Figure 18 : Central Alaskan coal fields are small, discontinuous, have limited CBM potential (1 Tcf), and have not yet undergone production testing.



Source: USGS, 2004

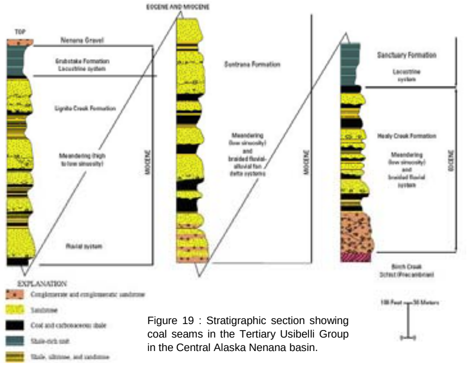
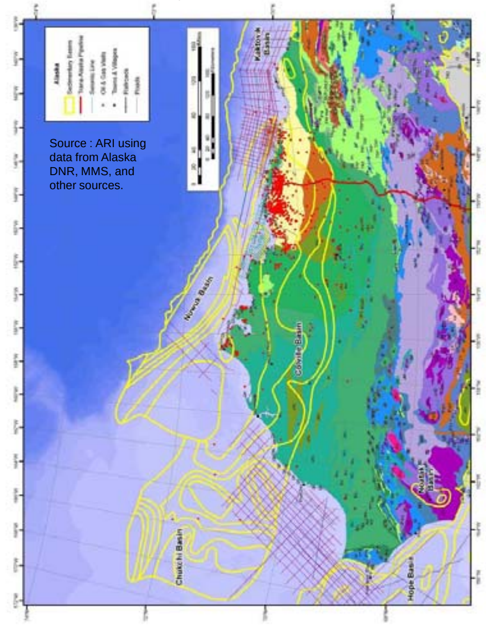


Figure 19 : Stratigraphic section showing coal seams in the Tertiary Usibelli Group in the Central Alaska Nenana basin.

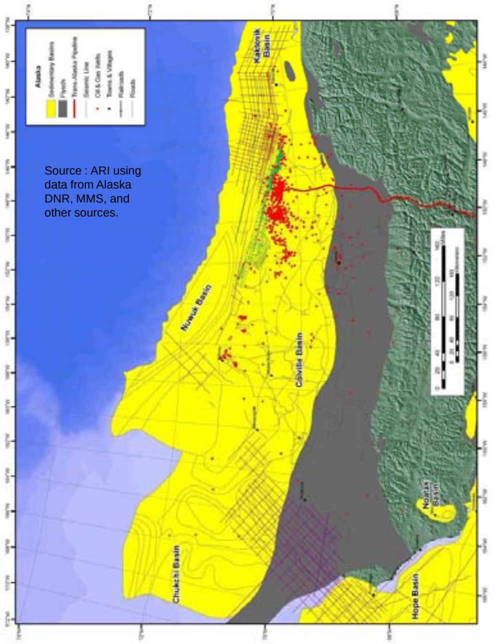
Source: Wahrhaftig, 1987

Figure 20 : Regional map of North Slope, northern Alaska, showing surface geology, well log and seismic data. The Colville basin is the principal basin on the North Slope. The Chukchi Sea lies offshore northwest Alaska, while the Beaufort Sea (Kaktovik basin) lies north and east of the North Slope oil fields.



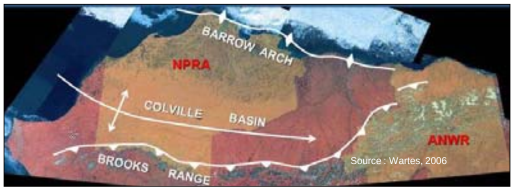
Source : ARI using data from Alaska DNR, MMS, and other sources.

Figure 21 : North Slope, northern Alaska, showing well log and seismic data.



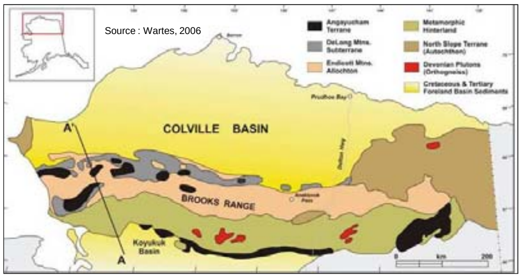
Source : ARI using data from Alaska DNR, MMS, and other sources.

Figure 22 : Major structural elements of the Alaska North Slope region. The Colville Basin contains thick clastic deposits with good reservoir characteristics and large CO_2 storage potential. Also shown is the Brooks Range Thrust and the Barrow Arch, which define the southern and northern limits of the Colville Basin. National Petroleum Reserve Alaska (NPRA) and Arctic National Wildlife Reserve (ANWR) also are shown.



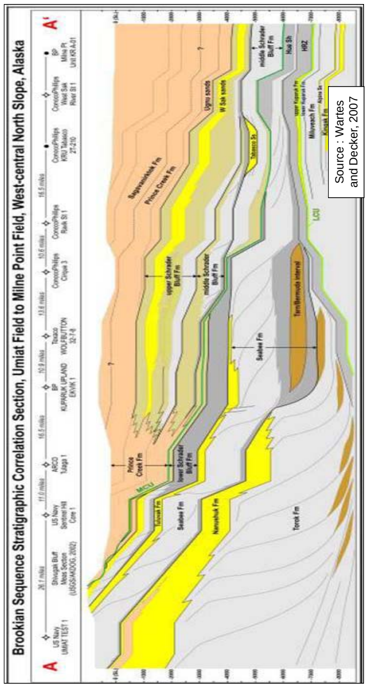
Source : Wartes, 2006

Figure 23 : Tectonic terranes in the Alaska North Slope region, showing the extent of Cretaceous and Tertiary foreland basin sediments in the Colville Basin. Sedimentary rocks in the Brooks Range are uplifted and deformed, thus not considered good targets for CO_2 storage.



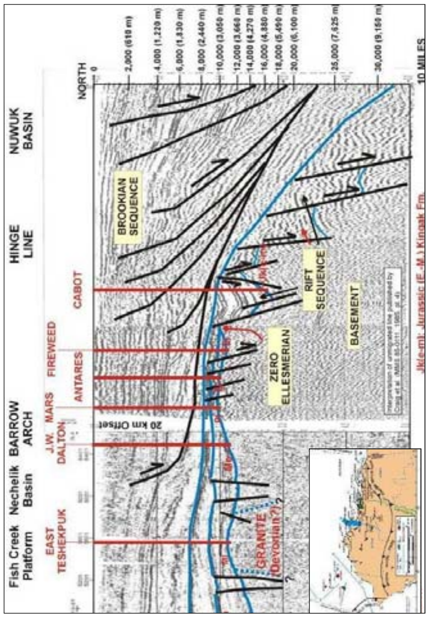
Source : Wartes, 2006

Figure 24 : North-south trending schematic stratigraphic correlation section of the Brookian Sequence in the North Slope. The sequence comprises the Cretaceous Torok, Nanushuk, Seabea, Tuluvak, and Shrader Bluff Formations as well as the Late Cretaceous to Paleocene Prince Creek and Paleocene-Ecocene Sagavanirktok Formations. The best targets for CO_2 storage appear to be thick and deep sandstones within the Torok and particularly the Nanushuk Formations.

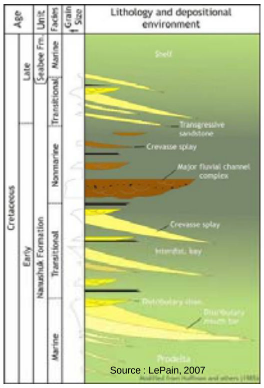


Source : Wartes and Decker, 2007

Figure 25 : Seismic cross section, central North Slope, showing Brookian sequence thickening offshore to the north.



Source : Sherwood, 2006



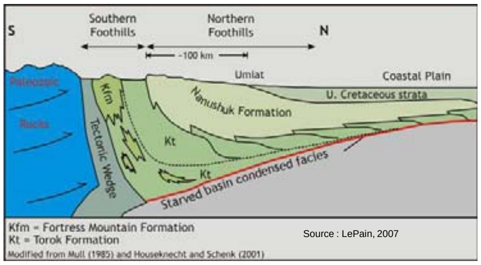
Source : LePain, 2007

Figure 26 (left): Stratigraphy of the Cretaceous Nanushuk Formation showing the lithology and depositional environment. Thick sandstones of non-marine fluvial channel and transitional to shallow marine depositional origin occur in this sequence.

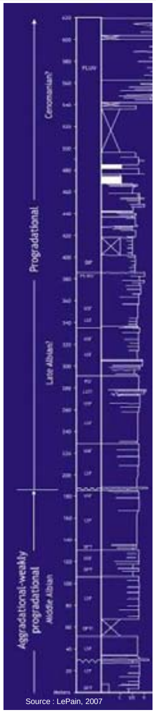
Figure 27 (bottom): Outcrop of the Cretaceous Upper and Lower Nanushuk Formation, south-central North Slope basin.

Source : Mull et al., 2008

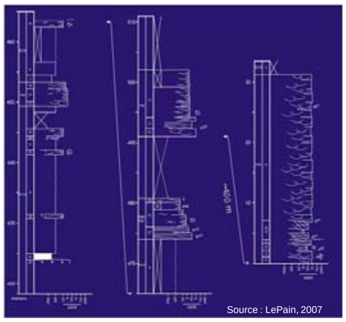
Figure 28 : Schematic cross section of the North Slope basin, showing Cretaceous Nanushuk Formation sandstones thickening to the south.



Source : LePain, 2007



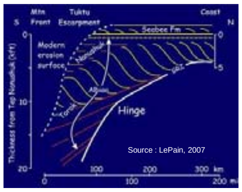
Source : LePain, 2007



Source : LePain, 2007

Figure 29 (top) : Depositional environment of the Cretaceous Nanushuk Formationi, North Slope basin. In order from bottom to top, Nanushuk facies range from alluvial floodbasin succession above crevasse splay sandstones, to trough cross-bedded sandstone, to pebble conglomerate with lenticular sandstone.

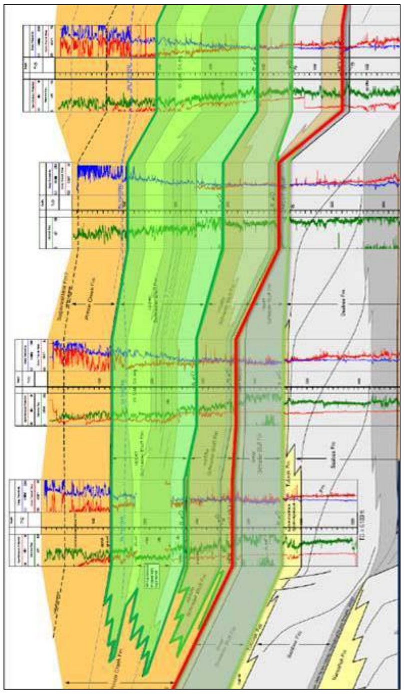
Figure 30 (left) : Measured outcrop section of the Nanushuk Formation, in the Kanayut River area, North Slope basin. The section measures a total 620 m thick, of which sandstone accounts for approximately 80% or 500 m.



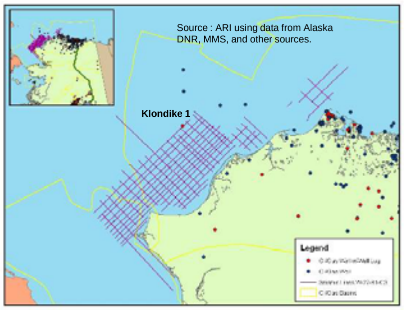
Source : LePain, 2007

Figure 31 (left) : Total Nanushuk formation thickness is approximately 10,000 feet (3 km).

Figure 32 : Detailed stratigraphic cross-section of the Seabea, Shrader Bluff and Prince Creek Formations, North Slope. Note rapid and complex facies changes.

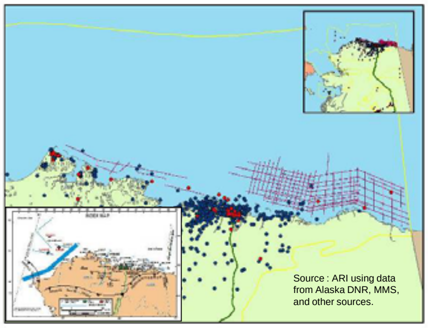


Source : Decker and Wartes, 2008



Source : ARI using data from Alaska DNR, MMS, and other sources.

Figure 33 : Seismic and well log data, Chukchi Sea region showing the location of the important Shell Klondike 1 petroleum exploration well.



Source : ARI using data from Alaska DNR, MMS, and other sources.

Figure 34 : Seismic and well log data, Beaufort Sea region.

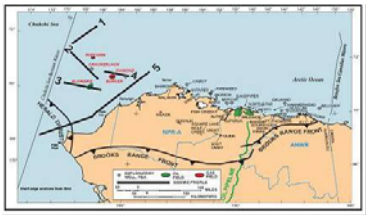
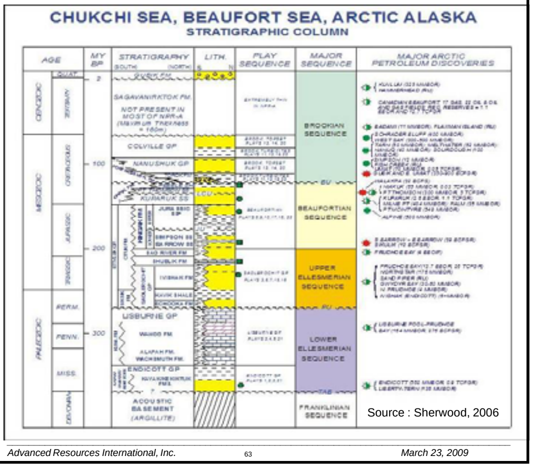


Figure 35 : Structural features of the Chukchi Sea showing well locations including the non-confidential Shell Klondike 1, a key data point.

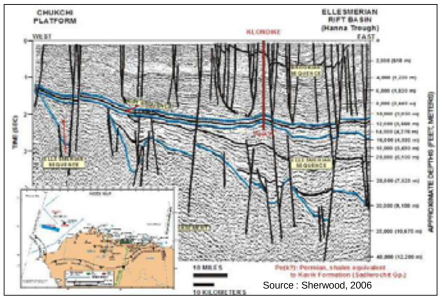
Source : MMS

Figure 36 : Stratigraphic column for the Chukchi and Beaufort Sea regions, northern Alaska. Note sand-rich, mainly Mesozoic Ellesmerian, Beaufortian, and Brookian sequences.



Source : Sherwood, 2006

Figure 37 : Seismic cross section, central Chukchi Sea, showing location of the Shell Klondike 1 exploration well and the Ellesmerian sequence thickening to the southeast.

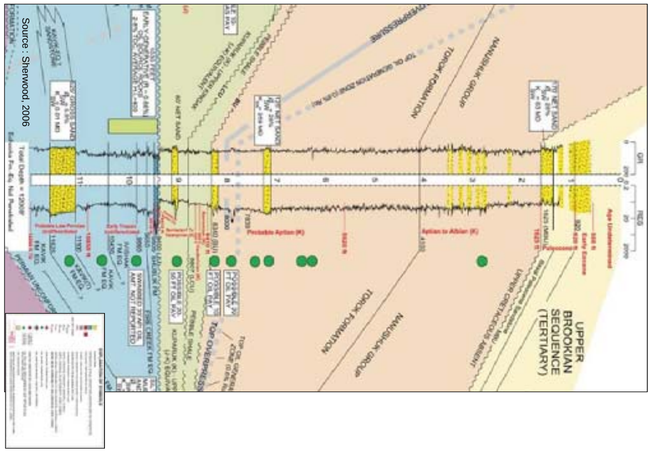


Source : Sherwood, 2006

Figure 38 : Time structure map of acoustic basement in the Hope basin, Chukchi Sea, based mainly on seismic interpretation (contour interval 0.25 sec two-way travel time). Structural elements in the Chukchi are extensions of those present in the onshore North Slope. Faults trend mainly northwest-southeast. The Ellesmerian reflector can be traced from onshore to an estimated depth of 45,000 feet in the Tunalik basin. The basin's southern margin is defined by thrusting associated with the Herald Arch. The Wainwright fault zone defines the northern boundary.

Source : Sherwood, 2006

Figure 39 : Sandstone and stratigraphic log from the Shell Klondike 1 well, Chukchi Sea, northern Alaska. Two sandstones in the Cretaceous Torok and Nanushuk Formations that were cored and analyzed had good porosity (28%) and permeability (63-259 mD).

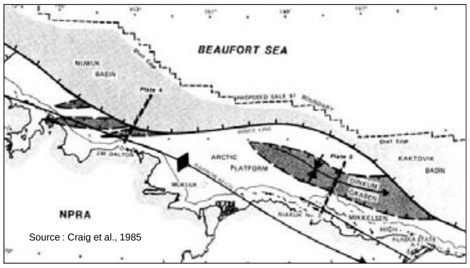


Source : Sherwood, 2006

Figure 40 : Sandstone depth and thickness recorded from the Shell Klondike 1 exploration well, Chukchi Sea, offshore northwestern Alaska. This well penetrated a total sandstone thickness of about 3405 feet. Three sidewall cores were analyzed, with good porosities (28%) in the two shallower samples and much lower porosity (6%) in the deepest sample. Permeability also was much higher in the shallow samples (63 to 259 mD vs 0 mD). Based on this small data set, the net CO2-prospective storage depth in the Chukchi Sea would seem to be in the range of roughly 3000-10,000 feet. The Klondike well encountered a net total of 1,880 feet of sandstone in the good porosity/permeability/depth range.

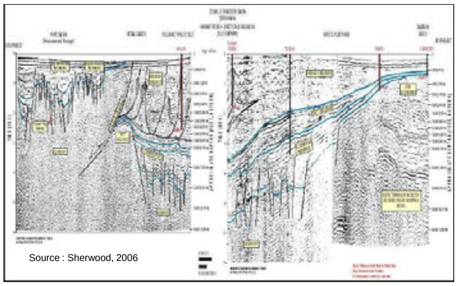
Depth (ft)	Age (Younger/Older)	Porosity (%)	Porosity Type	Permeability (mD)	Permeability Type	Isopach Unit	Top (ft)	Base (ft)	Isopach Gross (ft)	Net (ft)	Stratigraphy (Younger/Older)	Sequence	Other
560	Age Undetermined/Early Eocene										Upper Brookian Sequence (T)	Upper Brookian Sequence (Tertiary)	
600	Early Eocene					Sandstone	600	1025	425		Upper Brookian Sequence (T)	Upper Brookian Sequence (Tertiary)	
920	Early Eocene/Paleocene										Upper Brookian Sequence (T)	Upper Brookian Sequence (Tertiary)	
1150	Paleocene					Sandstone	1150	1260	110		Upper Brookian Sequence (T)	Upper Brookian Sequence (Tertiary)	
1370	Paleocene					Sandstone	1370	1625	255	170	Upper Brookian Sequence (T)	Upper Brookian Sequence (Tertiary)	
1625	Paleocene/Aptian to Albian	28%	Arith. Avg. Sidewall	63	Geom. Avg. Sidewall						U. Brookian Sequence (T)/Nanushuk (K)	Upper Brookian Sequence (Tertiary)	Mid-Brookian Unconformity
2240	Aptian to Albian					Sandstone	2240	2300	60		Nanushuk Group (K)	Lower Brookian Sequence (Aptian-Albian)	
2730	Aptian to Albian					Sandstone	2730	2800	70		Nanushuk Group (K)	Lower Brookian Sequence (Aptian-Albian)	
2850	Aptian to Albian					Sandstone	2850	2930	80		Nanushuk Group (K)	Lower Brookian Sequence (Aptian-Albian)	
3040	Aptian to Albian					Sandstone	3040	3125	85		Nanushuk Group (K)	Lower Brookian Sequence (Aptian-Albian)	
3210	Aptian to Albian					Sandstone	3210	3290	80		Nanushuk Group (K)	Lower Brookian Sequence (Aptian-Albian)	
3410	Aptian to Albian					Sandstone	3410	3450	40		Nanushuk Group (K)	Lower Brookian Sequence (Aptian-Albian)	
3490	Aptian to Albian					Sandstone	3490	3530	40		Nanushuk Group (K)	Lower Brookian Sequence (Aptian-Albian)	
4100	Aptian to Albian										Nanushuk Group (K)/Torok Formation (K)	Lower Brookian Sequence (Aptian-Albian)	
5620	Aptian to Albian/Probable Aptian										Torok Formation (K)	Lower Brookian Sequence (Aptian-Albian)	
7125	Probable Aptian	28%	Arith. Avg. Sidewall	259	Geom. Avg. Sidewall	Sandstone	7125	7275	150	125	Torok Formation (K)	Lower Brookian Sequence (Aptian-Albian)	
7839	Probable Aptian					Possible Oil Pay	7839	7869	30	30	Torok Formation (K)	Lower Brookian Sequence (Aptian-Albian)	Top Oil Generation Zone (0.6% Ro)
8000	Probable Aptian										Torok Formation (K)	Lower Brookian Sequence (Aptian-Albian)	Top Overpressure
8210	Probable Aptian					Sandstone	8210	8340	130		Torok Formation (K)	Lower Brookian Sequence (Aptian-Albian)	
8330	Probable Aptian					Possible Oil Pay	8330	8340	10		Torok Formation (K)	Lower Brookian Sequence (Aptian-Albian)	
8340	Probable Aptian										Torok Formation (K)/Pebble Shale (K)	Lower Brookian Sequence (Aptian-Albian)	Brookian Unconformity
8410	Probable Aptian/Barremian										Pebble Shale (K)	Rift Sequence (Late Jurassic-Early Cretaceous)	
8590	Barremian/Hauterivian										Pebble Shale (K)	Rift Sequence (Late Jurassic-Early Cretaceous)	
8660	Hauterivian/Berriasian to Valanginian										Pebble Shale (K)	Rift Sequence (Late Jurassic-Early Cretaceous)	
8807	Berriasian to Valanginian										Pebble Shale (K)/Kuparuk-U. Kingak (J-K)	Rift Sequence (Late Jurassic-Early Cretaceous)	Lower Cretaceous Unconformity
9020	Berriasian to Valanginian					Sandstone	9020	9150	130	80	Kuparuk-Upper Kingak (J-K)	Rift Sequence (Late Jurassic-Early Cretaceous)	
9020	Berriasian to Valanginian					Possible Oil Pay	9020	9070	50	50	Kuparuk-Upper Kingak (J-K)	Rift Sequence (Late Jurassic-Early Cretaceous)	
9400	Berriasian to Valanginian					Carbonate	9400	9505	105		Kuparuk-Upper Kingak (J-K)/Shublik (Tr)	Rift Sequence (Late Jurassic-Early Cretaceous)	Jurassic Unconformity
9400	Berriasian to Valanginian					Oil Source Rocks	9400	10430	1030		Kuparuk-Upper Kingak (J-K)/Shublik (Tr)	U. Ellesmerian (Late Permian to Early Jurassic)	Early Gen. (R=0.66%); 2-8% TOC; Avg. H.I.>400
9410	Berriasian to Valanginian/Carnian to Norian										Shublik Formation (Tr)	U. Ellesmerian (Late Permian to Early Jurassic)	
9510	Carnian to Norian/Early Triassic Undiff.										Shublik Formation (Tr)	U. Ellesmerian (Late Permian to Early Jurassic)	
9650	Early Triassic Undiff										Shublik Formation (Tr)/Fire Creek (Tr)	U. Ellesmerian (Late Permian to Early Jurassic)	
9865	Early Triassic Undiff										Fire Creek Formation (Tr)/ Ivishak (Tr)	U. Ellesmerian (Late Permian to Early Jurassic)	Swabbed 35 degree API Oil, amount not reported
10430	Early Triassic Undiff										Ivishak Formation (Tr)/Kavik(Tr-P)	U. Ellesmerian (Late Permian to Early Jurassic)	
10850	Early Triassic Undiff./Prob. Late Permian Undiff.										Kavik Formation (Tr)/Kavik (P)	U. Ellesmerian (Late Permian to Early Jurassic)	
11100	Prob. Late Permian Undiff.	6%	Arith. Avg. Sidewall	0	Geom. Avg. Sidewall	Sandstone	11100	11625	525		Kavik Formation (P)	U. Ellesmerian (Late Permian to Early Jurassic)	
12008	Prob. Late Permian Undiff.										Kavik Formation (P)	U. Ellesmerian (Late Permian to Early Jurassic)	Total Depth; Echooka Formation not penetrated
	TOTAL (All Depths)								**3405**	**455**			
	TOTAL (3000-10,000' Depth)								**1880**	**285**			

Figure 41 : Structural elements of the Beaufort Sea region, showing the petroleum- and CO_2-prospective area is restricted to a narrow belt paralleling the modern coast line and south of the Hinge Line.



Source : Craig et al., 1985

Figure 42 : Seismic section, southeastern Beaufort Sea region, showing northwest-thickening Brookian sedimentary wedge.



Source : Sherwood, 2006

Figure 43 : Exploration wells in the US Beaufort Sea remain confidential, but the Dome Petroleum Natsek E-56 well log, located 30 miles east of the US-Canada border, is available. This well encountered about __ feet of good-quality, fluvial sandstones and conglomerates (porosity >10%) in the Late Cretaceous to Early Eocene section at depths of 6,500-8,700 feet. Net sandstone thickness is about 1,500 feet. Additional marine sandstones were penetrated in the Late Cretaceous section below, but appear to have poor reservoir quality (porosity <10%). Siltstones, shales, and coal seams are intercalated with these sandstones. The sandstone sequence is overlain by thick (5,000 feet) and continuous Early Paleocene marine shales, which would seem to be an effective CO_2 seal.

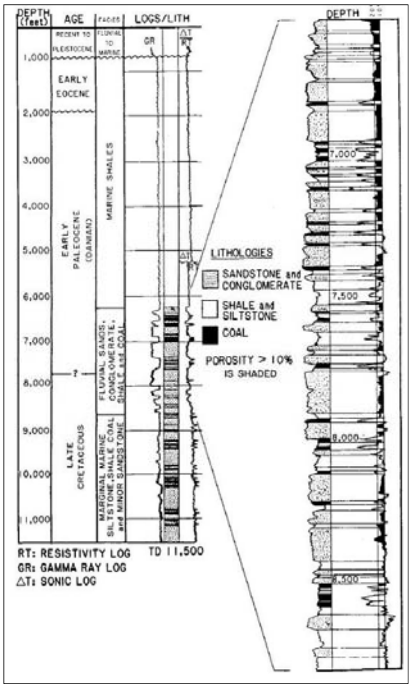
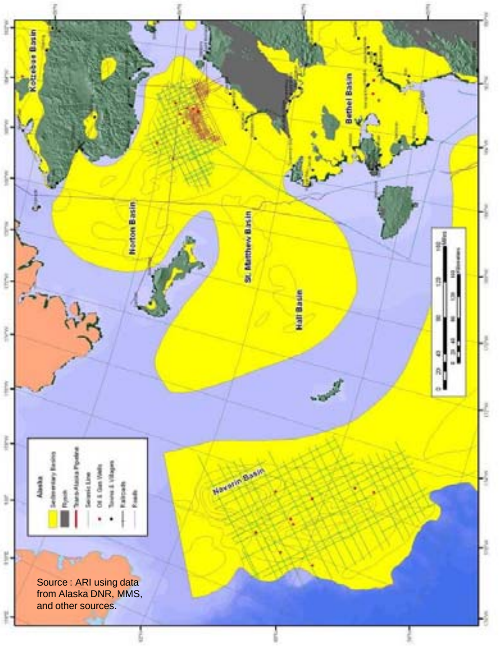
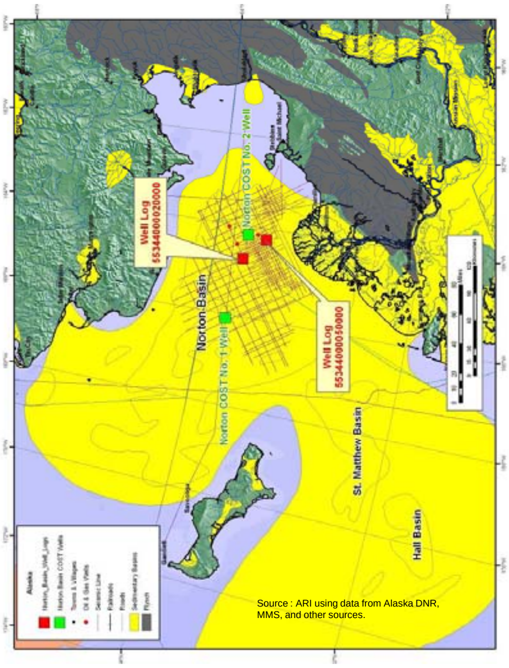


Figure 44 : Data location map for Norton, Navarin, other basins, offshore western Alaska.



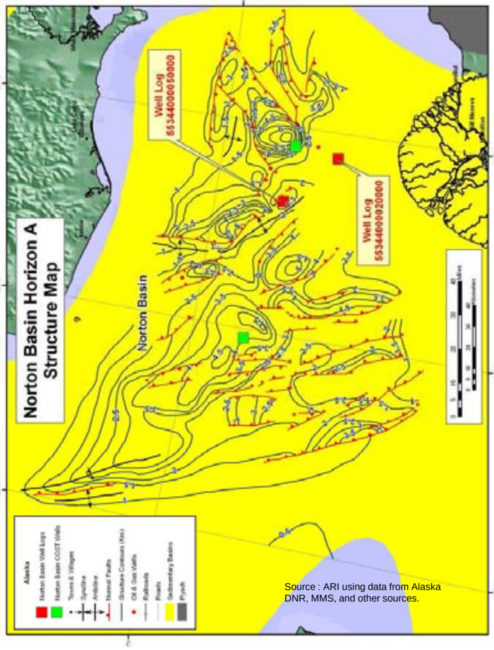
Source : ARI using data from Alaska DNR, MMS, and other sources.

Figure 45 : Data location map for the Norton Basin, offshore western Alaska, showing seismic and well log data for the COST 1 and 2 joint industry stratigraphic tests.



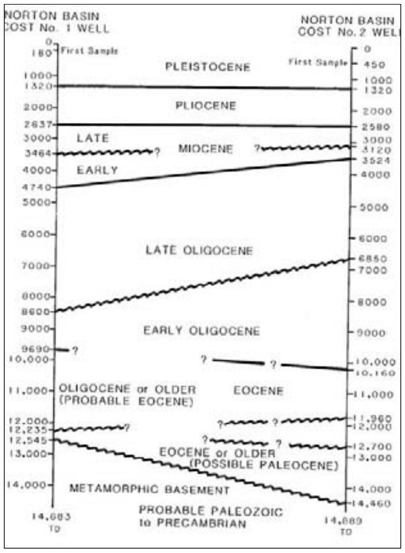
Source : ARI using data from Alaska DNR, MMS, and other sources.

Figure 46 : Structure map, Horizon A, Norton basin, offshore northwestern Alaska. The Norton basin is structurally complex with numerous mainly northwest-southeast trending faults and folds. The Yukon Horst separates the St. Lawrence and Stuart sub-basins.



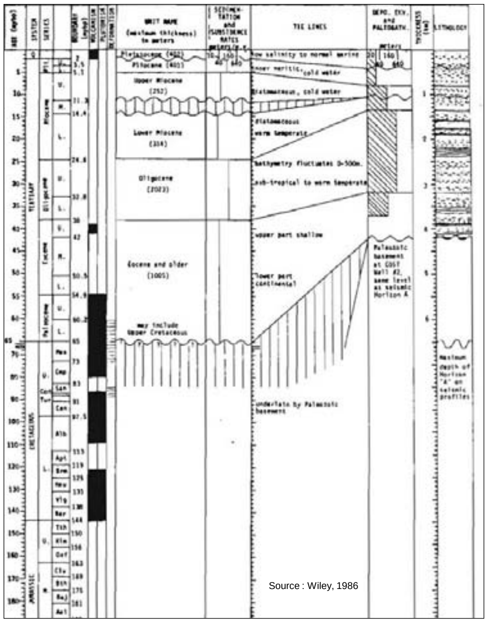
Source : ARI using data from Alaska DNR, MMS, and other sources.

Figure 47 : Generalized stratigraphic correlation, COST #1 and #2 wells, Norton basin, offshore western Alaska. These wells were drilled to metamorphic basement at depths of 12,500 to 14,500 feet, and encountered a clastic sequence of Eocene to Pleistocene sediments .



Source : Wiley, 1986

Figure 48 : Stratigraphy of the Norton Basin, offshore western Alaska. The best potential for CO_2 storage appears to be Oligocene turbiditic sandstones. Miocene diatomaceous mudstones are mostly immature and probably lack good porosity and permeability.



Source : Wiley, 1986

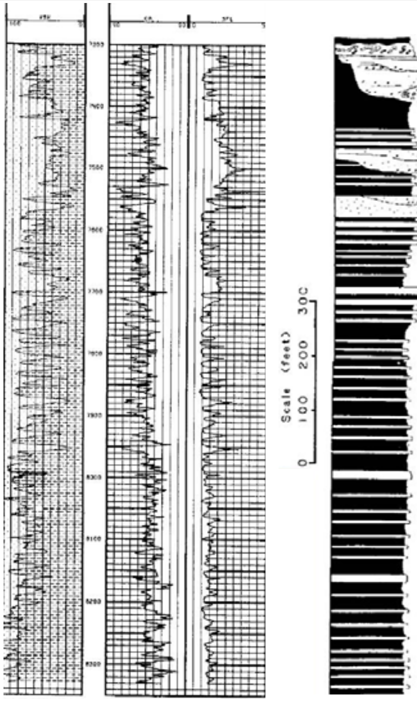
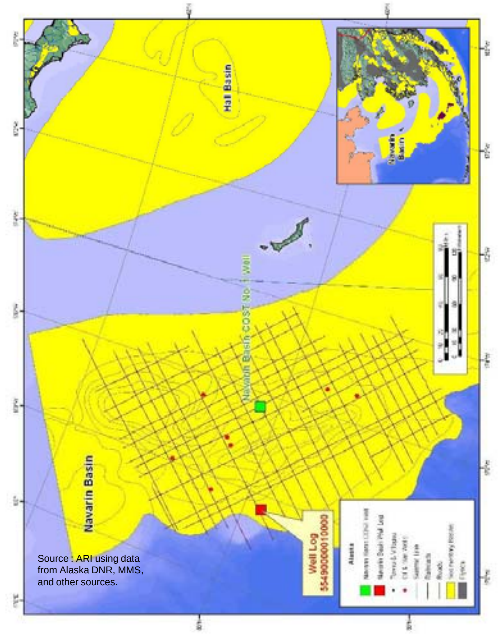


Figure 49: Detailed sandstone thickness log, COST #1 well, Norton basin, offshore western Alaska, showing turbidite sandstone development between depths of 7,200-8,350'.

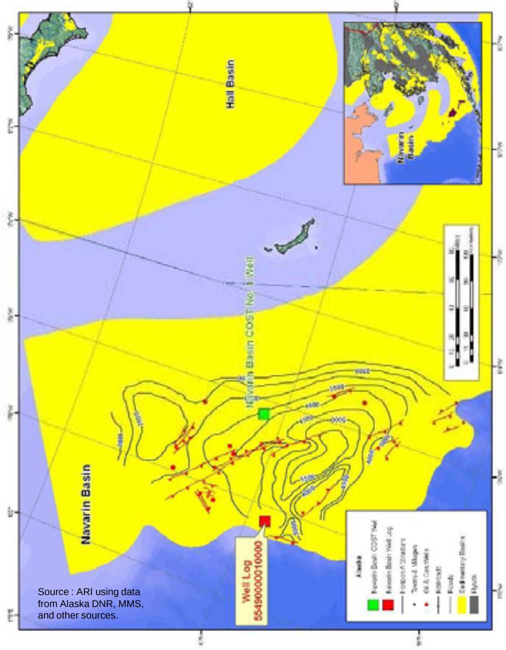
Source : Wiley, 1986

Figure 50 : Data location map of the Navarin Basin, Alaska, showing 2-D seismic data and the centrally located COST #1 well that was funded by an industry consortium. The other petroleum exploration wells drilled in this basin remain confidential.



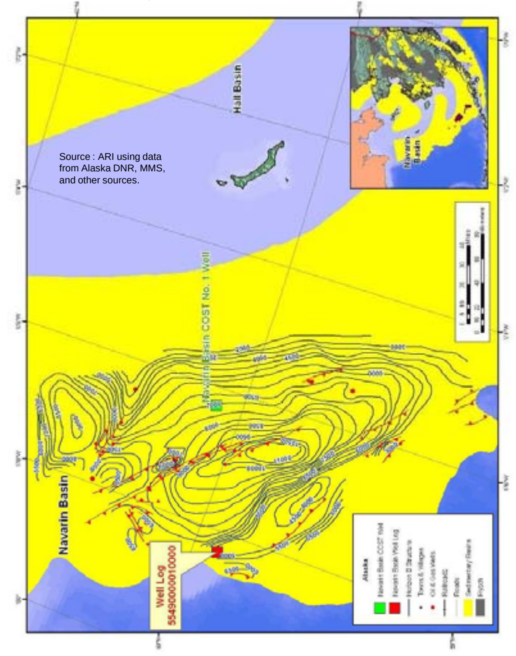
Source : ARI using data from Alaska DNR, MMS, and other sources.

Figure 51 : Structure map, Horizon A, Navarin Basin, Alaska. Map shows northwest structural trend and depth to 5,000 foot maximum for this acoustic reflector.



Source : ARI using data from Alaska DNR, MMS, and other sources.

Figure 52 : Structure map, Horizon B, Navarin Basin, Alaska. Map shows northwest structural trend and depth to over 11,000 foot maximum for this acoustic reflector.



Source : ARI using data from Alaska DNR, MMS, and other sources.

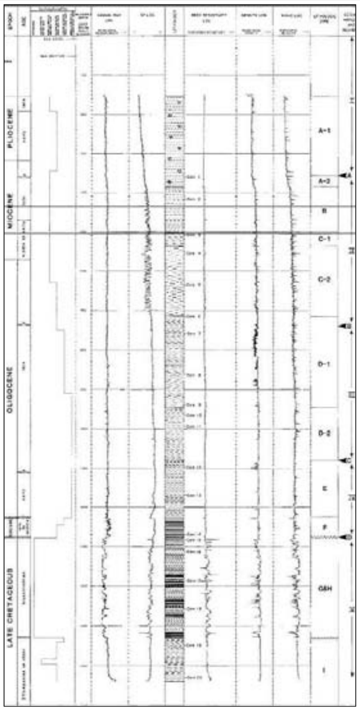


Figure 53 : Lithologic log from the COST #1 well, Navarin Basin, Alaska.

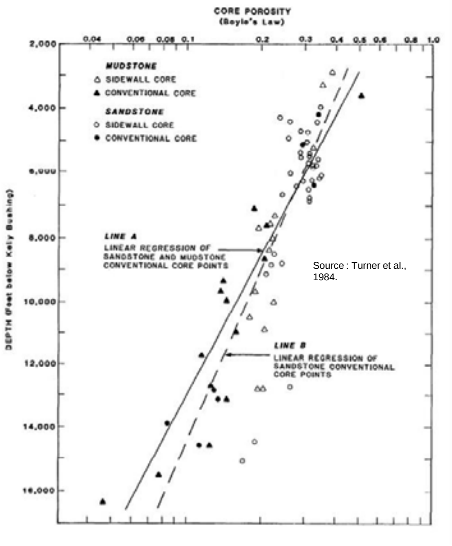
The lower section penetrated (13,000-16,400 ft) comprises Late Cretaceous that is unconformably overlain by a thin Eocene and much thicker Paleocene section from depths of about 5,700 to 13,000 feet. These are conformably overlain by Miocene and Pliocene deposits from about 1,500 to 5,700 foot depth

20 conventional cores were cut between 3,637-16,342 feet. The well was cased to a depth of 12,834 feet and a thin 20-foot interval from 6,278-6,298 feet was drill-stem tested.

Sandstones totaling 1,070 feet net in Zones C-1 and C-2 appear to have the best reservoir properties for CO_2 storage.

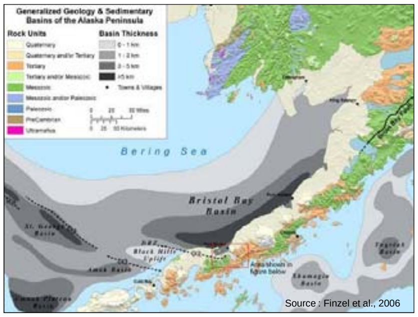
Source : Turner et al., 1984.

Figure 54 : Core porosity data from the Navarin Basin, offshore western Alaska exhibit a linear decline with depth.



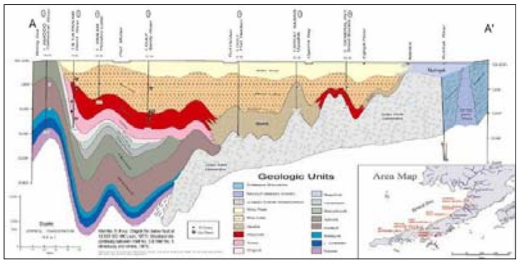
Source : Turner et al., 1984.

Figure 55 : The mainly offshore Bristol Bay foreland basin, southwestern Alaska and north of the Alaskan Peninsula. Sedimentary rocks range up to in excess of 5 km in this basin.



Source : Finzel et al., 2006

Figure 56 : Schematic cross section, trending southwest to northeast, onshore Alaskan Peninsula along Bristol Bay, southwestern Alaska.



Source : Alaska DNR.

Figure 57 (below left) : Stratigraphic column for Bristol Bay basin, southwestern Alaska, showing the Triassic to Tertiary sedimentary sequence, of which the Tertiary appears to have the most promising CO_2 storage potential.

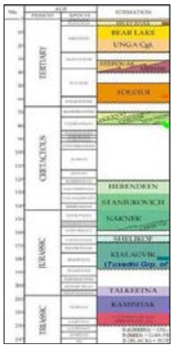
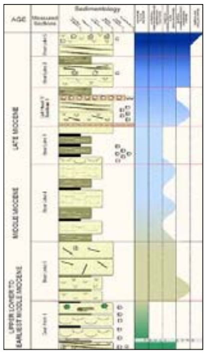


Figure 58 (right) : The Miocene Bear Lake Formation in the onshore Bristol Bay basin. The 1.2-km thick unit is considered the main oil and gas target. Sandstones in the Bear Lake Formation probably would be good CO_2-storage candidates. Multiple interbedded shales could be seals.

Source : Finzel et al., 2006

Source : Reifenstuhl et al., 2007



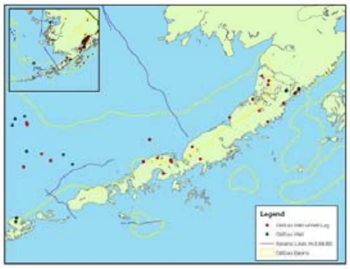
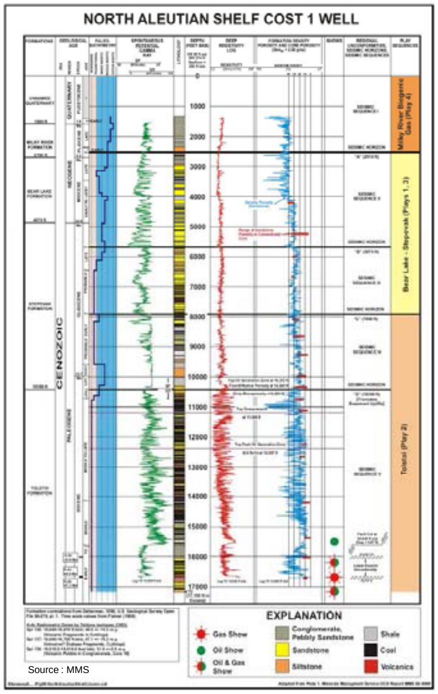


Figure 59 : Oil and gas wells and seismic lines available in the North Aleutian / Bristol Bay basin.

Source : ARI using data from Alaska DNR, MMS, and other sources.

Figure 60 : Stratigraphic log from the North Aleutian Shelf COST 1 test well. The well was drilled to total depth of 17,155 feet in an unidentified Eocene formation. The well penetrated the Tolstoi, Stepovak, Bear Lake, and Milky River Formations. Sandstones are particularly well developed in the upper Stepovak and Bear Lake Formations at a depth of 3,000 to 8,000 feet.



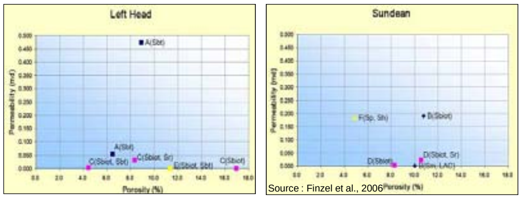
Source : MMS

Figure 61 : Sandstone core analysis from the COST 1 stratigraphic test well, North Aleutian Shelf, Alaska, showing overall average 22.6% porosity and 338 mD permeability.

North Aleutian COST 1 Well: Core Data

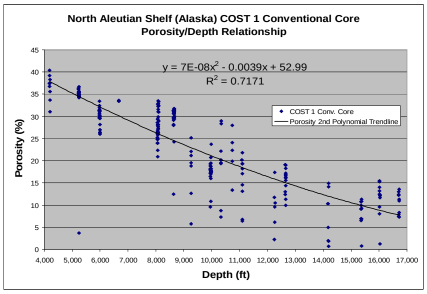
Sample Type	Core No.	Sample No.	Depth (ft bkb)	Perm (mD)	Porosity (%)	Lithology
Conv. Core Plug	2	1	4192	262	36.8	ss;f-cgr,slty,sc foss
Conv. Core Plug	2	2	4192	367	37.4	same
Conv. Core Plug	2	3	4193	84	37.5	ss;f-mgr,slty,sc foss
Conv. Core Plug	2	4	4195	35	39.2	same
Conv. Core Plug	2	5	4196	11	40.4	same
Conv. Core Plug	2	6	4197	11	38.3	same
Conv. Core Plug	2	7	4197	16	35.6	same
Conv. Core Plug	2	8	4198	18	33.7	same
Conv. Core Plug	2	9	4200	20	31.1	same
Conv. Core Plug	3	10	5227	1188	35.5	sd;vf-mgr
Conv. Core Plug	3	11	5229	1378	36.4	same
Conv. Core Plug	3	12	5230	988	36.1	same
Conv. Core Plug	3	13	5231	1419	36.1	same
Conv. Core Plug	3	14	5232	880	35.1	same
Conv. Core Plug	3	15	5233	1413	34.9	same
Conv. Core Plug	3	16	5234	1694	34.4	same
Conv. Core Plug	3	17	5235	1607	34.2	same
Conv. Core Plug	3	18	5235	0.04	3.7	ss;vf-fgr,calc
Conv. Core Plug	3	19	5236	1561	34.7	sd;vf-mgr
Conv. Core Plug	3	20	5237	1932	35.5	same;calc incls
Conv. Core Plug	3	21	5239	1228	35.3	sd;vf-mgr
Conv. Core Plug	3	22	5239	1592	34.9	same
Conv. Core Plug	3	23	5240	2203	36.7	same
Conv. Core Plug	3	24	5242	1620	35.7	same
Conv. Core Plug	3	25	5243	1190	34.4	same
Conv. Core Plug	3	26	5244	1094	34.5	same
Conv. Core Plug	3	27	5245	926	35	same
Conv. Core Plug	4	28	5970	129	31.3	ss;f-mgr,fn sh incls,foss
Conv. Core Plug	4	29	5972	58	31.1	same
Conv. Core Plug	4	30	5973	98	31.3	same
Conv. Core Plug	4	31	5973	61	31.4	same
Conv. Core Plug	4	32	5975	155	33.4	same
Conv. Core Plug	4	33	5976	53	31.3	same
Conv. Core Plug	4	34	5976	35	31.5	same
Conv. Core Plug	4	35	5978	181	32.4	same
Conv. Core Plug	4	36	5979	98	32	same
Conv. Core Plug	4	37	5979	66	29.8	same
Conv. Core Plug	4	38	5981	82	30.7	same
Conv. Core Plug	4	39	5982	67	29.8	same
Conv. Core Plug	4	40	5983	100	29.6	ss;f-mgr,fn sh incls,carb,foss
Conv. Core Plug	4	41	5984	93	29.7	same
Conv. Core Plug	4	42	5985	51	30.3	same
Conv. Core Plug	4	43	5985	61	30.2	same
Conv. Core Plug	4	44	5987	30	29.5	same
Conv. Core Plug	4	45	5987	57	31.2	ss;f-cgr,sh incls,glauc,foss
Conv. Core Plug	4	46	5989	84	30.1	same
Conv. Core Plug	4	47	5991	72	28.2	same
Conv. Core Plug	4	48	5992	17	27	ss;m-cgr,shy,glauc,foss
Conv. Core Plug	4	49	5993	7.8	26	same
Conv. Core Plug	4	50	5993	11	26.3	same
Conv. Core Plug	4	51	5995	18	26.4	same
Conv. Core Plug	4	52	5995	18	27	same
Conv. Core Plug	5	53	6665	7722	33.4	sd;m-cgr
Conv. Core Plug	5	54	6667	6299	33.6	same
Conv. Core Plug	5	55	6668	5215	33.4	same
Conv. Core Plug	6	56	8051	58	28.6	ss;vf-fgr,fn carb incls
Conv. Core Plug	6	57	8051		26.2	same *frac*
Conv. Core Plug	7	58	8055	6.24	26.2	same
Conv. Core Plug	7	59	8057		25.3	same *frac*
Conv. Core Plug	7	60	8058	10	24	ss;vf-mgr,fn carb incls
Conv. Core Plug	7	61	8058	23	24.8	same
Conv. Core Plug	7	62	8060	3.56	25.8	same;fn sh inbd
Conv. Core Plug	7	63	8061	21	27.9	same: fn sh inbd
Conv. Core Plug	7	64	8062	17	29.4	ss;vf-fgr
Conv. Core Plug	7	65	8064	520	32.8	ss;mgr
Conv. Core Plug	7	66	8064	95	29.3	ss;f-mgr
Conv. Core Plug	7	67	8065	8.15	26.9	ss;vf-fgr,sh inbd
Conv. Core Plug	7	68	8066	14	25	ss;vf-mgr,sh inbd
Conv. Core Plug	7	69	8067	9.72	20.9	same; sc peb
Conv. Core Plug	7	70	8069	9.71	28.2	ss;vf-fgr,sh inbd
Conv. Core Plug	7	71	8070	4.33	24	ss;vf-mgr,sh inbd
Conv. Core Plug	7	72	8071	6.29	26.1	same
Conv. Core Plug	7	73	8072	93	24.8	same *frac*
Conv. Core Plug	7	74	8072	3.97	22.4	same
Conv. Core Plug	7	75	8074	29	26.5	same; sc peb
Conv. Core Plug	7	76	8074	27	26.5	same
Conv. Core Plug	7	77	8076		28.2	same *frac*
Conv. Core Plug	7	78	8076	4.59	27.3	same
Conv. Core Plug	7	79	8078	39	28.2	same *frac*
Conv. Core Plug	7	80	8078	9.02	27.2	same
Conv. Core Plug	7	81	8079	3.26	26.4	same
Conv. Core Plug	7	82	8080		26.3	same *frac*
Conv. Core Plug	7	83	8081	496	27.7	ss;f-mgr
Conv. Core Plug	7	84	8083	697	29.9	same;sh incls
Conv. Core Plug	7	85	8083	1372	31.6	same
Conv. Core Plug	7	86	8084	476	32.2	same
Conv. Core Plug	7	87	8086	1802	32.3	same *frac*
Conv. Core Plug	7	88	8087	1584	32.9	same
Conv. Core Plug	7	89	8087	2358	32.9	same
Conv. Core Plug	7	90	8089	1478	31.1	ss;f-cgr
Conv. Core Plug	7	91	8089	1791	33.5	same
Conv. Core Plug	7	92	8090	1141	33.3	ss;f-mgr,carb incls
Conv. Core Plug	7	93	8091	849	32.4	same
Conv. Core Plug	7	94	8092		31	same;sh lams *frac.*
Conv. Core Plug	7	95	8093	217	29	same;sh lams
Conv. Core Plug	8	96	8629	79	29.2	ss;f-cgr
Conv. Core Plug	8	97	8629	109	29.8	same
Conv. Core Plug	8	98	8630	88	28.2	ss;f-vcgr
Conv. Core Plug	8	99	8632	340	31.3	ss;f-cgr
Conv. Core Plug	8	100	8633	224	31.2	same
Conv. Core Plug	8	101	8634	1040	30.7	ss;f-vcgr
Conv. Core Plug	8	102	8634	78	29.6	same
Conv. Core Plug	8	103	8636	0.98	12.5	ss;f-mgr,vcalc
Conv. Core Plug	8	104	8637	709	31.4	ss;f-vcgr
Conv. Core Plug	8	105	8637	67	28	same
Conv. Core Plug	8	106	8639	468	31.2	same
Conv. Core Plug	8	107	8640	349	30.8	same
Conv. Core Plug	8	108	8641	291	30.7	same
Conv. Core Plug	8	109	8642	929	30.7	same
Conv. Core Plug	8	110	8643	303	31.1	same
Conv. Core Plug	8	111	8643	473	31.8	same
Conv. Core Plug	8	112	8645	695	31.5	same
Conv. Core Plug	8	113	8646	284	30.8	same
Conv. Core Plug	8	114	8646	325	30.9	same;carb incl
Conv. Core Plug	8	115	8647	336	29.8	same;carb incl
Conv. Core Plug	8	116	8649	55	29.4	ss;f-mgr
Conv. Core Plug	8	117	8649	123	31.1	same
Conv. Core Plug	8	118	8650	186	30.9	same
Conv. Core Plug	8	119	8651	896	30.5	ss;m-cgr
Conv. Core Plug	8	120	8652	1010	31.3	same
Conv. Core Plug	8	121	8652	132	29.8	ss;vf-mgr
Conv. Core Plug	8	122	8653	244	29.7	ss;f-vcgr
Conv. Core Plug	8	123	8653	460	31.5	ss;f-cgr
Conv. Core Plug	8	124	8654	280	30.6	same;sh incls
Conv. Core Plug	8	125	8654		24.3	ss;vfgr,vshy,carb *frac*
Conv. Core Plug	8	126	8655	274	30.1	ss;f-mgr,sc peb *frac.*
Conv. Core Plug	8	127	8656		29.4	ss;vf-fgr,carb lams *frac.*
Conv. Core Plug	8	128	8657	1594	31.2	ss;m-vcgr,carb incls
Conv. Core Plug	8	129	8657	3193	31.7	ss;m-cgr
Conv. Core Plug	9	130	9256	13	19.6	sltst;sh inbd
Conv. Core Plug	9	131	9256	1615	25.2	ss;fgr
Conv. Core Plug	9	132	9257	189	18.8	sltst;sdy,carb *frac.*
Conv. Core Plug	9	133	9259	0.11	5.8	ss;vfgr, v peb,calc
Conv. Core Plug	9	134	9260	1.91	12.7	same
Conv. Core Plug	9	135	9261	867	21.2	ss;,gr,sh lams
Conv. Core Plug	9	136	9264	436	22.1	ss;fgr,carb lams
Conv. Core Plug	10	137	9945	10	19.3	ss;vfgr,slty
Conv. Core Plug	10	138	9946	0.15	16.5	ss;vf-fgr,slty
Conv. Core Plug	10	139	9948	0.52	17.2	same
Conv. Core Plug	10	140	9949	0.25	17.9	same
Conv. Core Plug	10	141	9951	1.73	18.8	same
Conv. Core Plug	10	142	9953	0.58	17.9	same
Conv. Core Plug	10	143	9953	0.51	18.2	same
Conv. Core Plug	10	144	9955	0.43	9.6	same
Conv. Core Plug	10	145	9956	59	18.1	same *frac*
Conv. Core Plug	10	146	9957	0.87	17.2	same
Conv. Core Plug	10	147	9958	0.04	10.9	same
Conv. Core Plug	10	148	9961	5.08	17.8	same
Conv. Core Plug	10	149	9962	1.63	18.7	same
Conv. Core Plug	10	150	9963	0.63	17.3	same
Conv. Core Plug	10	151	9964	2.89	17.5	same
Conv. Core Plug	10	152	9966	11	17.8	same
Conv. Core Plug	10	153	9968	0.42	17.0	same
Conv. Core Plug	10	154	9969	1.24	17.3	same
Conv. Core Plug	10	155	9970	4	16.0	ss;vf-fgr,v peb
Conv. Core Plug	10	156	9971	7.72	17.7	ss;vf-fgr,slty
Conv. Core Plug	10	157	9973	3.89	19.5	same
Conv. Core Plug	10	158	9974	4.57	20.7	same
Conv. Core Plug	10	159	9975	1.67	18.2	same
Conv. Core Plug	10	160	9976	1.3	17.6	same
Conv. Core Plug	10	161	9977	1.14	23.7	same
Conv. Core Plug	10	162	9979	5.43	17.5	same
Conv. Core Plug	10	163	9981	3.57	17.7	same
Conv. Core Plug	11	164	10327	1.83	19.6	ss;vf-mgr,foss
Conv. Core Plug	11	165	10328	2.07	20.2	same
Conv. Core Plug	11	166	10330	0.22	8.8	same, v foss
Conv. Core Plug	11	167	10332	0.06	7.3	same
Conv. Core Plug	11	168	10333	23	22.2	ss;vf-cgr,v foss
Conv. Core Plug	11	169	10334	43	19.4	same
Conv. Core Plug	11	170	10336	802	29.0	ss;c-vcgr
Conv. Core Plug	11	171	10337	544	28.3	same
Conv. Core Plug	12	172	10733	0.19	22.4	sltst;sdy
Conv. Core Plug	12	173	10737	130	24.1	ss;vfgr,carb
Conv. Core Plug	12	174	10738	0.95	13.4	ss;vf-fr,slty
Conv. Core Plug	12	175	10738	1.73	19.9	sltst;sid
Conv. Core Plug	12	176	10740	74	28.0	sltst;lig
Conv. Core Plug	13	177	11086	0.99	20.2	ss;vf-mgr,v peb
Conv. Core Plug	13	178	11090	0.13	18.2	ss;vf-mgr,slty
Conv. Core Plug	13	179	11092	0.08	6.8	cong
Conv. Core Plug	13	180	11092	5.63	19.4	cong;sdy
Conv. Core Plug	13	181	11096	0.23	14.6	ss;f-mgr,slty
Conv. Core Plug	13	182	11097	0.45	17.1	ss;f-vcgr,slty
Conv. Core Plug	13	183	11100	12	19.3	cong;sdy
Conv. Core Plug	13	184	11101	0.04	13.1	ss;vf-mgr,sc peb
Conv. Core Plug	13	185	11102	0.17	21.8	ss;vfgr
Conv. Core Plug	13	186	11103	0.04	6.4	sltst
Conv. Core Plug	14	187	12249	0.26	2.3	carb;sc pyr
Conv. Core Plug	14	188	12250	0.15	11.8	ss;vf-fgr,calc,sc carb incls
Conv. Core Plug	14	189	12252	5.02	6.2	sltst;carb,sc pyr
Conv. Core Plug	14	190	12256	0.04	9.6	ss;vf-mgr,calc,tuf
Conv. Core Plug	14	191	12258	1.74	17.4	same
Conv. Core Plug	14	192	12266	2.56	10.5	ls
Conv. Core Plug	15	193	12639	2.27	19.1	ss;vfgr,tuf
Conv. Core Plug	15	194	12641	0.32	13.0	ss;m-cgr,sc peb,calc,tuf
Conv. Core Plug	15	195	12641	0.02	12.4	same
Conv. Core Plug	15	196	12643	0.06	19.1	same
Conv. Core Plug	15	197	12644	0.04	17.2	same
Conv. Core Plug	15	198	12645	0.02	19.0	same
Conv. Core Plug	15	199	12646	0.04	18.3	same
Conv. Core Plug	15	200	12647	0.02	16.1	same
Conv. Core Plug	15	201	12647	0.01	15.6	same
Conv. Core Plug	15	202	12649	0.02	14.4	ss;c-vcgr,peb,calc,tuf
Conv. Core Plug	15	203	12650	0.04	16.9	same
Conv. Core Plug	15	204	12651	0.04	16.7	same
Conv. Core Plug	15	205	12652	0.02	16.2	same
Conv. Core Plug	15	206	12655	0.02	10.0	ss;m-vcgr,sc peb,calc,tuf
Conv. Core Plug	15	207	12656	0.02	16.3	ss;c-vcgr,peb,calc,tuf
Conv. Core Plug	15	208	12656	0.02	11.3	same
Conv. Core Plug	16	209	14166	0.02	10.3	sltst;tuf
Conv. Core Plug	16	210	14171	0.04	5.0	ss;m-vcgr,sc calc,tuf
Conv. Core Plug	16	211	14175	0.03	2.0	ss;f-cgr,sl calc,tuf
Conv. Core Plug	16	212	14179	0.09	10.3	ss;f-vcgr,calc,tuf
Conv. Core Plug	16	213	14182	0.02	0.7	ss;f-vcgr,sl calc,tuf
Conv. Core Plug	16	214	14183	0.04	1.9	same
Conv. Core Plug	16	215	14185	0.11	14.9	ss;vf-mgr,sl calc,tuf
Conv. Core Plug	16	216	14186	0.1	14.1	same
Conv. Core Plug	17	217	15347	0.02	9.1	ss;f-cgr,sl calc,tuf
Conv. Core Plug	17	218	15348	0.02	9.1	same
Conv. Core Plug	17	219	15350	0.02	6.5	same
Conv. Core Plug	17	220	15352	0.02	7.0	same
Conv. Core Plug	17	221	15354	0.02	10.0	same
Conv. Core Plug	17	222	15356	0.05	10.8	same
Conv. Core Plug	17	223	15358	0.05	10.8	same
Conv. Core Plug	17	224	15360	0.05	11.3	same
Conv. Core Plug	17	225	15362	0.02	6.9	same
Conv. Core Plug	17	226	15363	0.02	10.9	same
Conv. Core Plug	17	227	15365	0.02	9.3	same
Conv. Core Plug	17	228	15366	0.05	0.8	ss;vf-mgr,sl calc,tuf
Conv. Core Plug	18	229	16007	104	13.2	sh;fn calc lams *frac.*
Conv. Core Plug	18	230	16007	3.88	15.5	ss;vf-fgr,sh lam,calc,tuf
Conv. Core Plug	18	231	16011	12	9.6	same;sh lams *frac.*
Conv. Core Plug	18	232	16013	2.23	12.5	ss;vfgr,shy,calc,tuf
Conv. Core Plug	18	233	16015	0.02	8.1	volc;calc
Conv. Core Plug	18	234	16018	0.49	14.0	ss;vf-fgr,sh lams,calc,tuf
Conv. Core Plug	18	235	16018	4.25	15.3	same
Conv. Core Plug	18	236	16021	53	12.3	same *frac.*
Conv. Core Plug	18	237	16022	0.02	1.3	ss;vfgr,calc,tuf
Conv. Core Plug	18	238	16023	1.91	12.1	ss;vf-fgr,calc,tuf
Conv. Core Plug	18	239	16027	6.18	11.7	sltst;calc lams,tuf *frac.*
Conv. Core Plug	19	240	16703	0.7	12.4	ss;vfgr,calc,tuf
Conv. Core Plug	19	241	16703	1.7	13.0	same
Conv. Core Plug	19	242	16705	0.24	7.4	ss;vfgr,calc,tuf
Conv. Core Plug	19	243	16707	0.16	7.9	same
Conv. Core Plug	19	244	16708	2.01	12.2	same;sh lam
Conv. Core Plug	19	245	16711	0.04	7.3	volc;calc
Conv. Core Plug	19	246	16717	9.72	11.0	ss;vf-fgr,shy,calc,tuf *frac.*
Conv. Core Plug	19	247	16720	1.57	11.3	same
Conv. Core Plug	19	248	16720	0.56	13.6	same
Conv. Core Plug	19	249	16721	0.07	8.3	same
				338	22.6	Average

Figure 62 : Porosity and permeability measurements, Bristol Bay basin, southwestern Alaska. Porosity ranged from about 4% to 17%, generally averaging around 10%. Permeability was mostly quite low (<0.05 mD) although two samples from the Sundean location (right) measured significantly higher permeability at around 0.2 mD and one sample from the Left Head (left) location measured about 0.5 mD.



Source : Finzel et al., 2006

Figure 63 : Porosity vs depth relationship for the COST 1 well, North Aleutian Shelf, Alaska. Porosity averages about 20% at a depth of 10,000 feet in this well.



Source : ARI analysis of Cost 1 data

Figure 64 : Cross-section showing the Bear Lake, Stepovak, and Tolsoi Formations units in the Bristol Bay basin, southwestern Alaska. The Bear Lake Formation is the most laterally persistent, while the Stepovak and Tolstoi Formations were eroded or not deposited on paleo highs. However, all three units have thick sandstone packages with good porosity and permeabiolity, as well as interbedded shales with excellent hydrocarbon sealing capacities.

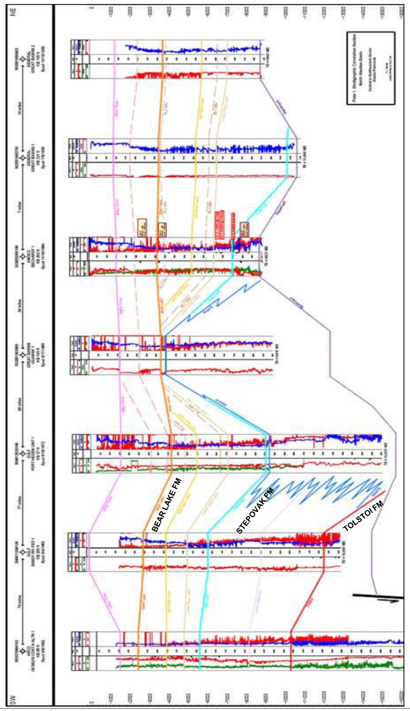
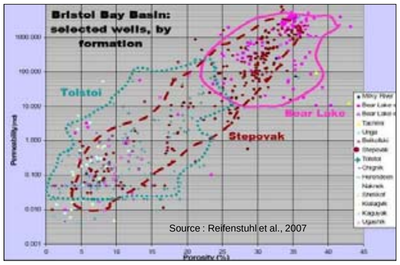


Figure 65 : Porosity and permeability measurements from deep petroleum exploration wells, central Bristol Bay basin, southwestern Alaska. The Tertiary Bear Lake Formation has the best porosity (25 to 40%) and permeability (10 to 4,000 mD), followed by the Stepovak (5-35%; 0.01-3,000 mD) and Tolstoi (0-25%; 0.02-200 mD) Formations.



Source : Reifenstuhl et al., 2007

Figure 66 : Hydrocarbon seal capacity of sedimentary rocks in the Bristol Bay basin. Seal capacity ranges in the Bear Lake, Tolstoi, and Staniukovich Formation ranges from several hundred to nearly 4,000 feet. This indicates good CO_2 sealing capacity in the basin.

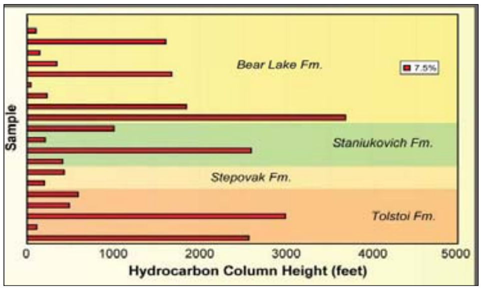
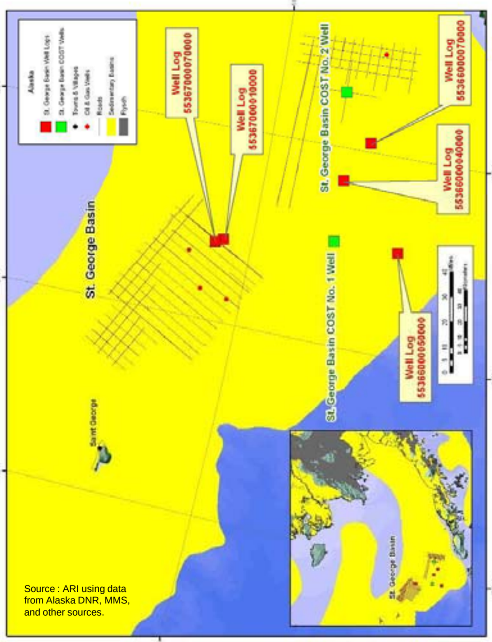


Figure 67 : Data location map for the St. George basin, offshore western Alaska.



Source : ARI using data from Alaska DNR, MMS, and other sources.

Figure 68 : Stratigraphic correlation of the COST 1 and 2 wells, St. George basin, offshore western Alaska. Thick sandstones encountered in the Oligocene to Pliocene section appear to have good CO_2 storage potential.

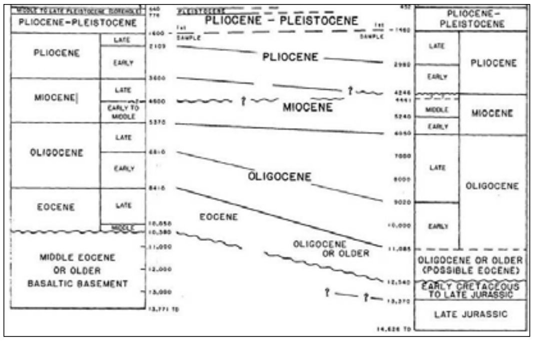


Figure 69 : Sandstone thickness and reservoir quality in the COST 1 and 2 wells, St. George basin, offshore western Alaska. Total sandstone thickness averages 2,505 m with 31% porosity. Permeability is fair.

Epoch	Cost Well	Depth Interval (feet)		No. Samples	Thickness (feet)	Gross Sand (feet)	Porosity (%)	Permeability (mD)
Pliocene	1	1600	3600	15	2000	1125	38	23
	2	1460	4246	13	2786	1525	37	81
Miocene	1	3600	5370	21	1770	775	38	7
	2	4246	6050	7	1804	200	28	96
Oligocene	1	5370	8410	62	3040	1650	28	158
	2	6050	11085	43	5035	1630	25	42
Total	1				6810		34	
	2				9625		29	
Average	**1+2**				**8,218**		**31**	
				meters	**2,505**			

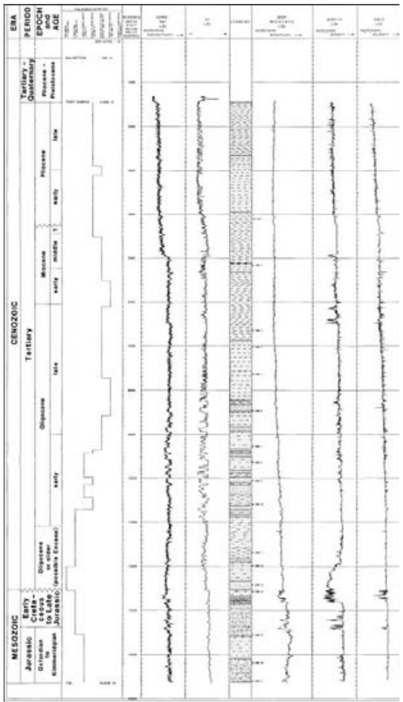


Figure 70 : Lithologic log for the COST #2 petroleum exploration well, St. George basin.

This well penetrated over 12,000 feet of volcaniclastic Cenozoic sediment and 2000 feet of the underlying Mesozoic sedimentary rocks.

The sandstones encountered in this well generally have good reservoir quality, totaled over 9,000 feet thick, and have 31% average porosity 50-100 mD of permeability.

Figure 71 : Regional data location map for the Gulf of Alaska basin, offshore southern Alaska, showing well log locations..

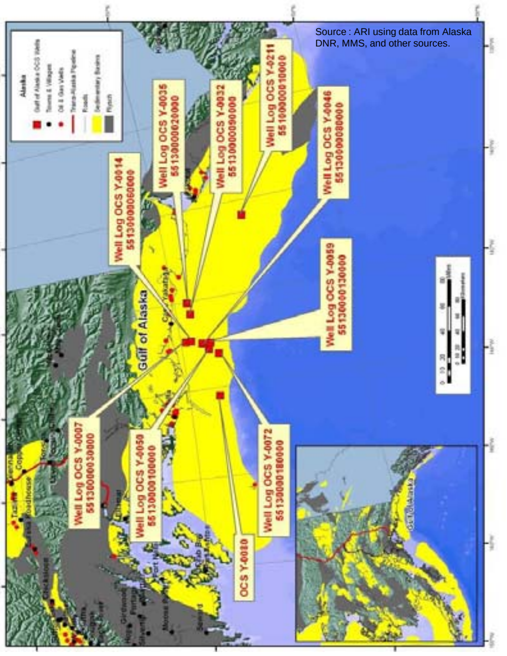
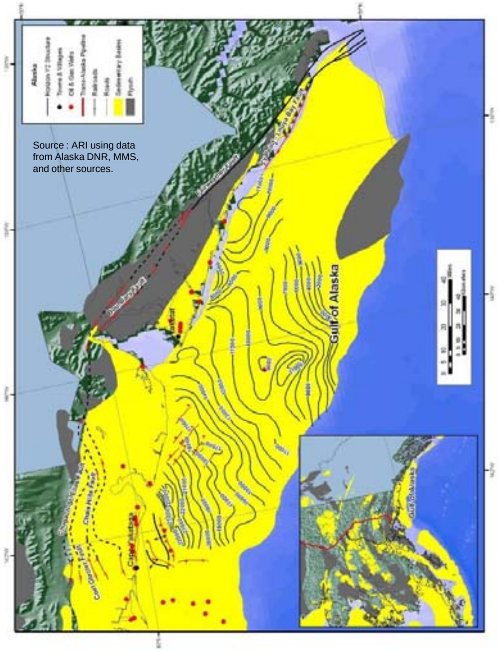
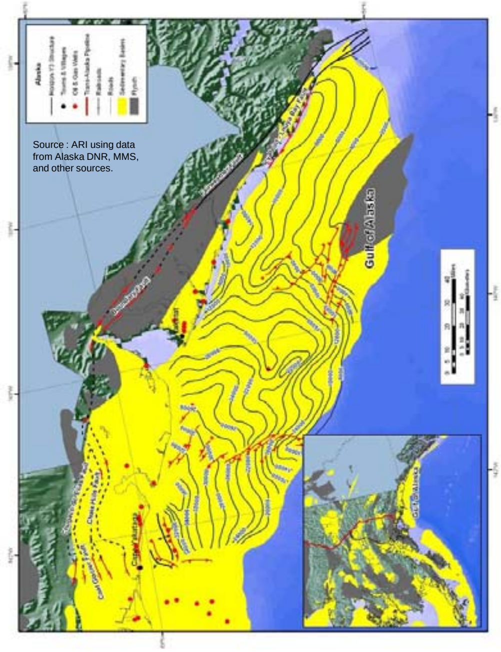

Source : ARI using data from Alaska DNR, MMS, and other sources.

Figure 72 : Structure map on Horizon Y2, Gulf of Alaska basin, offshore southern Alaska, showing gentle northwest regional dip. Structural levels range from -2000 feet in the south to below -23,000 feet in the deep basin center in the northwest.



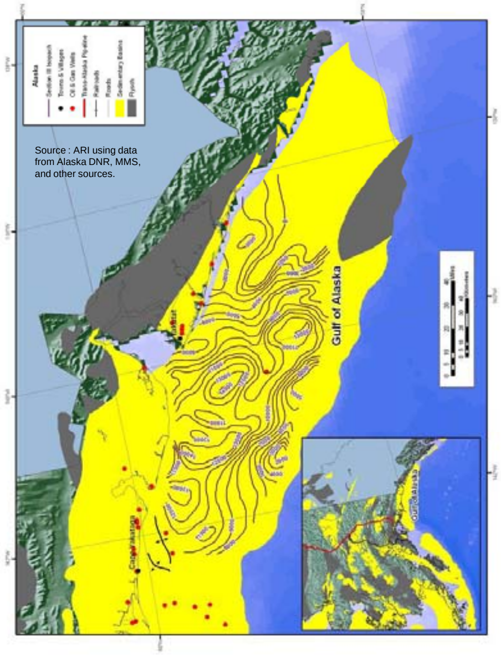
Source : ARI using data from Alaska DNR, MMS, and other sources.

Figure 73 : Structure map on Horizon Y3, Gulf of Alaska basin, offshore southern Alaska, showing gentle northwest regional dip. Structural levels range from -2000 feet in the southeast to below -36,000 feet in the deep basin center in the northwest.



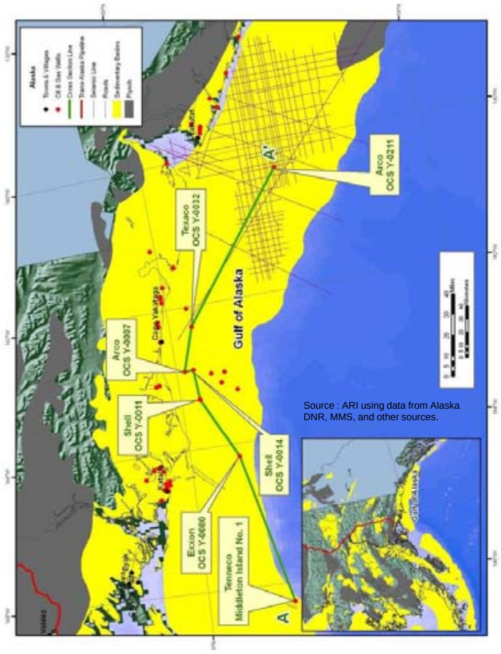
Source : ARI using data from Alaska DNR, MMS, and other sources.

Figure 74 : Isopach map for Section III, Gulf of Alaska basin, offshore southern Alaska. Total section isopach ranges from 2,000 to 14,000 feet, averaging about 10,000 feet.



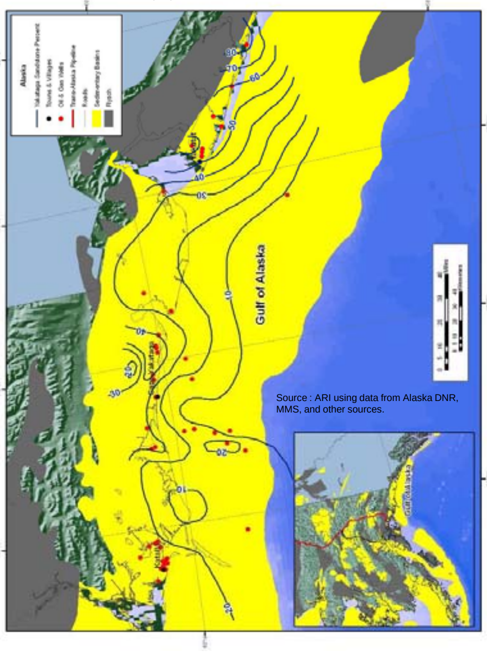
Source : ARI using data from Alaska DNR, MMS, and other sources.

Figure 75 : Medium-scale data location map for Gulf of Alaska basin, offshore southern Alaska, showing location of seismic cross section line and exploration wells.



Source : ARI using data from Alaska DNR, MMS, and other sources.

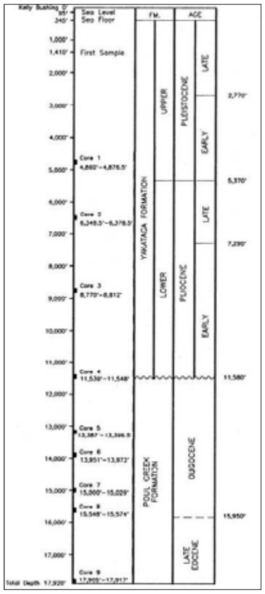
Figure 76 : Percent sandstone map for the Yakataga unit, Gulf of Alaska basin, offshore southern Alaska. Percent sandstone in this unit ranges from 10% in the south to about 80% in the northeast, averaging about 30%.

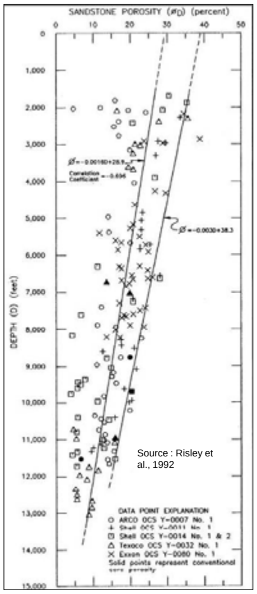


Source : ARI using data from Alaska DNR, MMS, and other sources.

Figure 77 (left) : Stratigraphic sequence penetrated by the Arco OCS Y-0007 exploration well. Thick but low-quality sandstones were encountered in the Tertiary Yakataga Formation.

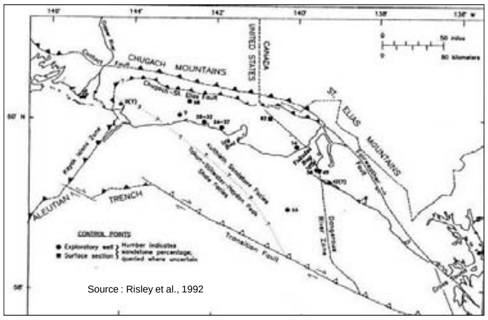
Figure 78 (right) : Sandstone porosity data from the Yakataga Formation from 5 offshore exploration wells in the Gulf of Alaska region. Porosity of this poorly sorted and mineralogically immature lithic arenite declines rapidly with depth, reaching about 15% at a depth of 8,000 feet.



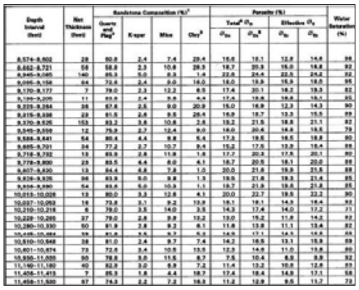


Source : Risley et al., 1992

Figure 79 : The Kultheith Formation, penetrated by the offshore OCS Y-0211 well, contains about 1,500 feet of total sandstone thickness comprising about 30 individual sandstone layers. It covers a roughly 200 by 50 mile area in the southeast corner of the Gulf of Alaska, close to the US-Canada border.



Source : Risley et al., 1992



Depth Interval (feet)	Net Thickness (feet)	Sandstone Composition (%)[1]				Porosity (%)				Water Saturation (%)
		Quartz and Plag[2]	K-spar	Mica	Clay[3]	Total[4] ϕ_T		Effective ϕ_E		
						ϕ_{Te}	ϕ_{Te}[5]	ϕ_{E}	ϕ_{E}	
8,574–8,602	28	60.8	2.4	7.4	29.4	16.6	18.1	12.8	14.6	99
8,662–8,721	59	58.8	2.3	10.6	28.3	18.7	20.3	15.0	16.8	92
8,945–9,085	140	85.3	5.0	8.3	1.4	22.6	24.4	22.5	24.2	92
9,095–9,159	64	72.6	2.4	9.0	16.0	18.0	19.9	15.9	18.0	95
9,170–9,177	7	79.0	2.3	12.2	6.5	17.4	20.1	18.2	19.3	82
9,199–9,209	11	[illegible]	2.4	[illegible]	4.4	17.4	19.8	18.8	19.1	85
9,223–9,264	38	67.6	2.5	9.0	20.9	15.0	16.9	12.3	14.3	90
9,315–9,338	23	61.5	2.6	9.5	26.4	16.9	18.7	13.3	15.5	99
9,370–9,525	153	83.2	3.6	10.6	2.6	19.2	21.5	18.8	21.1	82
9,545–9,556	12	75.9	2.7	12.4	9.0	18.0	20.6	16.6	19.5	79
9,588–9,641	54	80.4	4.4	9.8	5.4	17.3	19.6	16.5	18.8	80
9,665–9,701	36	77.2	2.7	10.7	9.4	15.2	17.5	13.3	16.4	88
9,718–9,732	15	83.9	2.8	11.8	1.6	17.7	20.3	17.6	20.1	80
9,778–9,800	23	83.5	4.4	8.0	4.1	16.7	20.5	18.1	20.0	88
9,807–9,820	13	84.4	6.8	7.8	1.0	20.0	21.6	19.9	21.5	88
9,828–9,926	98	83.9	5.0	9.8	1.3	19.5	21.6	19.3	21.4	85
9,936–9,990	54	83.6	5.0	10.3	1.1	19.7	21.9	19.6	21.8	85
10,013–10,028	13	80.0	3.3	12.6	4.1	20.0	22.7	19.5	22.2	90
10,037–10,053	16	73.8	3.1	9.2	13.9	16.1	18.1	14.3	16.4	92
10,210–10,218	8	79.0	3.5	14.0	3.5	14.3	17.4	14.0	17.2	71
10,229–10,265	37	79.0	2.6	9.8	13.2	13.0	15.2	11.8	14.2	92
10,280–10,330	50	81.9	2.8	9.2	6.1	11.6	13.8	11.1	13.4	82
10,449–10,484	35	81.8	3.5	9.7	5.2	14.9	17.1	14.5	16.6	69
10,510–10,548	38	81.0	2.4	9.7	7.4	14.2	16.5	13.1	15.9	69
10,601–10,674	73	72.6	3.4	10.5	13.5	12.3	14.6	11.0	13.6	80
10,950–11,000	50	78.8	3.0	11.5	6.7	7.5	10.4	6.9	9.9	92
11,140–11,180	40	82.9	3.0	6.9	7.2	11.4	13.2	10.8	12.6	83
11,406–11,413	7	85.3	1.6	4.4	18.7	17.4	18.4	14.9	17.1	58
11,458–11,530	67	74.3	2.2	7.2	16.3	11.2	12.9	9.5	11.7	72

Figure 80 : Sandstone thickness, depth, and porosity in the Kultheith Formation, penetrated by the offshore OCS Y-0211. A total 1,500 feet of sandstone in 29 layers was encountered in this well. Porosity declined from about 20% at 8,500 foot depth to 10% at 11,500 feet.

Source : Risley et al., 1992

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ALASKA GEOLOGIC CARBON SEQUESTRATION POTENTIAL ESTIMATE: SCREENING SALINE BASINS AND REFINING COAL ESTIMATES

Diane P. Shellenbaum & James G. Clough
Alaska Department of Natural Resources

DOE Contract No.: DE-FC26-05NT42593
Contract Period: October 1, 2005 - May 11, 2011

Arnold Schwarzenegger
Governor

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SCREENING SALINE BASINS AND REFINING COAL ESTIMATES

PIER FINAL PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
State of Alaska, Department of Natural Resources

April, 2010

500-XX-XX

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Acknowledgments

The authors would like to recognize and thank Paul Decker (ADOG) for his significant input and insights regarding the characterization of Alaska's sedimentary basins with regards to geologic sequestration potential.

The authors would also like to acknowledge the significant insights gained from discussions with Bob Swenson, David LePain, Marwan Wartes (ADGGS), and Paul Anderson (ADOG), which provided important additional insights into the formation and characterization of Alaska's sedimentary basins; Gary Stricker (USGS) and Steve Roberts (USGS retired) for their discussions and providing data applicable to Alaska coal seam sequestration properties; Keith Moodhe (ARI) for sharing data that helped in the final coal interpretations; and to Cari Ruffino (ADOG) and Kandace Krejci, John Burdick (ADGGS) and Mary Fleming (Resources Data, Inc.) for their cartographic support, without which this project would not have been possible.

Please cite this report as follows:

Shellenbaum, D.P., and Clough, J.G. 2010. Alaska Geologic Carbon Sequestration Potential Estimate: Screening Saline Basins and Refining Coal Estimates: California Energy Commission, Public Interest Energy Research Program.

Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

- PIER funding efforts are focused on the following RD&D program areas:
- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Alaska Geologic Carbon Sequestration Potential Estimate: Screening Saline Basins and Refining Coal Estimates is the final report for the Alaska Geologic Carbon Sequestration Potential Estimate: Screening Saline Basins and Refining Coal Estimates Project under contract number MR-045, conducted by the Alaska Department of Natural Resources. The information from this project contributes to PIER's Environmentally Preferred Advanced Generation Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

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Abstract

Preliminary screening for CO_2 storage potential in Alaska saline basins and coal seams, while following established DOE methodology, failed to account for the uniqueness of the Alaskan environment and economy. Data such as depth, salinity, presence and capacities of seals and traps, porosity, permeability and geochemistry, are all needed to make reasonable quantitative volumetric estimates for CO_2 storage capacity in sedimentary basins. Data such as coal rank, volume, quality, thickness, volume, rank, and permeability are needed to make the estimates for storage capacity in unmineable coal seams. This data is sparse or lacking in most of the vast sedimentary and coal basins in and offshore Alaska. With the exception of the Colville Basin on the North Slope, and the Cook Inlet Basin in south central Alaska, the lack of constraining data makes obtaining reasonable volumetric estimates of saline basin storage potential problematic. Enough data does exist, including economic and logistical factors related to working in extremely remote or offshore environments, to support a more qualitative approach in determining saline reservoir storage potential for those basins, and those results are included in this report.

For coal estimates, sufficient data were available to refine volumetric estimates for the Northern Alaska Province, the Nenana Basin, and the Cook Inlet Basin. Numerous geologic reports, coal studies and geologic maps were compiled, researched and reviewed to obtain the information necessary to revise the previous estimate of Alaska coal seam CO_2 storage capacity.

This report presents the background and analysis resulting in the qualitative summary of the CO_2 storage potential in sedimentary basins in Alaska, and a refined quantitative summary of the sequestration potential in unmineable coal seams in Alaska's major coal bearing basins. The final products discussed in this report are presented in Geographic Information System (GIS) layers, which include:

1) Outlines of sedimentary basins deeper than 1000 meters, with multiple attributes gathered to support an overall Sequestration Potential. Sequestration Potential is a qualitative estimate of how suitable a particular basin would be for CO_2 sequestration, and is based on analysis of the supporting attributes. The most important attributes impacting Sequestration Potential are a) reservoir and seal potential, and b) logistical and economic considerations such as distance from roads, or the need to work in an offshore environment.
2) Outlines of major coal bearing basins with qualitative attributes assigned that collectively determine the potential for CO_2 sequestration and provide revised quantitative estimates for volume of coal seam sequestration. The major factors that affect the storage capacity of coal seams include coal rank, coal volume, coal quality, coalbed methane presence and quantification, coal permeability, and permafrost presence and depth.

The sedimentary basins are shown relative to roads and large CO_2 stationary sources to illustrate proximity of the major sources to the potential sinks. Sources and proven sinks are closely co-located for much of the North Slope and south central Alaska, but very far removed for central (interior) Alaska.

Keywords: Alaska, Carbon capture and sequestration, CCS, carbon dioxide, coal, coalbed methane, saline basins, CO_2 emissions, source-sink matching, West Coast Regional Carbon Sequestration partnership, WESTCARB geologic sequestration

Executive Summary

This report presents refined saline basin screening and improved coal storage capacity estimates which take into account data coverage, geologic and tectonic environments and gross measures of economic feasibility. Its purpose is to augment and improve, as part of WESTCARB Phase II, understanding and estimates of storage potential in saline aquifers and coal seams for Alaska as part of a larger DOE effort to assess carbon sequestration potential nationwide.

Preliminary screening for CO_2 storage potential in Alaska saline basins and coal seams, while following established DOE methodology, failed to account for the uniqueness of the Alaskan environment and economy. Initial studies (Stevens and Moodhe, 2009) indicated very large area with potential for sequestration in northern Alaska and offshore saline aquifers [16,700 Gigatons (Gt)] and onshore coal seams (120 Gt). However, taking the next step and incorporating factors for sedimentary basins such as known and expected water salinity, tectonic environment, offshore environments and distance from infrastructure; and for coal seams, coal rank, cleating, and permafrost, will significantly constrain these resource estimates. Logistical constraints alone of working offshore reduces the storage estimate for saline basins by over 11,000 Gt.

This report provides a qualitative summary of multiple geologic and economic risk factors for both onshore and offshore basins, that impact the storage potential of the basins incorporated into GIS layers (Figures ES-1 and ES-2.)

Improved screening data for saline basins was obtained by integrating:

- Amount and quality of data available to screen the basin
- Likelihood of sufficient porosity and permeability, traps and seals
- Distance from infrastructure and sources of CO_2.
- Likely depositional environment (impacting predictions of salinity)
- Contribution of seismic (tectonic activity) risk to long term storage risk

This report also presents improved volumetric estimates for CO_2 sequestration in unmineable coal seams. Based on recently updated USGS coal resource estimates, preliminary estimates indicated that Alaska has a total geologic CO_2 storage capacity of 120 Gt in deep coal seams (Stevens and Moodhe, 2009). However, it is likely that only a portion of the 120 Gt is considered favorable for CO_2 sequestration, due to low permeability, seam geometry, surface access, faulting, deep permafrost and other site-specific conditions.

Results summarized in this report reflect augmented and refined estimates for storage potential for coal seams in Alaska by:

- Constraining the volumetric estimate of coal distribution and depth using new data and existing mapping,
- Producing a derivative map (Figure ES-2) of coal available for sequestration using filters that include coal rank, depth, lateral distribution, permafrost presence and depth, cleating and availability of infrastructure.

The revised estimate of Alaska coal seam CO_2 storage capacity is significantly lower than the previous estimate of 120 Gt. This study suggests that the combined CO_2 storage capacity deep, unmineable coal in three major Alaska coal basins is 49.24 Gt.

Estimates are in accordance with established methodology unless otherwise documented.

While revised estimates show the saline and coal sequestration potential is much lower than initial estimates, and is "high" only in the Cook Inlet basin in south central Alaska, and in a limited area on the central north slope, the sequestration potential in those two places is still likely to be more than large enough to handle the volumes of CO_2 available for capture in Alaska for many years. The limiting factors for CCS will be the economics of capture, transport (very long distances in the case of interior Alaska) injection, and long-term monitoring, and the establishment of laws and regulations for long term CO_2 storage.

The saline basin screening (Figure ES-1) and the updated estimates of coal storage potential (Figure ES-2, Table ES-1) have both been delivered to the WESTCARB GIS data clearinghouse maintained by the Utah Automated Geographic Reference Center.

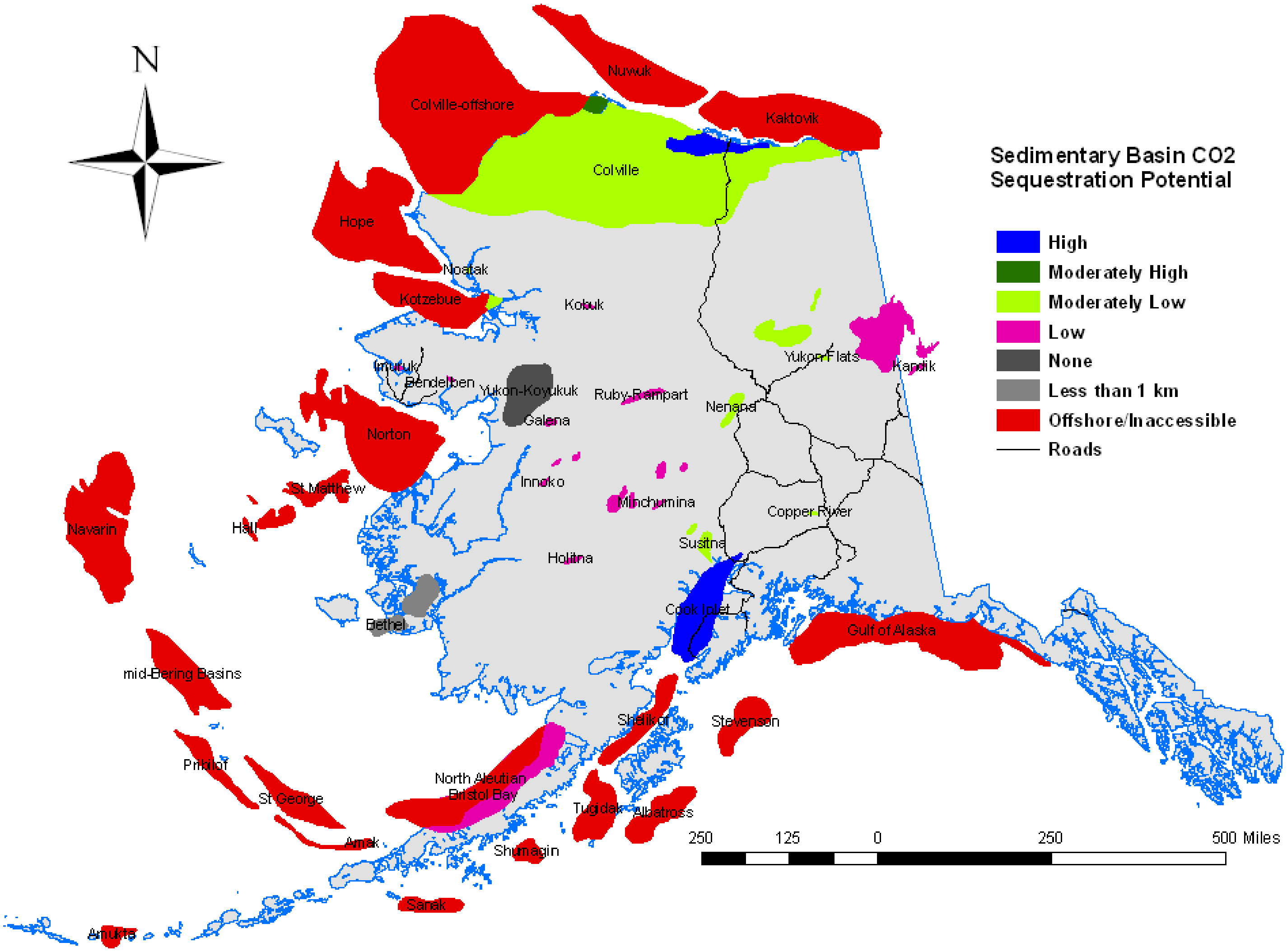

Figure ES-1. Alaska Saline Sedimentary Basin CO_2 Storage Potential

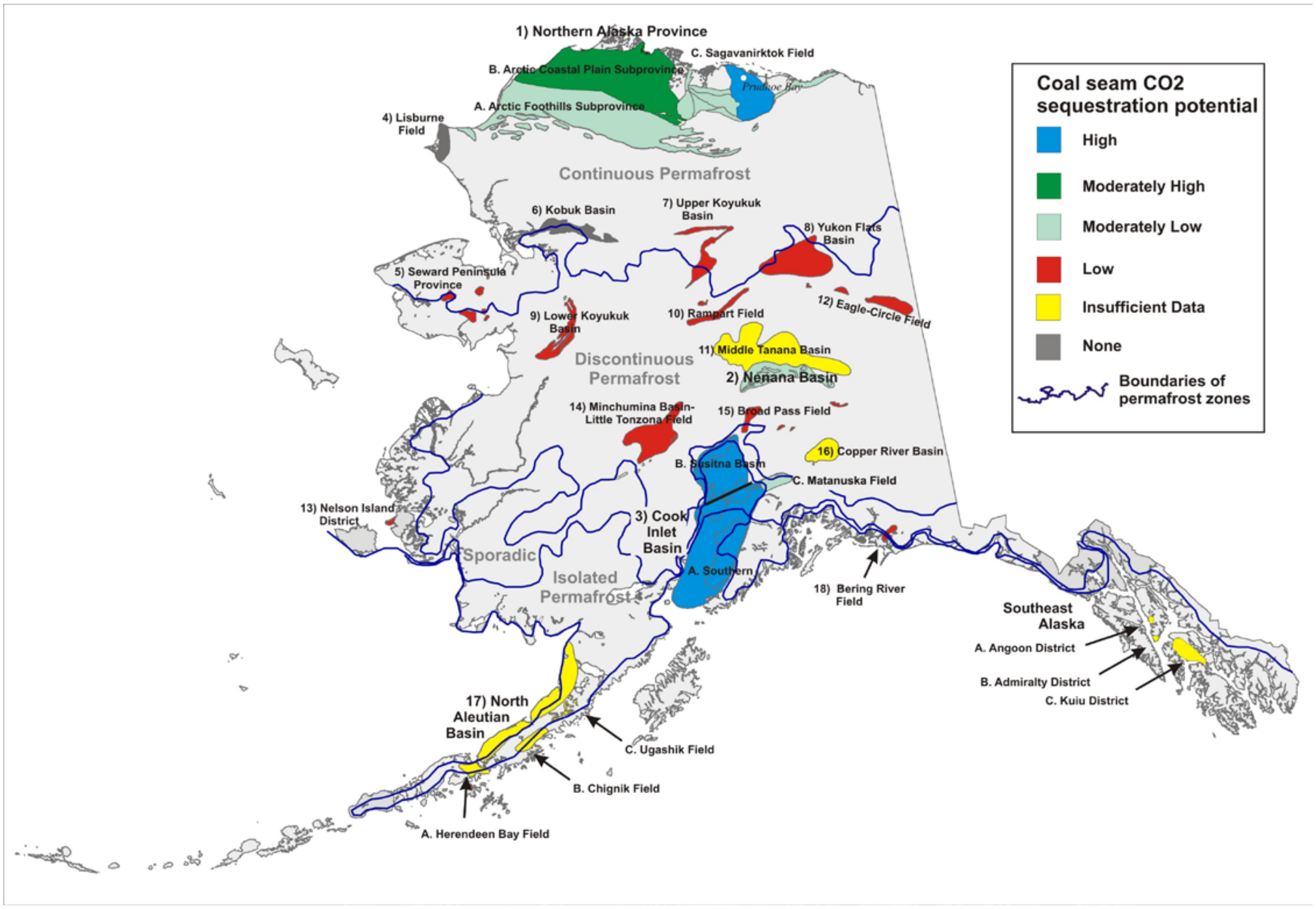

Figure ES-2. Alaska Coal Basin CO_2 Sequestration (storage) Potential

(1) REGION	(2) IDENTIFIED & HYPOTHETICAL COAL RESOURCES (billions of short tons)	(3) AVERAGE COAL RANK	(4) ARI Estimated CBM Resources (based on daf) (Tcf)	(5) ARI Estimated CO2 Storage Potential		(6) USGS Estimated CBM Resources* (Tcf)	(7) CO2 Storage Potential based on USGS CBM Resources*		(8) REVISED ESTIMATE OF COAL SEAM CO2 STORAGE POTENTIAL (this report) (Gt)
				(Tcf)	(Gt)		(Tcf)	(Gt)	
1) Northern Alaska Province	3,753.00		621	1,862	98	17.2	120.4	6.32	5.83
A. Arctic Foothills Subprovince	1,290.00	Bituminous							
B. Arctic Coastal Plain Subprovince	1,910.00	Subbituminous	No Data	Not Subdivided		15	105	5.53	5.08
C. Sagavanirktok Field	553.00	Subbituminous				2.2	15.4	0.79	0.75
Total North Slope	**3,753.00**		**621**	**1,862**	**98**	**17.2**	**120.4**	**6.32**	**5.83**
2) Nenana Basin	17.00	Lignite to subbituminous	1	3	0	1	10	0.52	0.41
3) Cook Inlet Basin. Includes A. Southern, B. Susitina and C. Matanuska resources	1,570.30	Subbituminous to anthracite	136	407	21	140	980	50.58	43.00
TOTAL ALL "BASINS"	**5,340.30**		**758.00**	**2,273**	**120.00**	**158.20**	**1,110**	**57.32**	**49.24**

*North Slope based on Roberts et al., 2008

Table ES-1. Summary table of estimates of deep coal seam CO_2 storage potential in Gigatons (Gt) based on attributes evaluated in this report (column 8). Coal resource estimates (column 2) and average coal rank (column 3) compiled from Merritt and Hawley, 1986 and Flores et al., 2004. ARI estimated CBM resources based on dry ash free coal (column 4) and estimated CO_2 storage potential (column 5) from Stevens and Moodhe, 2009. USGS estimated CBM resources (column 6) from Flores, et al., 2004; Montgomery and Barker, 2003; Roberts, et al., 2006; and Roberts, et al., 2008. Column 7, CO_2 storage potential was determined during the course of this study and is based on the 2008 assessment of North Slope recoverable CBM.

1.0 Introduction

Carbon dioxide capture and storage (CCS) technologies could play a critical role in mitigating the impact of fossil-fuel-based energy generation on greenhouse gas buildup in the atmosphere. The U.S. Department of Energy (DOE) is actively engaged in the second phase (CCS technology validation pilot studies) for its network of regional partnerships to determine the CCS technologies best suited for different regions of the country. In parallel, the PIER program is conducting research to define least-cost greenhouse gas mitigation strategies appropriate for California, including an assessment of the potential for carbon sequestration.

The West Coast Regional Carbon Sequestration Partnership (WESTCARB) in partnership with California Energy Commission is identifying and validating carbon sequestration opportunities in California, the surrounding states of Alaska, Arizona, Hawaii, Nevada, Oregon, and Washington, and the Canadian Province of British Columbia. Findings from the first phase of WESTCARB's regional characterization of geologic formations and land management suitable for long-term CO_2 storage (known as "sinks") indicated a lack of data in many key areas. Enhancing the geologic characterization of the WESTCARB region is necessary to be able to produce a robust regional CCS implementation strategy.

Preliminary screening for Alaska, while following established DOE methodology, failed to account for the uniqueness of the Alaskan environment and economy. Previous studies indicated a large area with potential for sequestration in saline aquifers and coal seams. Those numbers, however, need further refinement as many Alaska basins are underexplored, with little to no well control and/or seismic data, or are far from infrastructure or offshore. In offshore basins (estimated at over 11,000 Gt capacity), storage estimates for saline reservoirs are much higher than can currently be realized due to logistical considerations of working in harsh, often ice-covered, waters. In addition, factors such as known and expected water salinity (where fresh waters will be significantly deeper than usual related to fluvial depositional environments) unknown seal capacities, unknown impact of seismicity on sealing capacity in basins without proven hydrocarbons, and most significantly, economic and logistical hurdles related to the long distances between remote interior basins and CO_2 sources and roads or pipelines, will severely constrain saline and coal storage potential.

Coal capacity estimates will also be constrained from initial estimates when a number of factors that include coal rank, cleating, and permafrost are incorporated. It is important to note, that no direct measurement of CO_2 adsorption capacity of Alaskan coal has been measured in the laboratory. Therefore, estimates of coal seam CO_2 storage capacity are based on comparison to coal basins elsewhere as analogues.

The goals of this project were to augment and improve, as part of WESTCARB Phase II, preliminary estimates of storage potential in saline aquifers (qualitatively) and coal seams (quantitatively) in the DOE Carbon Sequestration Atlas for Alaska. The refined saline basin screening and improved coal storage capacity estimates take into account data coverage, geologic and tectonic environments and gross measures of economic feasibility.

2.0 Results and Discussions

Project results of saline basin screening and updated estimates of coal storage potential have been delivered to the WESTCARB GIS data clearinghouse maintained by the Utah Automated Geographic Reference Center. Significant to interpreting these results is the size and proximity of these potential CO_2 storage locations with CO_2 sources and with infrastructure. Source sizes and locations are briefly described in Section 2.1. Section 2.2 describes the analysis and results of the saline basin screening, and Section 2.3 describes the procedures and results of the analysis of storage potential in unmineable coal seams.

2.1 Stationary CO_2 Sources in Alaska

Stationary sources of greenhouse gas (GHG) account for approximately 21 million metric tons (mmt) of Alaska's 52 mmt total CO_2 equivalent (CO_2e) GHG emissions (ADEC, 2008)[1]. The largest stationary source locations and amounts are displayed in Figure 1. (Emissions were calculated based on fuel burned in all facilities requiring Title V EPA permits. Facilities that did not require a Title V permit were deemed minor emitters.) Of the 21 mmt related to stationary sources, approximately 15 mmt were generated in the production of oil and gas, primarily a result of natural gas combustion in generating power for hydrocarbon extraction, transport, and refining. This industry is focused in the producing fields on the North Slope, and to a lesser extent, the Cook Inlet, and is a critical economic driver in the State. Emissions in interior Alaska, ~ 2 mmt, are predominantly from the combustion of coal and diesel in power generation.

High storage potential exists in the proven oil and gas basins on the North Slope and the Cook Inlet, in depleted fields, in enhanced hydrocarbon recovery, and in saline reservoirs in those basins.
Fortunately, since CO_2 from oil and gas operations produces 75% of Alaska stationary sources, source and sink locations are essentially co-located (Figure 2.) More than half of the remaining 25% of Alaska stationary emissions is from power generation and industry in the Anchorage and Kenai areas, and is relatively close to potential CO_2 storage reservoirs there as well.

Storage of captured emissions in the interior (~10% of stationary emissions) is much more problematic and economically challenged. To date, no high potential saline or coal storage potential have been identified in the area, and any captured CO_2 would have to be shipped (no CO_2 pipelines currently exist in Alaska) to proven oil and gas basins either on the North Slope or in Cook Inlet.

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[1] CO_2e values were calculated by the Alaska Department of Environmental Conservation (ADEC) based on 2002 fuel burned in facilities requiring Title V Clean Air Act permits. 52 mmt is ~.7% of all US GHG emissions (US EPA, 2007.)

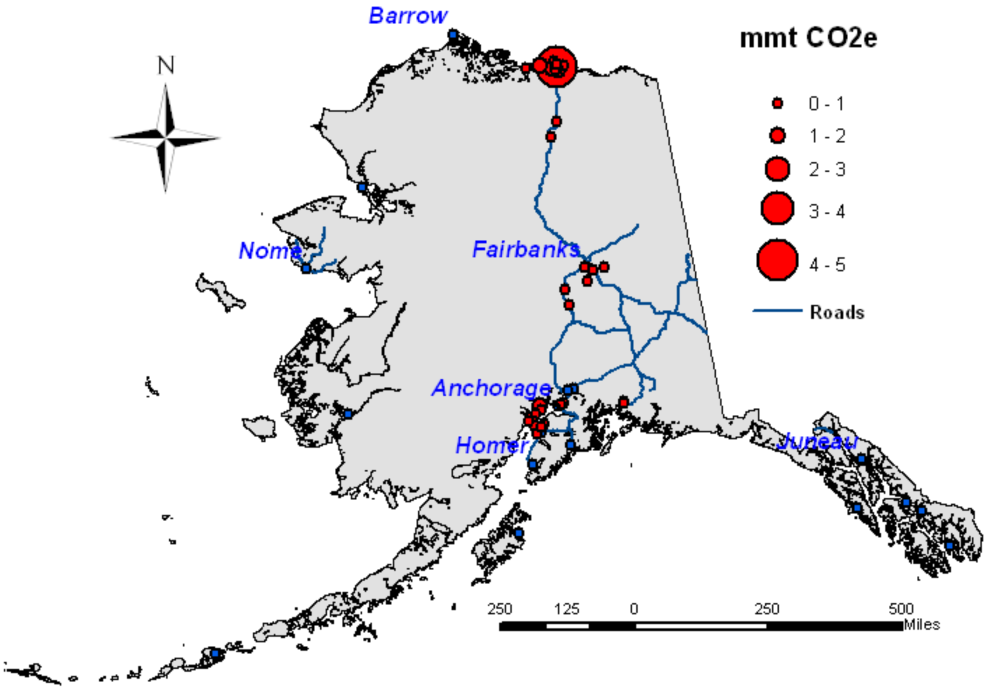

Figure 1: Largest CO2e emissions (as calculated by the Alaska DEC from fuel burned in Alaska facilities requiring Title V EPA permits) displayed in million metric tons of CO_2 equivalent.

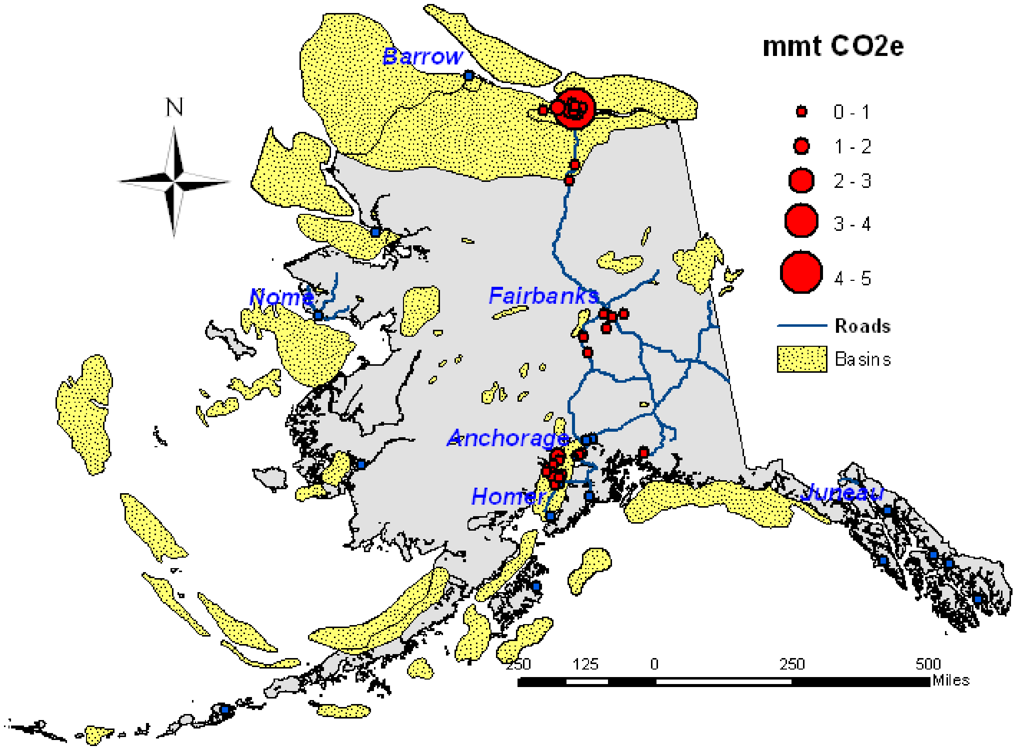

Figure 2: Stationary Sources of CO_2 (red) and deep sedimentary basins (stippled-yellow). Proven hydrocarbon basins are displayed in green.

2.2 CO_2 Storage Potential in Saline Sedimentary Basin Reservoirs

Data such as depth, salinity, presence and capacities of seals and traps, porosity, permeability and geochemistry, are all needed to make reasonable quantitative volumetric estimates for CO_2 storage capacity in sedimentary basins. This data is sparse or lacking in many of the vast sedimentary basins in and offshore Alaska. With the exception of the Colville Basin on the North Slope, and the Cook Inlet Basin in south central Alaska, both which have producing oil and gas fields and have significant seismic and well data coverage, the lack of constraining data in most basins makes obtaining reasonable volumetric estimates of storage potential problematic. Enough data does exist, however, to support a more qualitative approach as an initial step in determining saline reservoir storage potential for those basins.

Refined basin level screening for storage potential in Alaskan saline basins was obtained by assessing and incorporating the following:

- Depth: impact on storage volume potential. At depths greater than 800 meters CO_2 is in its dense, supercritical liquid state. Storing CO_2 in the supercritical state is not required, but is desirable for two reasons. First, significantly more CO_2 can be stored in the same storage volume, and second, the liquid is a less mobile and less buoyant state, and therefore more likely to stay contained.
- Amount of seismic and well data available for basin: impact on confidence and risk. For portions of the Colville Basin on the North Slope, and the Cook Inlet Basin in south Alaska, there is a significant amount of data, including seismic, well logs, gravity, and magnetics. In most other basins the paucity of seismic and well data translates to minimal knowledge of porosity, permeability, seals and traps. Surface mapping, gravity and recent tectonic activity may be the only geological and geophysical measurements available to categorize a basin.
- Environment of deposition (fluvial non-marine vs. marine, sand to shale ratio): impact on depth-salinity relationship and likelihood of seal formation
- Tectonic activity: impact on likelihood of seal integrity where no other information is available, and
- Distance from infrastructure and CO_2 sources: impact on economics. The cost to construct a pipeline over large distances, with no road support, is enormous. Many basins in Alaska are currently economically and logistically unfeasible for this reason. Offshore basins are effectively inaccessible due to the harsh operating environments. Even in the relatively protected waters of the Cook Inlet, seasonal ice and expensive facilities will likely preclude operations in the offshore portions of the basin.

2.2.1 Sedimentary Basin Attributes

Information was gathered from many sources to describe the types and kinds of information that exist for and about sedimentary basins in Alaska. The following attributes, along with a description of their significance and the source of the data, were captured in the GIS basin outline shape file. While all attributes are listed here for completeness, some have significantly more impact than others on overall “Sequestration Potential.” The attribute fields are in bold (followed by the actual field name in parenthesis, if different.)

1) **Basin Name.** Names and outlines are from published sedimentary basin maps (Kirschner, 1988, Troutman, 2007, Meyer, 2008, and Van Kooten, 1997). In most cases, basin outlines reflect estimated depths greater than 1000 meters. Figure 2 shows the basin outlines in conjunction with the largest CO_2 sources.

2) **Exploration Wells (Exploratio).** The number of exploration wells in the basin.The amount and sampling of well log data is critical to describing how much is known about basin porosity, permeability, seal capacity and salinity.
Public well data in Alaska is available though the Alaska Oil and Gas Conservation Commission (AOGCC.)[2]

3) **Seismic Coverage (Seismic_Co)**. Seismic data is needed to determine the presence or absence of significant faulting and regional architecture and potential presence and extents of seals, as well as illuminating any possible trapping mechanisms. Estimates of publicly available data were made from the USGS National Archive of Marine Seismic Surveys website[3], Alaska Department of Natural Resources North Alaska Oil and Gas Resource Map Series (2008), and seismic broker maps.

4) **Depositional Environment (Deposition)**. Depositional environment (Figure 3) is important in understanding likely depth- salinity relationships, especially when little to no well data is available to supply direct measurements. Whereas a non-marine environment of deposition will not necessarily lead to a completely freshwater basin, it is expected that in these basins the depth of non-saline water will be deeper than average, and will impact overall pore-space estimations. Depositional environment can also impact the likelihood of the presence of seals, though that is more difficult to predict. In cases of sparse to no well data, geologic field work documented in literature was used to categorize the basins as marine, marine-non-marine mixed, and non-marine. Where the depositional environment is non-marine or marine-non-marine (represented as "Mixed" in the Expected Salinity attribute defined below), the risk is higher that the depth where salinity reaches 10,000 ppm TDS will be deeper than average. This is known to be the case for the Cook Inlet Basin (completely non-marine, primarily fluvial deposition), where bicarbonate concentrations are high, but salinity is low. Most basins in Alaska are believed to be at fluvial (non-marine) or a mixture of non-marine and marine (Sherwood, 1988 and Kirschner, 1988).

5) **Salinity**. The expected salinity attribute is derived either from measured well data, or qualitatively interpreted from depositional environment (previous attribute.) Qualitative values of Low, Normal, and Mixed were used to describe salinity, with normal being typical marine deposition. Low=non-marine, Mixed=marine and non-marine, Normal=marine.

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[2] Alaska Oil and Gas Conservation Commission (AOGCC) - Public wells in Alaska lands and waters, http://doa.alaska.gov/ogc/

[3] USGS National Archive of Marine Seismic Surveys, (NAMMS) http://walrus.wr.usgs.gov/NAMSS/

6) **Average Depth in m (Average_De).** This estimate is based on well and seismic data where available, or gravity measurements where seismic and well data is sparse (a majority of the interior basins.) The average depth of the basin is equivalent to average thickness where water depths or elevations are small, and are estimated from Kirschner, 1988. Values are in meters.

7) **Basin_Age**. Predominate age (by Era) of sediments in basin (Sherwood, 1988 and Kirschner, 1988.) This attribute did not directly impact any estimates of storage potential.

8) **Porosity and Permeability (Porosity).** Direct porosity measurements are sparse to nonexistent in most Alaska basins. This qualitative attribute (values of unlikely, possible, and proven) was estimated from well data where available, and geologic field work and published maps and literature where well data was not available. This attribute is highly generalized, and is assumed to tie directly to permeability and reservoir quality where no other direct measurements exist.

9) **Oil and Gas Production (Oil_and_Ga).** Identifies those basins where production of oil and gas resources has occurred. Considering the similarity in fluid properties between light oil and supercritical CO_2, and between natural gas and gaseous CO_2, seals and traps suitable for hydrocarbons are deemed likely suitable for CO_2 storage as well. Hydrocarbon production is considered proof of porosity, permeability, reservoir, seal and trap. (Whereas trap is not a factor in the DOE estimates of saline reservoir storage capacity, it is likely that the presence of a trap could lower the risk of eventual leakage.)

10) **Map Unit**. Basins are categorized as either undifferentiated sedimentary or flysch (Kirschner, 1988.) Alaskan flysch basins are mostly Mesozoic, typically lightly to pervasively metamorphosed and deformed, and individual sand and shale layers are typically thin with very poor reservoir quality. Undifferentiated sedimentary basins contain a wide variety of largely non-marine clastic rock types with a variety of reservoir and seal characteristics.

11) **Seismic Risk (Seismicity).** A qualitative estimate (high, medium, low) of seismic risk based on USGS Seismic Hazard Maps for Alaska (Wesson, et al., 2007). Hazard maps (Figure 4) were constructed using historic earthquake activity, paleoseismic information, and current understanding of earthquake potential. A higher seismic risk could be linked to a higher risk of leakage of stored CO_2 where seismic activity might open up fault conduits, or adversely impact seal capacity. However, high earthquake risk is not always indicative of high leakage risk, as is evident in the Cook Inlet where natural gas accumulations indicate that numerous seals have not been breached, even though there continues to be strong and frequent seismic activity in the area.

12) **Distance from infrastructure (Distance_f).** Infrastructure includes CO_2 sources, primary roads and pipelines. This is a qualitative measure of how far, and how expensive, it would be to transport captured CO_2 to the storage site. Attribute values are near, far, and offshore. At this time, logistical

hurdles related to using any offshore basin for the storage of CO_2 are huge, especially when ice is a factor. Figure 2 illustrates that many of the sedimentary basins in Alaska are either located offshore or very far from CO_2 sources and infrastructure.

13) **Reservoir and Seal Potential (Reservoir_)** – A qualitative attribute, based on the best well and seismic data available, of both reservoir and seal potential is shown in Figure 5. A value will be assigned (Good, Fair-Good, Limited, or Poor) if the basin has at least one well. This is highly generalized, as in all but productive hydrocarbon basins, the well control is completely insufficient to describe the reservoir and seal characteristics for the entire basin. With that caveat, this attribute is an attempt to illustrate whether a particular basin could have significant amounts of CO_2 storage capacity, independent of economic or logistical considerations.

14) **Sequestration Potential (Sequestrat)** – A qualitative attribute based on the other attributes, and shown in Figure 6. Values are High, Moderately High, Moderately Low, Low, None, Less than 1 km, and Offshore/Inaccessible. This attribute is further described in Section 2.2.2.

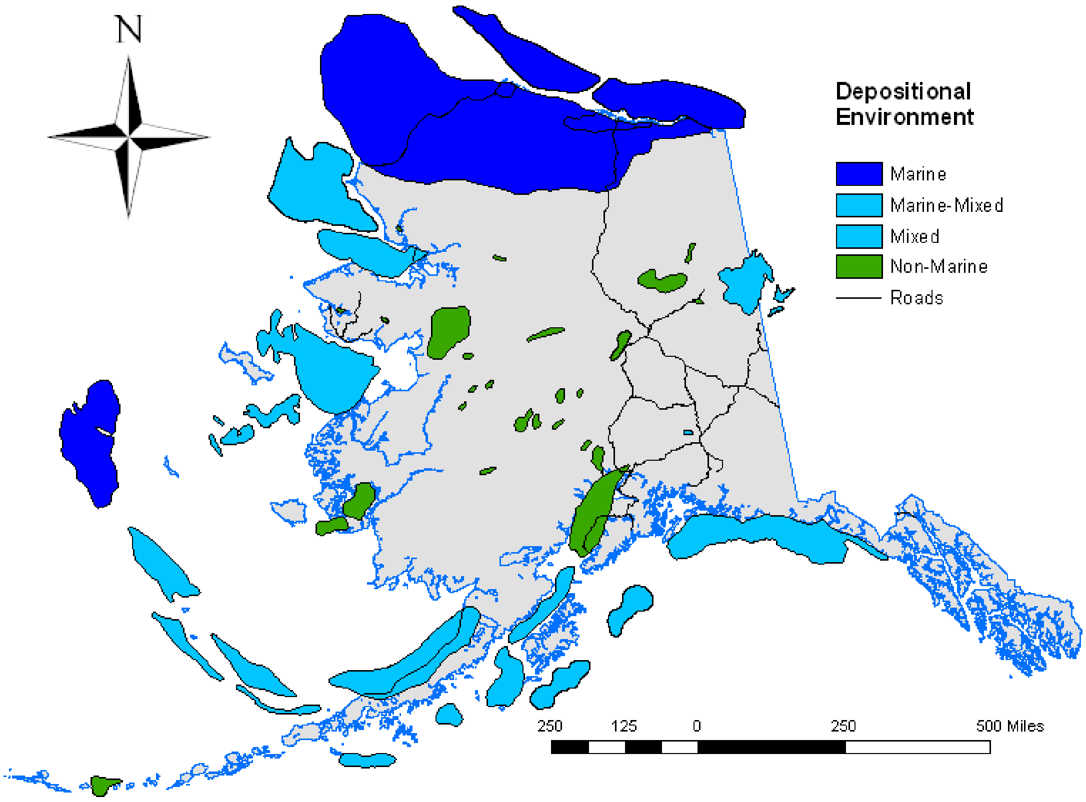

Figure 3: Alaska sedimentary basin "Depositional_Environment" attribute. Those basins deposited in non-marine or mixed environments are likely to have deeper than usual non-saline waters.

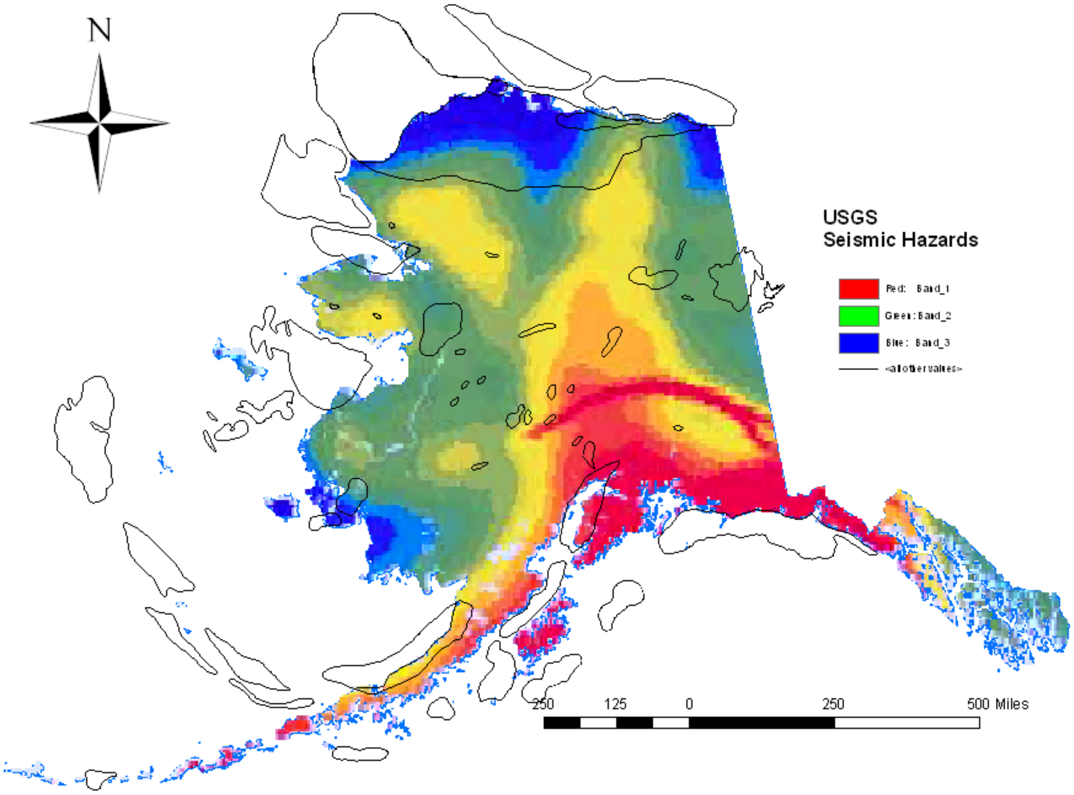

Figure 4: USGS Seismic hazards map with basin outlines. (From Wesson, et.al. 2007, Revision of time-Independent probabilistic seismic hazard maps for Alaska)

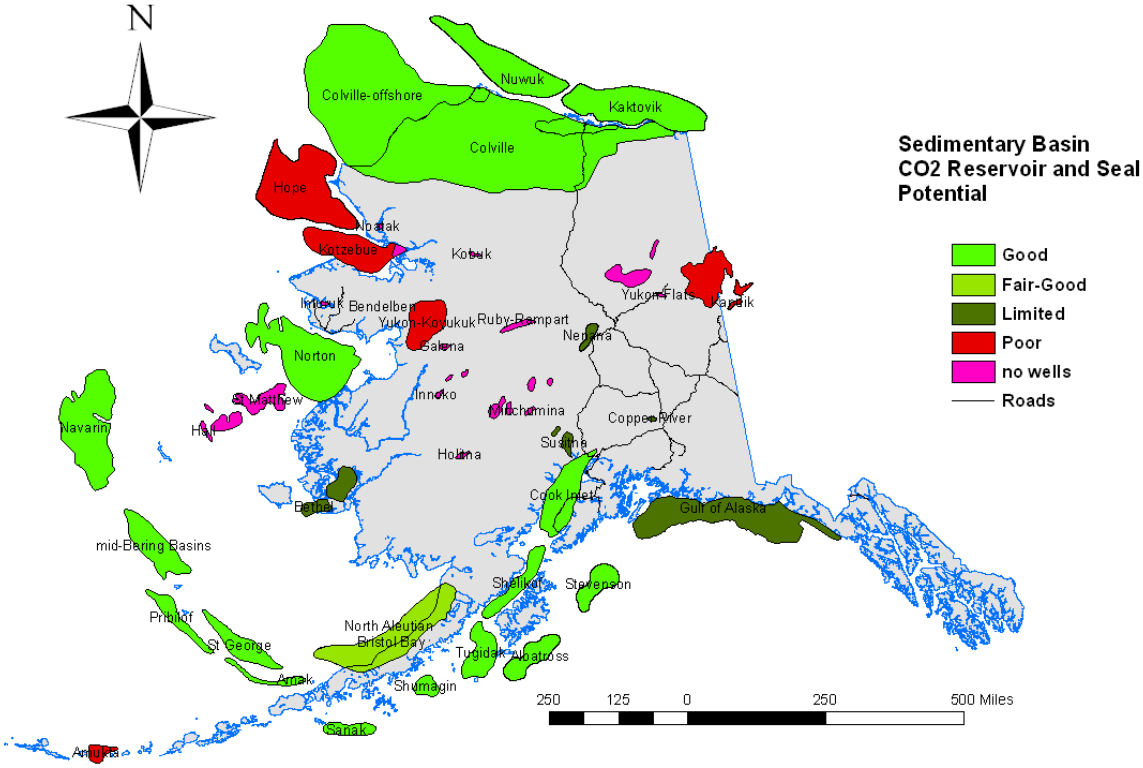

Figure 5: Alaska sedimentary basin “Reservoir_ Seal_Potential” attribute.

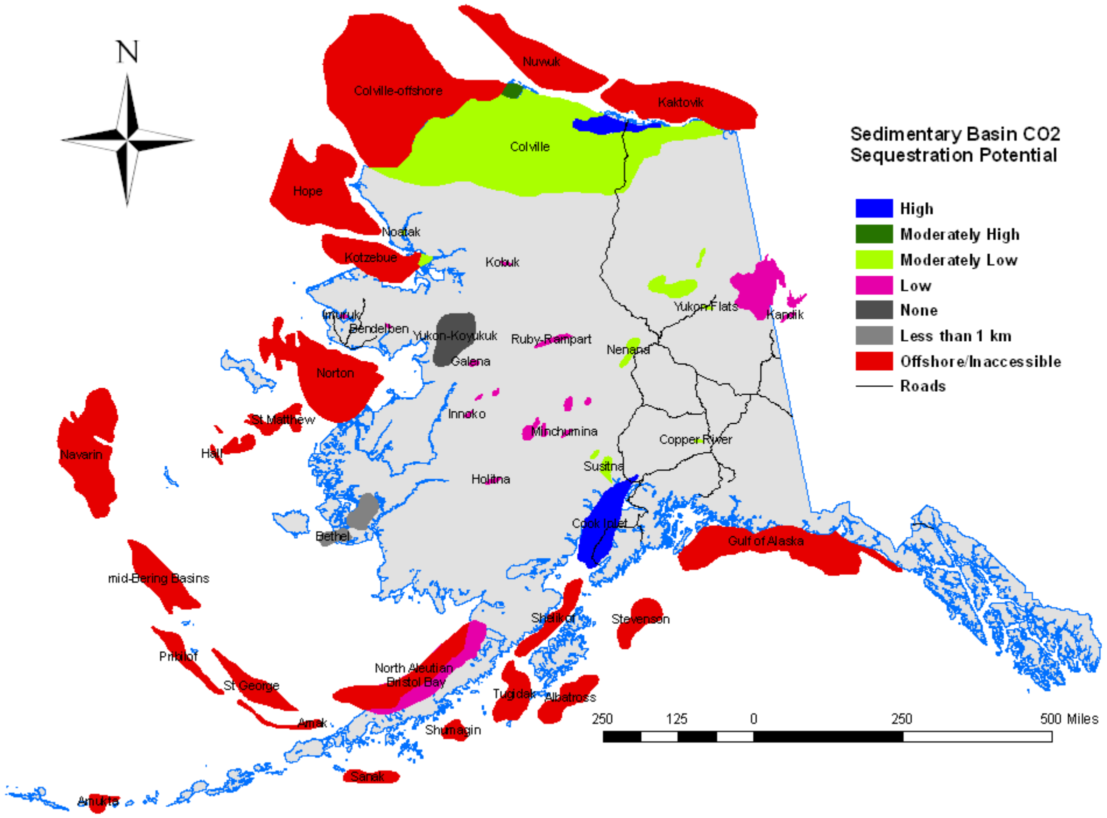

Figure 6: Alaska sedimentary basin storage potential GIS shape file, illustrating the "Sequestration_Potential" attribute, which incorporates logistical and economic factors such as lack of infrastructure, scarce knowledge of reservoir and seal, and challenges in working in an offshore environment

2.2.2 Saline Basin Sequestration Potential Attribute

Sequestration Potential, as shown in Figure 6, is a qualitative estimate of the likelihood a particular basin will be suitable for geologic sequestration of CO_2, and is based on the analysis of the other attributes as described in Section 2.2.1. Factors that most impacted the ranking were:

1) Degree of uncertainty on the presence of reservoir, seal and trap. This follows from the kinds and types of data available to describe a basin. The attributes describing the number of exploration wells and amount of seismic data were key in determining the degree of uncertainty. For the many basins defined primarily on gravity data (little or no well or seismic data collected), the degree of uncertainty is very high. If the knowledge of reservoir, seal or trap is very low this leads to a sequestration potential categorization of 'Low'.

2) Hydrocarbon exploration activity. If wells are being drilled or planned in a basin, the sequestration potential is rated higher, as oil and/or gas exploration success would provide both a confirmation of reservoir, seal and trap as well as improvements to infrastructure. For those basins with current exploration interest, further exploration with well log and seismic data will increase the knowledge

base leading to higher ranking of potential, , i.e.. For the Nenana, Yukon Flats, and much of the Colville basin the sequestration potentials were raised from 'Low' to 'Moderately Low' based on exploration interest.

3) Distance from infrastructure. Many basins are far from CO_2 sources and the road system (Figure 2). Offshore basins (with the exception of the Cook Inlet Basin) are categorized as 'Offshore/Inaccessible' to reflect that working offshore in harsh weather environments and ice coverage is currently not economically feasible. However, oil or gas exploration success in one of those basins could also prove up sequestration potential for CO_2 emissions generated as part of oil and/or gas production operations.

4) Hydrocarbon production. Current evidence of hydrocarbon accumulations is weighted heavily. For example, the Cook Inlet Basin is categorized as 'High' sequestration potential, in spite of the fact that it is also in the highest category of seismic risk. The trapped hydrocarbons are proof that the high current seismicity does not impact the sealing capacity for reservoirs in this basin.

2.3 Coal Seam CO_2 Storage Potential

Alaska has enormous deposits of coal, with hypothetical coal resources estimated to be in excess of 5 trillion metric tons (5.5 trillion short tons). The map of Alaska's coal resources by Merritt and Hawley, 1986 was utilized as the base to define the numerous coal basins screened for determining CO_2 coal seam storage potential. This map divides coal-bearing basins into a loose hierarchy of "coal provinces", "subprovinces", "coal fields," and "coal districts." This study only considered nineteen onshore coal-bearing sedimentary basins, shown on Figure 7 (areas 1-19), and did not evaluate the numerous small "single-point" coal occurrences delineated on the 1986 Merritt and Hawley map. These single-point coal occurrences lack subsurface data that provides any information on the presence or thickness of any deep coals. With the exception of the Cook Inlet Basin, the apparent offshore counterparts to onshore coal basins were reviewed but due to the absence of sufficient drill hole data, the offshore coal is very poorly delineated. Several coal-bearing basins were further subdivided into A, B and C. The coal basins reviewed are:

1. Northern Alaska Province: A–Arctic Foothills Subprovince, B–Arctic Coastal Plain Subprovince, C–Sagavanirktok coal field;
2. Nenana Basin and A and B;
3. Cook Inlet Basin, A–Southern, B–Susitna Basin, C–Matanuska Field;
4. Lisburne Field;
5. Seward Peninsula Province;
6. Kobuk Basin;
7. Upper Koyukuk Basin;
8. Yukon Flats basin;
9. Lower Koyukuk Basin;
10. Rampart Field;
11. Middle Tanana Basin;
12. Eagle-Circle field;

13. Nelson Island District;
14. Minchumina Basin-Little Tonzona Field;
15. Broad Pass Field;
16. Copper River Field;
17. North Aleutian Basin–A. Herendeen Bay Field, B–Chignik Field, C–Ugashik District;
18. Bering River Field;
19. Southeast Alaska, A–Angoon District, B–Admiralty District, and C–Kuiu District.

The screening process involved examining the coal seam CO_2 storage attributes (described below in section 2.3.1) for each of the 19 coal areas. The coal areas were then placed into six categories of potential for coal seam CO_2 storage (shown in Figure 7), High, Moderately High, Moderately Low, Low, Insufficient Data, and None.

After reviewing publically-available geologic and coal resource data for these 19 coal areas, only the Northern Alaska Province (area 1), the Nenana Basin (area 2) and the Cook Inlet Basin (area 3) have sufficient and reliable subsurface and coal quality data to make reasonable estimates of CO_2 coal seam storage capacity and are in proximity to existing or potential future infrastructure. These areas have also demonstrated coalbed methane potential from both published reports and unpublished information. The North Aleutian Basin (area 17), including the Herendeen Bay, Chignik and Ugashik fields, may have CO_2 potential, but it is considered low due to extensive faulting and lack of lateral continuity in the region (Tyler, et al., 2000). Particularly in the Chignik region, the coals are extensively folded and thrusted and structurally discontinuous (Smith, 1995). Even though there are anecdotal reports of methane from onshore underground mine adits in the Herendeen Bay (area 17A), there is no directly measured coalbed methane content data. Here, the subsurface volume of deep coals is unknown and the coals are likely structurally discontinuous.

Coal rank and ash content affect the capacity of a coal seam to hold gas, whether it is methane or CO_2. Coal has a higher adsorption affinity for CO_2 than for methane. The ratio of CO_2 adsorbed versus CH_4 desorbed at any given pressure is known as the storage ratio (Massarotto, et al., 2005). For higher rank medium to high volatile bituminous coals the storage ratio is about 2:1 at low to medium pressures, decreasing to some extent at higher pressures. As the coal rank decreases, the storage ratio for CO_2 increases, and has been measured for subbituminous coal between 7:1 and 10:1. For the lowest rank coals, lignite the ratio is as high as 13:1 (Burruss, 2002).

2.3.1 Coal Seam CO_2 Storage Attributes

Numerous geologic reports, coal studies and geologic maps were compiled, researched and reviewed to obtain the information necessary to revise the previous estimate of Alaska coal seam CO_2 storage capacity. Sixteen attributes (1-16 listed below) assigned to GIS shape files were selected for the process of screening coal "basins" for their CO_2 storage potential and to provide quantitative estimates for CO_2 coal seam storage capacity in the coal basins with sufficient data to permit a reasonable estimate. These attributes were selected after reviewing available literature deemed important to CO_2 coal seam storage capacity assessment. Attributes 17 and 18 provide information on the area (in meters^2) and the length (in meters) of the polygons. The following list show the attributes assigned to the GIS coal basin outline shape files shown in Figure 7.

1) **CoalBasin** – Coal Province/Basin/Field or District Name – Names and outlines from Merritt and Hawley, 1986 Special Report 37 map. Outlines are of coal basins, coal provinces or coal field and districts basins that contain coal. These outlines delineate the 19 coal basins evaluated.

2) **BasinAge** – Predominate age (by Era) of coal-bearing formation, Tertiary, Cretaceous or Mississippian (Kirschner, 1988; and Merritt and Hawley, 1986). Basin age is generally related to coal rank and structural complexity. The Cretaceous and Mississippian age coals tend to be higher in rank and have undergone greater tectonic stresses.

3) **DepoEnviro** – Coal depositional environment: fluvial, lacustrine, fluvial deltaic system. Certain coal-forming environments develop into coal deposits that are much more laterally continuous. Fluvial-related coals form in smaller, often truncated coal swamps. (Ahlbrandt , et al., 1979; Burke, 1965; Flores, et al., 2004; Merritt and Hawley, 1986; Reifenstuhl and Decker, 2008; and Wahrhaftig, et al., 1994).

4) **StructSet** – Structural setting of the basin or coal forming swamp if known (Kirschner, 1988; Merritt and Hawley, 1986; and Swenson, 1997). There exists a wide range of structural settings that range from simple depressions, to more complex grabens and transpressional foreland basins. For the older "precursor" Cretaceous basins, the structural setting is poorly understood. The structural setting is related to the tectonic forces that created the coal basin and subsequently affected the sediments in the depocenter. The older and especially more complex settings contain coals that are more highly deformed, and less suitable for CO_2 sequestration.

5) **Map_Unit** – Outlines of coal-bearing geologic map units, based on available and numerous geologic maps (Merritt and Hawley, 1986). The geologic maps can provide information on coal outcrops, strike and dip of beds and specific details on the outline of surface exposures of nonmarine coal-bearing rocks. The strike and dip of a coal-bearing unit provides information on the potential for subsurface coal at depth.

6) **Rank of coal** – Rank of coal, qualitative value based on published coal analyses. This is the main factor in determining CO_2 sequestration potential of an area (Merritt and Hawley, 1986; Flores, et al.2004; U.S. Geological Survey, National Coal Resources Data System, US Coal Quality Database; and unpublished data files). The rank of coal affects the CO_2 storage capacity of coal seams in two ways. Lower rank coals have greater storage ratios of CO_2 to methane. However, higher rank coals have greater capacity for cleating and thus have higher permeabilities than lower rank coals.

7) **NetCoalThk** – Net coal thickness in the stratigraphic section, where known. (Flores, et al., 2004; McGee, 1973; McGee and O'Connor, 1975; Merritt and Hawley, 1986; Roberts, 1991; Roberts, et al., 1992; Wahrhaftig, 1973; and Wahrhaftig, 1987). A greater net coal thickness in beds 1 feet or thicker equates to greater potential CO_2 gas storage.

8) **CoalVolume** – Volume of coal (in short tons) in a particular coal basin or province if known for that specific area. (Flores, et al., 2005; McGee, 1973; McGee and O'Connor, 1975; Merritt and Hawley, 1986; Roberts, 1991; Roberts, et al., 1992; Wahrhaftig, 1973; and Wahrhaftig, et al., 1994). .

9) **QualData** – Whether coal quality data exists for a particular polygon (Yes or No.) (Affolter, et al., 1994; Rao, 1980; U.S. Geological Survey, National Coal Resources Data System, US Coal Quality Database, and unpublished data). Coal quality is determined by analyzing coal for calorific value (or heat content), ash (the non-burnable portion), moisture, and sulfur. These factors affect the gas storage capacity of coals, higher ash coals has a lower gas storage potential than low ash coal.

10) **CBM_Data** – If CBM data is published or available for a particular coal basin, province field. (Bailey, 2007; Clark, et al., 2009; Flores, et al., 2004; Montgomery and Barker, 2003; ,Roberts, et al., 2006; Smith, 1995; Thomas, et al., 2004; and Tyler, et al., 2000). Where data is published or available, volume is reported in standard cubic feet per ton (sfc).

11) **CO2_Stor** – CO_2 storage capacity in Gt derived in this study and based on data resulting from numerous sources and methodology provided in Brennan and Burruss, 2003; Clarkson and Bustin, 1997; Reeves, 2001; Roberts, et al., 2008; Stanton, et al., 2001; Stanton, et al., 2002; Stevens and Moodhe, 2009; and Stricker and Flores, 2003.

12) **CoalPerm** – Published data on permeabilities of coal bearing units in millidarcies. Permeabilities can only be determined by pressure testing a seam which has only been reported and published for only two sites in Alaska. Unfortunately, coal permeabilities could not be determined empirically from coal quality data because there are too many undefined variables in the existing data for Alaska coal. The permeability of a coal seam depends upon a number of factors including ash content, mineral inclusions, fractures, maceral types, and confining coal seam pressure. Both maceral type (determined through coal petrography, and this data is lacking) and confining coal seam pressure are unknowns for most coal deposits in Alaska. (Clarkson and Bustin, 1997 and Dawson and Esterle, 2009)

13) **InfraStruc** – Infrastructure within or adjacent to coal basin, field or district. Roads, pipeline, rail, marine.

14) **Permafrost** – Type of permafrost extent in coal basin, field or district. (Ferrians, 1965 and Jorgenson, et al. , 2008). Permafrost is frozen soil or rock, at or below 0 °C and is classified as continuous, discontinuous, sporadic, or isolated zones. In the continuous zones, permafrost occupies the entire area (except below large rivers and lakes), notably present in the northern half of Alaska. On the North Slope, depths to the base of the permafrost are as great as 660 meters in the Prudhoe Bay region. In the discontinuous zone, 50% to 90% of the surface is underlain by permafrost with depths to the base of the permafrost highly variable but as great as 119 meters in the northern Yukon Flats basin. In sporadic

permafrost zones, the percentage of the surface underlain by permafrost is less than 50% with depths to the base of the permafrost as great as 184 meters in the lower Kuskokwim River area in southwest Alaska. The isolated zone of permafrost contains patches of permafrost, with depths to 53 meters (Jorgensen, et al., 2008). The presence of permafrost impacts the storage of CO_2 in coal seams that are frozen by clogging the pores and fractures with ice crystals. Gas storage in coal seams in areas of thick permafrost must occur below the base of the permafrost.

15) **PFrostDepth** – Depth to base of permafrost based on contours derived from oil and gas exploration wells (North Slope) and boreholes in Interior Alaska and Seward Peninsula. (Collett, et al., 1989; Deo, 2008; Ferrians, 1965; Jorgenson, et al., 2008; Osterkamp and Payne, 1981).

16) **CO2_Poten** – Potential for CO_2 sequestration based on depth of coals and permafrost (Bachu, 2003; Flores, et al., 2004; Gunter, et al., 2004; Roberts, et al., 2006; and Stevens and Moodhe, 2009). Areas are ranked High, Moderately High, Moderately Low, Low or Insufficient Data. Areas of Insufficient data lack information to make a reasonable estimate of CO_2 storage capacity. Areas of Low potential have potentially thick coal seams, but their subsurface presence and extent is unknown. The Moderately Low area in the Brooks Range foothills contains thickest coals at shallow depths within the zone of continuous permafrost. The Moderately High area contains known CBM resources at the far western end and coals beneath the permafrost zone, however a large portion of the coal resources are based on hypothetical estimates. The High areas have proven CBM resources and are close to sources of CO_2 generation from Oil and gas combustion and gas, coal and diesel electrical power generation.

17) **Shape_Area** – Area of polygon in meters squared.

18) **Shape_Length** –Length of polygon in meters.

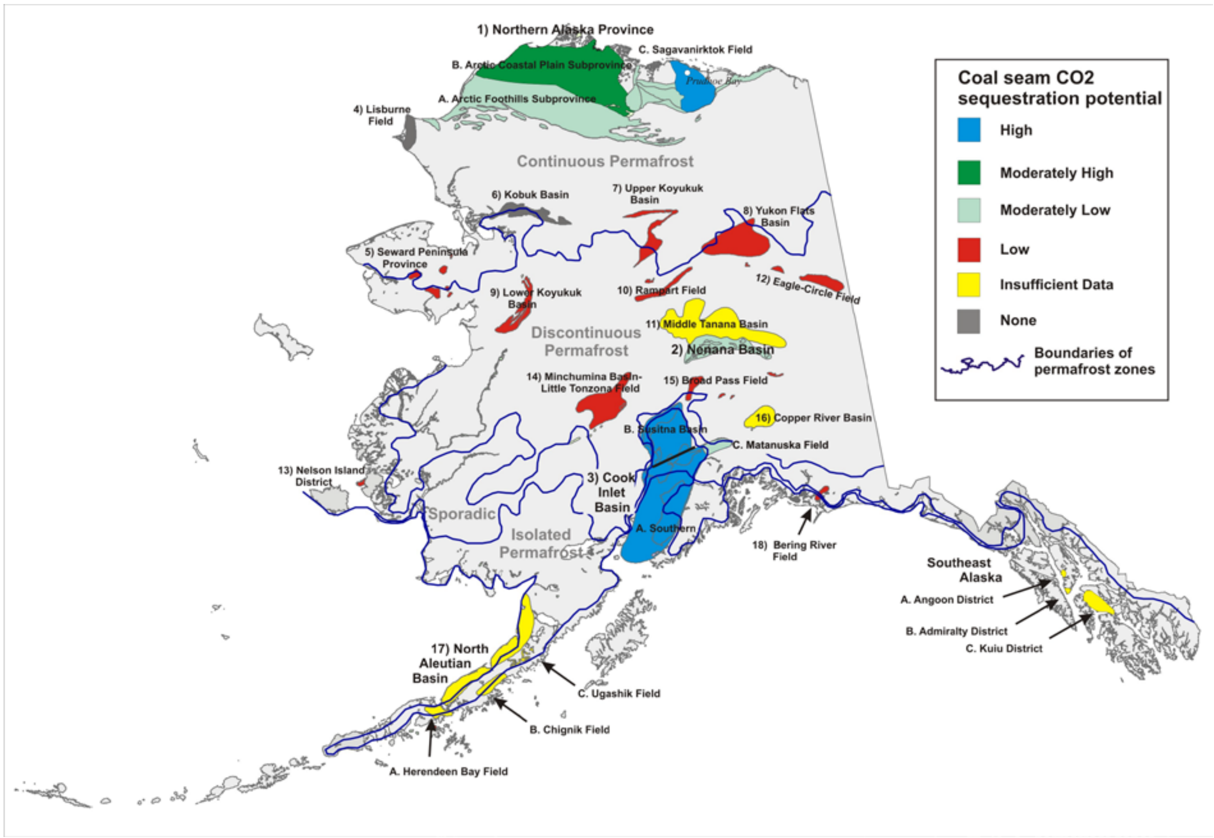

Figure 7: Alaska coal basin storage potential GIS shape file, illustrating the qualitative sequestration potential (CO2_Poten) attribute

3.0 Conclusions and Discussion

3.1 Saline Basin Sequestration Conclusions and Discussion

Using established DOE methodologies, huge potential volumes for CO_2, estimated at 16,700 Gt, have been reported for saline basins on the North Slope and offshore Alaska (Stevens and Moodhe, 2009). When these volumes are further constrained with additional geological and logistical variables, estimates will decrease dramatically (by at least a factor of 10.) The most significant factors are:

a) Logistical hurdles in transporting and working offshore in harsh, often ice covered, environments make it unlikely that offshore basins, over 11,000 Gt of initial estimated storage capacity, will be a resource in the foreseeable future.
b) Prohibitive costs to transport CO_2 long distances between remote basins and infrastructure (including roads) and CO_2 sources, and
c) Insufficient knowledge of porosity, permeability, and seal in the basins to ensure that CO_2 could be injected, and once injected, would not leak.

Additional factors that would diminish, but not necessarily eliminate a basin's sequestration potential, are:

a) Depth of 'fresh' water likely to be deeper than usual in basins deposited in non-marine environments
b) Interaction between faulting, seal capacity and tectonic activity in the next 100-1000 years.

Of more significance, while actual storage potential could be at least an order of magnitude lower than initial estimates made without logistical and additional geologic constraints, the known areas of "high" potential shown in Figure 6 are still likely to provide more than enough storage space for all the CO_2 available for capture in Alaska at current and projected CO_2 emission volumes. Pore space will not be the limiting factor in the successful implementation of CCS in Alaska, it will be the economics of capture and transport. The high storage potential that exists in the proven oil and gas basins on the North Slope and the Cook Inlet (in enhanced hydrocarbon recovery, in depleted fields, and in saline reservoirs near, above and below hydrocarbon reservoirs) needs to be further delineated in order to maximize the potential of geologic sequestration in Alaska. [Preliminary studies show that there is significant potential for EOR in Alaska oil and gas basins (ARI, 2005; Patil, 2006, and Patil, 2008).] Detailed studies are needed to further delineate the sequestration potential in:

a) Enhanced oil recovery in the existing North Slope oil fields
b) Enhanced oil recovery in Cook Inlet oil fields
c) Depleted oil and gas fields
d) Saline reservoirs already delineated in and around the existing North Slope and Cook Inlet fields, and
e) Undiscovered saline reservoirs, using the USGS reserves estimation methodology

It is important to obtain realistic estimates for storage potential in Alaska's saline basins. That information, along with significantly improved economics for CO_2 capture, transport, injection, and long-term monitoring, and the establishment of laws and regulations for CO_2 storage, will maximize the chances of effective implementation of CCS technology in Alaska.

3.2 Coal Seam CO_2 Sequestration Conclusions and Discussion

A preliminary published estimate of Alaska CO_2 coal seam storage capacity for the WESTCARB project, based on an estimate of 776 Tcf CBM resources, was 84 Gt (Stevens and Bank, 2007). This estimate was subsequently revised to 120 Gt of CO_2 storage capacity (Stevens and Moodhe, 2009). These studies further noted that it was likely that only a portion of their estimate would be "considered favorable for CO_2 sequestration, due to permeability, seam geometry, surface access, faulting, and other site-specific but currently unknown conditions" (Stevens and Bank, 2007, p. 1). This report addresses those aspects, as well as revised estimates of North Slope CBM resources detailed in Roberts, et al., 2008, improved estimates of thickness of permafrost on the North Slope (Deo, 2008), and distance from sources of anthropogenic CO_2. For both distance from infrastructure and lack of data, we excluded the offshore areas of Alaska, where, with the exception of Cook Inlet, subsurface data on coal seams is lacking and reliable estimates of coal volume is not possible. The Northern Alaska Province (area 1 on Figure 7), the Nenana Basin (area 2 on Figure 7), and the Cook Inlet Basin (area 3 on Figure 7) have a combined deep, unmineable coal seam CO_2 sequestration of 49.24 Gt based on our study of available data (Table 1).

Our revised estimate of CO_2 storage potential is based largely on the 2006 and 2008 assessment of North Slope by Roberts, et al., 2008. Their study took into consideration the thick continuous permafrost extant throughout the North Slope region. Roberts, et al., 2008, concluded that coalbed methane production from within the permafrost would be very unlikely due to lack of permeability in frozen coal seams. This removed a significant portion of the coal seams from consideration, resulting in about only about 6% of the storage potential reported by Stevens and Moodhe, 2009. This permanently frozen coal is not suitable for CO_2 sequestration under current technology. Additionally, we utilized revised estimates of the depth to base of permafrost determined from exploration revisions of well bottom hole temperatures by Deo, 2008. Finally, we utilized CO_2:CH_4 storage ratios based on varying coal rank, as outlined in Burruss, 2002 and Massarratto, et al., 2005 to determine our revised estimate of CO_2 storage potential in Alaska coal seams presented in column 8 of Table 1. Unfortunately, we found throughout the literature compilation process that details on coal cleating and fracture density, along with coal seam porosity is totally lacking in the available literature. Until the advent of coalbed methane exploration, these details were not considered important parameters of data to collect and analyze. Availability of this data would enable further refinement of the CO_2 coal seam storage potential for Alaska.

Estimates of CO_2 sequestration potential in Alaska can be improved through laboratory measurements of CO_2 adsorption and permeability of coal cores collected from exploration wells that penetrate deep coal seams.

(1) REGION	(2) IDENTIFIED & HYPOTHETICAL COAL RESOURCES (billions of short tons)	(3) AVERAGE COAL RANK	(4) ARI Estimated CBM Resources (based on daf) (Tcf)	(5) ARI Estimated CO2 Storage Potential		(6) USGS Estimated CBM Resources* (Tcf)	(7) CO2 Storage Potential based on USGS CBM Resources*		(8) REVISED ESTIMATE OF COAL SEAM CO2 STORAGE POTENTIAL (this report) (Gt)
				(Tcf)	(Gt)		(Tcf)	(Gt)	
1) Northern Alaska Province	3,753.00		621	1,862	98	17.2	120.4	6.32	5.83
A. Arctic Foothills Subprovince	1,290.00	Bituminous	No Data	Not Subdivided					
B. Arctic Coastal Plain Subprovince	1,910.00	Subbituminous				15	105	5.53	5.08
C. Sagavanirktok Field	553.00	Subbituminous				2.2	15.4	0.79	0.75
Total North Slope	**3,753.00**		**621**	**1,862**	**98**	**17.2**	**120.4**	**6.32**	**5.83**
2) Nenana Basin	17.00	Lignite to subbituminous	1	3	0	1	10	0.52	0.41
3) Cook Inlet Basin. Includes A. Southern, B. Susitina and C. Matanuska resources	1,570.30	Subbituminous to anthracite	136	407	21	140	980	50.58	43.00
TOTAL ALL "BASINS"	**5,340.30**		**758.00**	**2,273**	**120.00**	**158.20**	**1,110**	**57.32**	**49.24**

*North Slope based on Roberts et al., 2008

Table 1. Summary table of estimates of deep coal seam CO_2 storage potential in Gigatons (Gt) based on attributes evaluated in this report (column 8). Coal resource estimates (column 2) and average coal rank (column 3) compiled from Merritt and Hawley, 1986 and Flores, et al., 2004. ARI estimated CBM resources based on dry ash free coal (column 4) and estimated CO_2 storage potential (column 5) from Stevens and Moodhe, 2009. USGS estimated CBM resources (column 6) from Flores, et al., 2004; Montgomery and Barker, 2003; Roberts, et al., 2006; and Roberts, et al., 2008. Column 7, CO_2 storage potential was determined during the course of this study and is based on the 2008 assessment of North Slope recoverable CBM.

3.2.1 Northern Alaska Province Coal Seam CO_2 Storage Potential

The Northern Alaska Province, comprised of the Arctic Foothills subprovince, Arctic Coastal Plain Subprovince and the Sagavanirktok Field is underlain by the Lower to Upper Cretaceous-age fluvial-deltaic Nanushuk Formation and the Tertiary-age Sagavanirktok Formation. Coal rank ranges from lignite A to high-volatile A bituminous, with a mean rank of high-volatile C bituminous. These coals are within the optimum rank for thermogenic coalbed methane generation (and hence CO_2 storage potential) and cleating has been demonstrated in both coal cores from exploration wells and in outcrop.

Initial estimates of the coalbed methane potential for this region were as high as 800 Tcf. However, a recent detailed evaluation by Roberts, et al., 2008 based on the Total Petroleum System concept indicated a coalbed methane potential of 17.2 Tcf (mean value).

Permafrost zones underlie 80% of Alaska, and include continuous (32%), discontinuous (31%), sporadic (8%), and isolated (10%) permafrost (Jorgenson, et al., 2008). The Northern Alaska Province lies entirely within the continuous permafrost region, where depths to the base of the permafrost are as great as 660 m in the vicinity of Prudhoe Bay to 20 m or less near the base of the Brooks Range. Of all of the factors influencing storage of CO_2 in deep, unmineable coal seams, the presence of a thick permafrost cap has the greatest impact in reducing potential storage capacity. A permanently frozen coal reservoir detrimentally blocks permeability pathways due to incipient ice-filled cleat fracture system. Therefore, the CO_2 storage capacity of the Northern Alaska province is significantly reduced in areas of currently deep permafrost conditions.

It should be noted that studies are underway to examine the potential for creating carbon dioxide-hydrates in these environments as a stable gas hydrate to be sequestered in various reservoir geological formations (see Uddin, et al., 2008). Whether this will be possible in deep frozen coal seams remains to be evaluated. Based largely on the presence of thick permafrost, the volume of available deep, unmineable coal seams for CO_2 sequestration is reduced to between about 6% of the available 98 Gt of CO_2 storage reported by Stevens and Moodhe, 2009. CO_2 storage capacity in the Northern Alaska Province is estimated to be 5.83 Gt (Table 1). Stevens and Moodhe, 2009 did not consider the vast and thick and continuous permafrost on the North Slope in their assessment of CO_2 coal seam storage potential. We reviewed the available data and found, like Roberts et al., 2008 that coal within a large portion of the Northern Alaska Province is within the permafrost zone. Where the coal is thickest, it is also shallowest in the western part of the basin and contained by permafrost (moderately low on Figure 7). In the deeper portion of the basin, the coals are either within the permafrost zone, or a great depth. Roberts, et al., 2008 took this into consideration in their evaluation of the CBM potential.

Unfortunately, while the Prudhoe Bay region has excellent access to infrastructure and large sources of CO_2, it also has the deepest permafrost zones in Alaska (up to 660 m thick). CO_2 sequestration potential in that area, the Sagavanirktok Field, is likely very small, on the order of 0.75 Gt.

3.2.2 Nenana Basin Coal Seam CO_2 Storage Potential

The Nenana Basin contains Tertiary-age coals ranging from lignite to subbituminous in rank. There is little available data on the coalbed methane content of these lower rank coals. Although lower rank coals are more favorable for CO_2 sequestration, having up to a 10:1 replacement for methane, they are higher in ash and poorly cleated and the total resources are small, compared to the Northern Alaska Province and the Cook Inlet Basin. The CO_2 storage potential in available coal seams in the Nenana Basin is estimated to be 0.41 Gt (Table 1). Although the volume of coal in the Nenana Basin is small, about 17 billion short tons, it has lower rank coals that have a potentially higher CO_2:CH_4 ratio, on the order of 10:1. Stevens and Moodhe, 2009 used a lower CO_2 to methane ratio of 3:1 in determining that CO_2 storage potential within coal seams in the Nenana Basin is nil. Recent oil and gas exploration in the deeper portion of the Nenana Basin indicates the presence of a fairly thick section of coal-bearing rocks[4] with the potential for CO_2 sequestration in an enhanced CBM production process. Should storage be found to be feasible in coals in the Nenana basin, they could provide storage for CO_2 captured in and near Fairbanks, including the existing coal-burning power plant in nearby Healy.

3.2.3 Cook Inlet Basin Coal Seam CO_2 Storage Potential

The Cook Inlet Basin contains extensive Tertiary-age coal resources in the Tyonek Formation at favorable depths for CO_2 sequestration. Coal rank ranges from subbituminous to high-volatile bituminous coal. Montgomery and Barker, 2003 indicated potential coalbed methane resources at 140 Tcf. We estimate the CO_2 sequestration potential in deep, unmineable coal seams to be 43.0 Gt (Table 1). This estimate includes both onshore and offshore Cook Inlet subsurface coal seams. Our estimate is higher than the 21 Gt reported by Stevens and Moodhe, 2009. We utilized a different CO_2:CH_4 coal storage ratio (approximately 7:1) and our review of available data resulted in a higher coal resource (1,570 billion short tons) than Stevens and Moodhe, 2009 who reported 1,292 billion short tons of coal.

Of the three coal-bearing basins evaluated, the Cook Inlet Basin has the greatest potential for near term CO_2 sequestration in deep, unmineable coal seams (43.0 Gt, Table 1). Infrastructure consisting of numerous roads and pipelines surrounds much of the northern and eastern portion of the basin, and it sits adjacent to major CO_2 emission sources. As oil and gas development moves westward across the Northern Alaska Province, this region is likely to become more prospective for injecting CO_2 emissions from oil and gas activities into deep coal seams.

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[4] Confidential communication

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CARBON DIOXIDE RESOURCE ASSESSMENT – OIL AND GAS FIELDS OF CALIFORNIA

Stephen D. Thomas

Golder Associates Inc.

DOE Contract No.: DE-FC26-05NT42593

Contract Period: October 1, 2005 - May 11, 2011

Golder Associates Inc.
2200 6th Avenue, Suite 600
Seattle, Washington 98101
Telephone: (206) 267 1166
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TECHNICAL MEMORANDUM

TO: Larry Myer, Ph.D. – CIEE
CC: Paul R. LaPointe, Ph.D.
FR: Stephen D. Thomas, C.HG.
RE: **CARBON DIOXIDE RESOURCE ASSESSMENT – OIL AND GAS FIELDS OF CALIFORNIA**

DATE: December 16, 2008
OUR REF: 063-1282.500

1.0 INTRODUCTION

WESTCARB (the West Coast Regional Carbon Sequestration Partnership) is one of seven research partnerships co-funded by the U.S. Department of Energy (DOE) to characterize regional carbon sequestration opportunities and to develop action plans for pilot-scale validation tests. WESTCARB is exploring opportunities in a six-state region (California, Oregon, Washington, Nevada, Arizona, and Alaska) for removing carbon dioxide (CO_2) from the atmosphere by enhancing natural processes and by capturing it at industrial facilities before it is emitted; both will help slow the atmospheric buildup of this greenhouse gas (GHG) and its associated climatic effects.

A key part of the project is identifying subsurface locations to store the captured CO_2; such sinks include deep geologic formations such as oil and gas reservoirs, and saline formations that are essentially leak-proof. These potential sinks will then be matched with the major CO_2 sources such as the main utilities and industrial emitters. In addition to identifying subsurface locations, an estimate of the total storage capacity of these locations needs to be made.

Golder Associates, Inc. (Golder) has been contracted to determine estimates for the storage capacity (or resource) of depleted and active onshore oil and gas reservoirs for the state of California. using historical production and current (2005) reserve data. Estimates were made on a field level and do not include State- or Federally-owned offshore fields. The following document provides the methodology used for capacity estimation and the results of the numerical analysis.

2.0 METHODOLOGY

2.1 Overview

The principles used to estimate CO_2 storage capacity of oil and gas reservoirs are outlined in publications prepared for the Department of Energy's National Energy Technology Laboratory (DOE, 2008). The fundamental assumption for estimating the storage resource is that the volume in the reservoir that was occupied by the produced hydrocarbons (oil or gas) becomes fully available for

CO_2 storage. Estimation also assumes that the CO_2 will be injected into the depleted oil and gas reservoirs until the reservoir pressure is brought back to the original reservoir pressure.

2.2 Previous Resource Estimates

In 2006, the California Department of Conservation (CDOC) developed estimates for onshore CO_2 resource storage potential using volumetric information for fields and basins. This involved calculating the volume of each field beneath a threshold depth, applying reservoir properties such as porosity) and assuming a subsurface CO_2 density of 700 kg/ m^3 (equivalent to an average depth of 800 meters). The results are summarized below:

TABLE 1

Summary of Oil and Gas Storage Estimates using Volumetric Methodology

Fields Group	**No. Fields**	**Storage capacity**	
		Millions of metric tons[(1)]	*Giga metric tons* [(2)]
Oil	176	3,563	3.56
Gas	128	1,666	1.67
Total		5,229	5.23

Notes: (1) – Mt; (2) – Gt.

2.3 Revised Methodology

2.3.1 Overview

A revised methodology was selected to perform the resource estimate calculations. This methodology is presented in the Dept. of Energy's Guidance Manual (August 2008; pages 9 through 12) and is based on using production and reserve records (rather than volumetric data). High and low estimates were made for both onshore oil and gas reservoirs in California on a field basis based on historical production and field pressure and temperature data obtained from the 2005 annual oil and gas report by the CDOC (CDOC, 2005). The sum of the estimates obtained from oil and gas data gave a total estimate for the CO_2 storage capacity in a given California field. Estimates were also obtained for each California basin by summing the estimates of the fields within each basin, and for the entire state of California. The specific methods for oil and gas and oil reservoir records are described in the following sections.

2.3.2 CO_2 Capacity Estimation of Oil Reservoir

The theoretical mass of CO_2 ($M_{CO2,t}$) that can be stored in an oil reservoir can be estimated from the historical volume of oil produced (V_{prod}) and the estimated volume of oil remaining in the reservoir ($V_{reserves}$) using the following equation:

$$M_{CO2,t} = \rho_{CO2,r} \frac{V_{prod} + V_{reserves}}{B_f}$$

where B_f is the volume formation factor of the reservoir and $\rho_{CO2,r}$ is the in situ density of carbon dioxide. Based on the gas law the mass can be expressed in terms of the pressure and temperature as follows:

$$M_{CO2,t} = \frac{\left(V_{prod} + V_{reserves}\right) \cdot P_r \cdot T_s \cdot Z_{CO2,s}}{B_f \cdot P_s \cdot T_r \cdot Z_{CO2,r}}$$

Since multiple pressures and temperatures were given for each field, a high mass estimate and low mass estimate was made for each field. High mass estimates were obtained assuming a volume formation factor of 1.2 and by applying the pool pressure and temperature that resulted in the highest mass when applied to the entire field. Low mass estimates were obtained by assuming a volume formation factor of 1.5 and applying the pool pressure and temperature that resulted in the lowest mass estimate when applied to the entire field.

2.3.3 CO_2 Capacity Estimation of Gas Reservoir

The theoretical mass of CO_2 ($M_{CO2,t}$) that can be stored in a gas reservoir can be estimated using the following equation:

$$M_{CO2,t} = V_{NR,r} \cdot \rho_{CO2,r}$$

where $V_{NG,r}$ is the volume of natural gas originally in the reservoir (i.e. the volume of the reservoir occupied by gas) and $\rho_{CO2,r}$ is the in situ density of carbon dioxide both of which are pressure (P) and temperature (T) dependent. By using the gas factor for natural gas (Z_{NG}) for both surface conditions (s) and reservoir conditions (r), the gas law (PV=ZnRT) can be used to estimate gas reservoir volume from gas surface volume, where the surface volume is the sum of the produced gas (V_{prod}) and the estimated reserves ($V_{reserves}$), with the following equation:

$$V_{NG,r} = \frac{\left(V_{prod} + V_{reserves}\right) \cdot P_s \cdot T_r \cdot Z_{NG,r}}{P_r \cdot T_s \cdot Z_{NG,s}}$$

The density of CO_2 at reservoir conditions can also be estimated using the gas law and the gas factor for CO_2 at both surface conditions and reservoir conditions with the following equation:

$$\rho_{CO2,r} = \rho_{CO2,s} \frac{P_r \cdot T_s \cdot Z_{CO2,s}}{P_s \cdot T_r \cdot Z_{CO2,r}}$$

Therefore, the mass of CO2 that can theoretical stored in the gas reservoir can be expressed as a function of the reservoir pressure and temperature as follows:

$$M_{CO2,t} = \left(V_{prod} + V_{reserves}\right) \frac{Z_{NG,r} \cdot Z_{CO2,s}}{Z_{NG,s} \cdot Z_{CO2,r}}$$

The gas factors for both natural gas and carbon dioxide are pressure and temperature dependent and were estimated for each reservoir using an Excel spread sheet used to estimate pressure, volume, and temperature properties of oil and gas (McMullan, 2007). Production volumes and reserve volumes were obtained for each field from data compiled in the 2005 annual oil and gas report by the California Department of Conservation (CDOC, 2005).

However, the data contained pressure and temperature data by pool (field subset) rather than by field. Therefore, each gas field contains multiple pressure and temperature data. Since multiple pressures and temperatures were given, a high mass estimate and low mass estimate was made for each field.

High mass estimates were obtained by applying the pool pressure and temperature that resulted in the highest mass when applied to the entire field, and low mass estimates were obtained by applying the pool pressure and temperature that resulted in the lowest mass estimate when applied to the entire field.

3.0 RESULTS

Table 2 summarizes the total oil and gas records obtained for 2005 by basin, and Figures 1 and 2 show the total oil and gas (produced and reserve) for each basin graphically. Three basins – the Central Valley, Los Angeles and Ventura – contribute 86 percent and 94 percent of the total oil and gas for the State, respectively.

Table 3 summarizes the low and high estimates for CO_2 resource potential for oil fields, gas fields and combined by basin using both produced and reserve capacities. The total resource estimates range from 0.31 Gt (low) to 1.17 Gt (high). The potential storage in oil fields contributes the majority of these total estimates (up to 99 percent). The largest potential is found in the Central Valley Basin (60 percent of the total for the high estimate) and Los Angeles (41 percent of the total for the low estimate).

• Low Estimate – from Oil Fields	0.30 Gt (metric tons x 10^9)
• High Estimate – from Oil Fields	1.16 Gt
• Low Estimate – from Gas Fields	0.003 Gt
• High Estimate – from Gas Fields	0.005 Gt
• Low Estimate – from Oil and Gas Fields	0.31 Gt
• High Estimate – from Oil and Gas Fields	1.17 Gt

The revised estimates are therefore significantly smaller than those developed using the volumetric approach by CDOC (see Table 1; Section 2.2). The new oil (high) estimate is approximately 33 percent of the original oil field volume, and the new gas (high) estimate is 0.3 percent of the original value.

4.0 REFERENCES

Bachu, S. 2008. Comparison between Methodologies Recommended for Estimation of CO_2 Storage Capacity in Geological Media by the CSLF Task Force on CO_2 Storage Capacity Estimation and the USDOE Capacity and Fairways Subgroup of the Regional Carbon Sequestration Partnerships Program, Phase III Report.

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McMullan, J. (2007). PVT Properties of Oil, Gas, and Water Add-in for Microsoft Excel. http://www.enrg.lsu.edu/pttc/pvt/

Attachments;

Tables

Figures

TABLES

TABLE 2

Summary of Oil and Gas Production and Reserves by Basin (2005)

Basin	**No. Fields**	**Oil Produced** ***(bbl x 10^9)***	**Oil Reserve** ***(bbl x 10^9)***	**Oil – Total** ***(bbl x 10^9)***	**Gas Produced** ***(Tcf)***	**Gas Reserve** ***(Tcf)***	**Gas – Total** ***(Tcf)***
Central Valley	276	13.64	2.26	15.90	22.28	2.08	24.36
Cuyama	9	0.72	0.04	0.76	0.572	0.02	0.59
Eel River	2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
La Honda	4	0.27	<0.01	0.28	0.31	0.01	0.32
Livermore	2	<0.01	<0.01	<0.01	0.12	<0.01	0.12
Los Angeles	70	5.73	0.19	5.92	6.26	0.11	6.37
Orinda	2	2.70	0.34	3.04	1.24	0.08	1.32
Salinas	11	0.12	0.01	0.13	0.01	0.01	0.02
Ventura	87	3.01	0.16	3.17	4.54	0.08	4.63
Totals	**463**	**26.2**	**3.00**	**29.2**	**35.32**	**2.40**	**37.7**

Note: bbl = barrels; Tcf = trillions of cubic feet
Source: CDOC, 2005

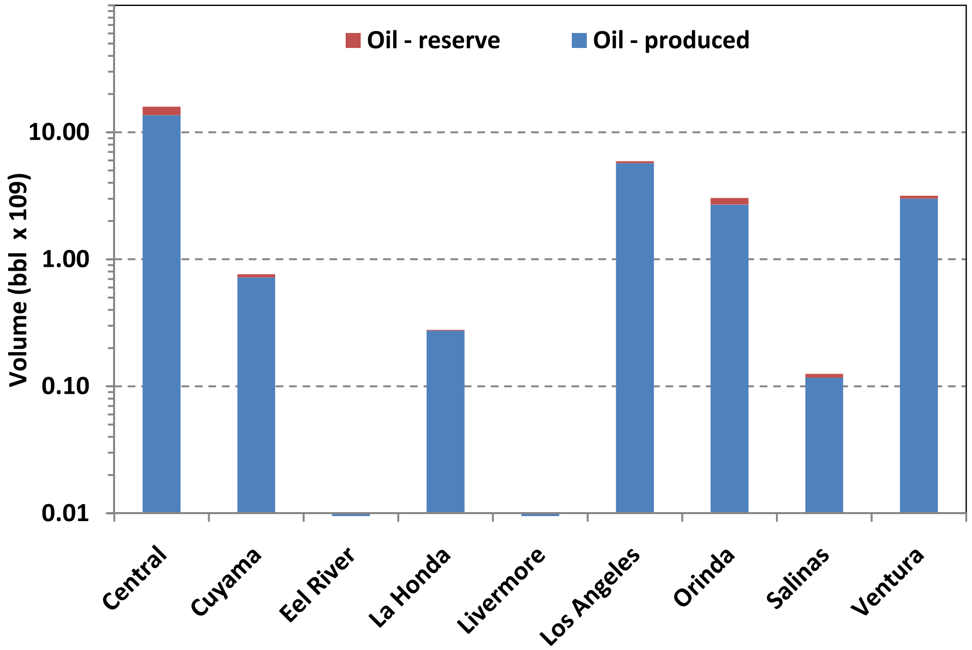
TABLE 3

Summary of Carbon Dioxide Resource Estimates by Basin

Basin	**No. Fields**	**Oil**		**Gas**		**Total**	
		Low Estimate	*High Estimate*	*Low Estimate*	*High Estimate*	*Low Estimate*	*High Estimate*
Central Valley	276	112,899.4	700,833.9	1,842.6	3,285.9	114,742.0	704,119.8
Cuyama	9	7,638.4	39,424.4	55.2	113.2	7,693.7	39,537.6
Eel River	2	<0.1	<0.1	18.1	18.1	18.1	18.1
La Honda	4	89.3	113.7	0.1	0.1	113.8	89.3
Livermore	2	78.0	169.0	28.0	35.0	105.9	204.1
Los Angeles	70	125,130.8	297,173.8	705.1	1,076.5	125,835.9	298,250.4
Orinda	2	0.1	0.6	0.1	0.1	0.2	0.7
Salinas	11	4,493.0	7,353.1	5.8	6.3	4,498.8	7,359.4
Ventura	87	54,455.2	115,640.2	380.7	643.8	54,835.9	116,274.9
Totals	**463**	**304,784**	**1,160,709**	**3,036**	**5,170**	**307,820**	**1,165,879**

Note: all units are millions of metric tons (Mt)

FIGURES



Source: CDOC, 2005

Golder Associates

TITLE

Reported Oil Produced and Reserve (2005) – By Basin

WESTCARB – Resource Estimates for Oil and Gas Fields in California

DRAWN	SDT	DATE	12/16/08	PROJECT No.	063-1282.500
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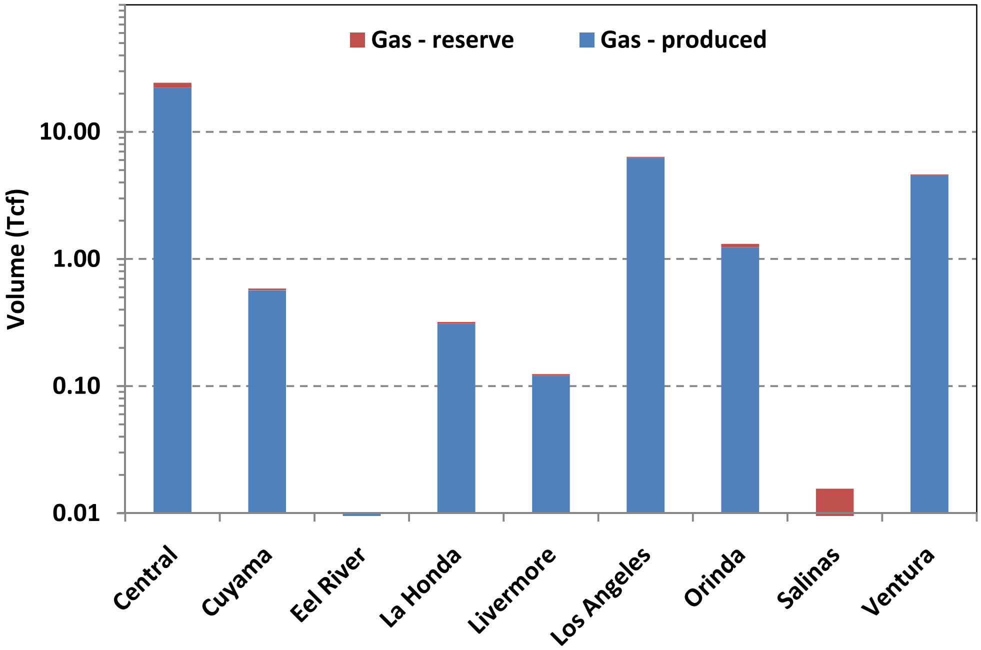

Source: CDOC, 2005

Golder Associates

TITLE

Reported Gas Produced and Reserve (2005) – By Basin

WESTCARB – Resource Estimates for Oil and Gas Fields in California

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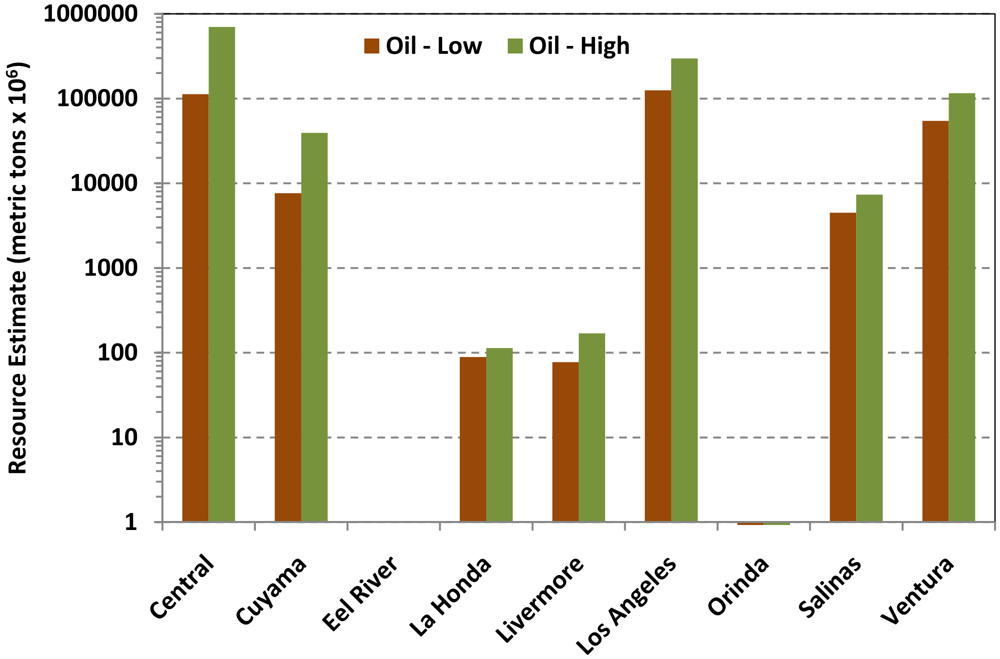

Golder Associates

TITLE
Estimated Resource Potential in Oil Fields – By Basin

WESTCARB – Resource Estimates for Oil and Gas Fields in California

DRAWN SDT	DATE 12/16/08	PROJECT No. 063-1282.500
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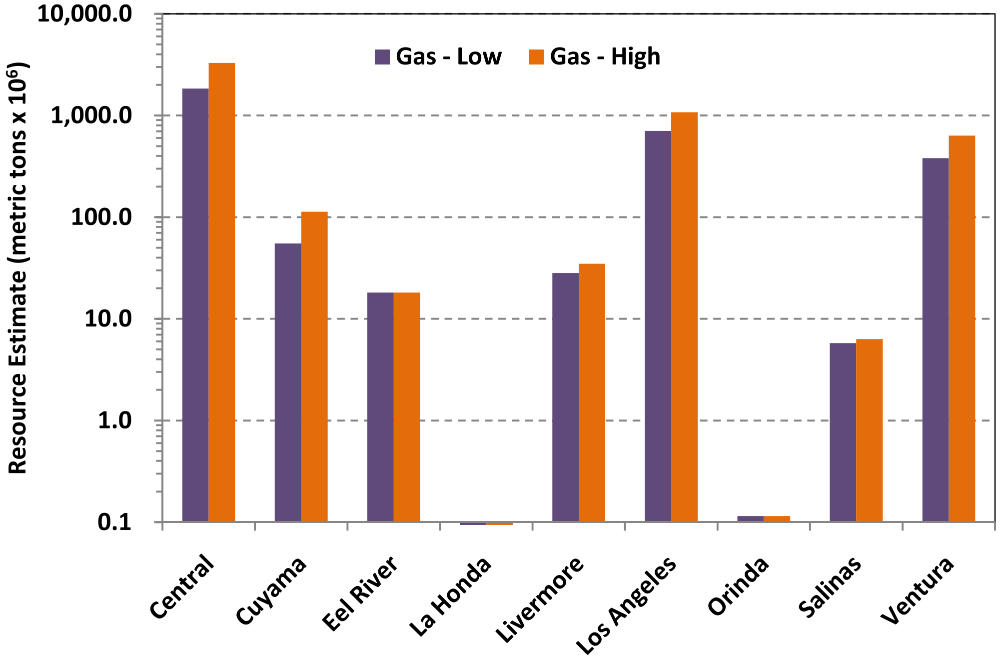

Golder Associates

TITLE
Estimated Resource Potential in Gas Fields – By Basin

WESTCARB – Resource Estimates for Oil and Gas Fields in California

DRAWN SDT	DATE 12/16/08	PROJECT No. 063-1204.500
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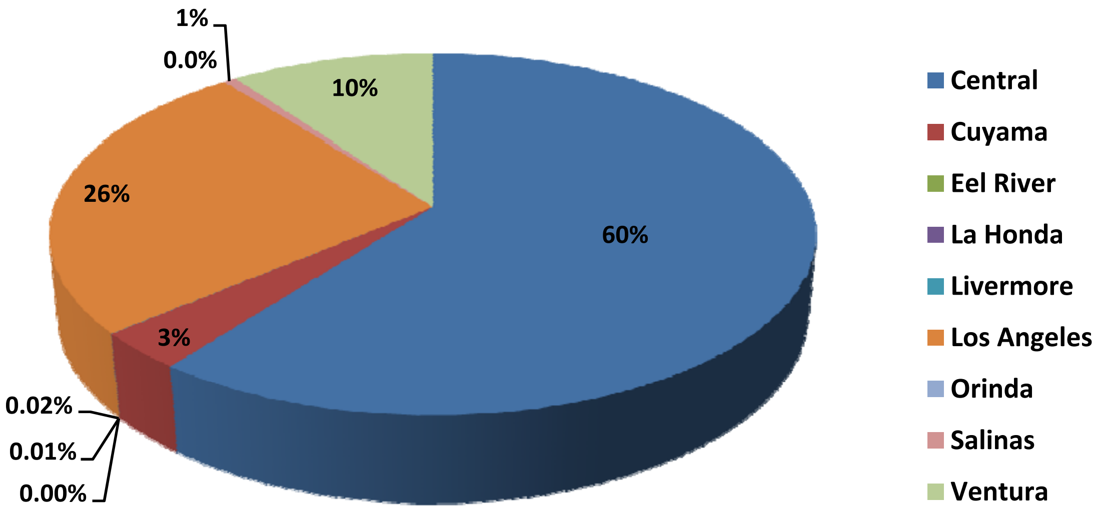

Golder Associates

TITLE
Total Oil and Gas Fields Resource Estimate – Low Estimate

WESTCARB – Resource Estimates for Oil and Gas Fields in California

DRAWN SDT	DATE 12/16/08	PROJECT No. 063-1282.500
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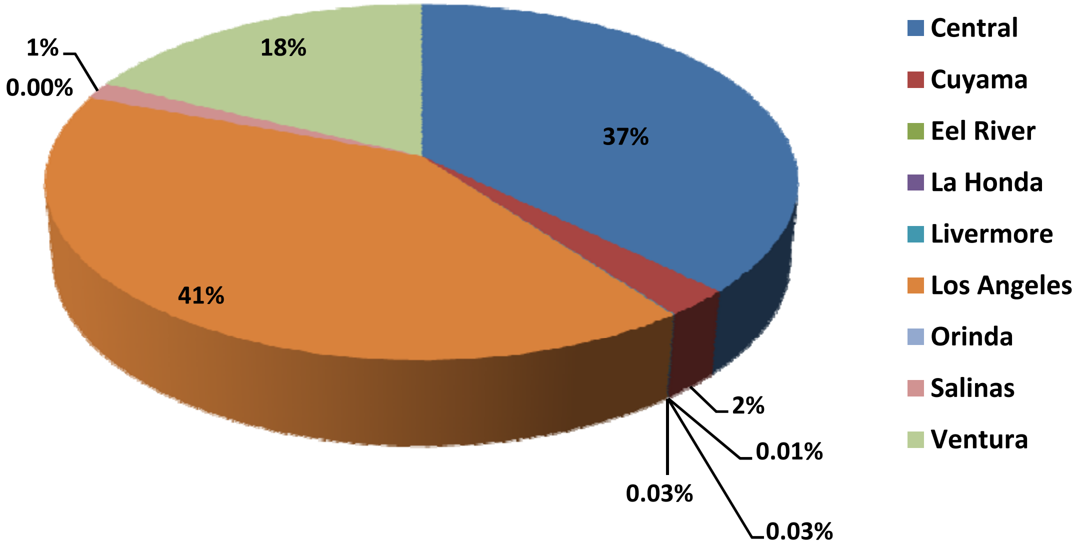

Golder Associates

TITLE
Total Oil and Gas Fields Resource Estimate – High Estimate

WESTCARB – Resource Estimates for Oil and Gas Fields in California

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REVIEWED PLP	FILE No. CA_O&G_figs.pptx	FIGURE No. 6

CORRECTIONS TO:

Carbon Dioxide Resource Assessment - Oil and Gas Fields of California (2009)[1]

Lorraine J. Hwang, Ph.D.
California Institute for Energy and Environment
January 2010

SUMMARY

Previous work completed by Thomas[1] to estimate the storage capacity of depleted and active onshore oil and gas reservoirs for the state of California misplaces the formation factor, B_f, in the denominator of the equation used to calculate the theoretical mass of carbon dioxide that can be stored in an oil reservoir. The correct form of the equation should be:

$$M_{CO2,t} = \rho_{CO2,r}\,(V_{prod} + V_{reserves})\,B_f$$

To correct for this error, their original estimates are multiplied through by the high and low formation factors to give the revised estimates:

$$M_{Revised\ (CO2,t)} = B_{f,low}\,B_{f,high}\,M_{CO2,t}$$

In addition, two typographic errors occur in the final form of their equations used to estimate $M_{CO2,t}$ for oil and gas. The surface density of $\rho_{CO2,s}$ was dropped from both the final equations on page 3. The final form should be for oil:

$$M_{CO2,t} = B_f\,\rho_{CO2,s}\,(V_{prod} + V_{reserves})\,\frac{(P_r T_s Z_{CO2,s})}{(P_s T_r Z_{CO2,r})}$$

For gas:

$$M_{CO2,t} = ⍰_{⍰⍰2,⍰}\,(⍰_{⍰⍰⍰⍰} + ⍰_{⍰⍰⍰⍰⍰⍰⍰⍰})\,\frac{(⍰_{⍰⍰,⍰}\,⍰_{⍰⍰2,⍰})}{(⍰_{⍰⍰,⍰}\,⍰_{⍰⍰2,⍰})}$$

Density is correctly applied in their original calculations.

Table 3 is corrected for both the errors in the oil calculation and errors in the original summation.

DERIVATION

The theoretical mass of carbon dioxide that can be stored in an oil or gas reservoir is given as:

$$M_{CO2,t} = \rho_{CO2,r}\,(V_{prod} + V_{reserves})\,B_f \qquad (1)$$

Where:

$M_{CO2,t}$ = theoretical Mass of CO_2
$\rho_{CO2,r}$ = density of CO_2 at reservoir pressure and temperature
V_{prod} = volume of oil produced (surface)
$V_{reserves}$ = estimated volume of oil remaining (surface)
B_f = formation factor; converts standard oil or gas volume to subsurface volume at

---

[1] Thomas, Stephen D., 2009. Carbon Dioxide Resource Assessment Oil and Gas Fields of California, Technical Memorandum, Golder and Associates.

formation pressure and temperature.

For supercritical CO_2 The Ideal Gas Law thermodynamically corrected can be applied:

$$PV=ZnRT \qquad (2)$$

Where:

P = pressure
V = volume
Z = gas factor
n = moles
R = gas constant
T = temperature

OIL

Correction for Formation Factor, B_f

To estimate CO_2 storage potential for oil reservoirs, Thomas (2009)[1] uses the following form for theoretical mass of carbon dioxide:

$$M_{CO2,t} = \rho_{CO2,r} (V_{prod} + V_{reserves}) / B_f$$

Comparing this to equation (1) shows that B_f has been misplaced into the denominator. To correct, the formation factor needs to be multiplied out to revise both the low and high estimates. For:

$B_{f,high}$ = 1.2
$B_{f,low}$ = 1.5

The revised estimates are:

$$M_{LowRevised\ (CO2,t)} = B_{f,low} B_{f,high} M_{low(CO2,t)}$$
$$M_{HighRevised\ (CO2,t)} = B_{f,low} B_{f,high} M_{low(CO2,t)}$$

Equivalent to a factor of:

= $B_{f,high*} B_{f,low}$
= 1.2*1.5
= 1.10

This will raise by 10%, the previous high and low estimates.

Omission of Surface Density of CO_2, $\rho_{CO2,s}$

The density of CO_2 at reservoir conditions can be expressed by substituting the following expression for volume in (2):

$$\text{▯} = \frac{\text{▯}}{\text{▯}}$$

Such that:

$$\frac{PM}{\rho} = ZNRT$$

If we treat M, n, and R as constants, then:

$$\frac{M}{nR} = \frac{ZT\rho}{P}$$

This is equal to the same constant at the surface and at reservoir conditions such that:

$$\frac{\square_{CO2,r}\ \square_{r}\ \square_{\ CO2,r}}{\square_{r}} = \frac{\square_{CO2,s}\ \square_{s}\ \square_{\ CO2,s}}{\square_{s}}$$

$$\rho_{\ CO2,r} = \frac{Z_{CO2,s} T_s \rho_{\ CO2,s} P_r}{P_s Z_{CO2,r} T_r} \qquad (2)$$

where:

$\rho_{CO2,s}$ = density of CO_2 at surface pressure and temperature
$\rho_{CO2,r}$ = density of CO_2 at reservoir pressure and temperature
$Z_{CO2,s}$ = gas factor at surface conditions
$Z_{CO2,r}$ = gas factor at reservoir conditions
T_s = temperature at the surface
T_r = temperature at the reservoir

Substituting (2) into (1) gives:

$$M_{CO2,t} = B_f \rho_{\ CO2,s} \left(V_{prod} + V_{reserves} \right) \frac{(P_r T_s Z_{CO2,s})}{(P_s T_r Z_{CO2,r})} \qquad (3)$$

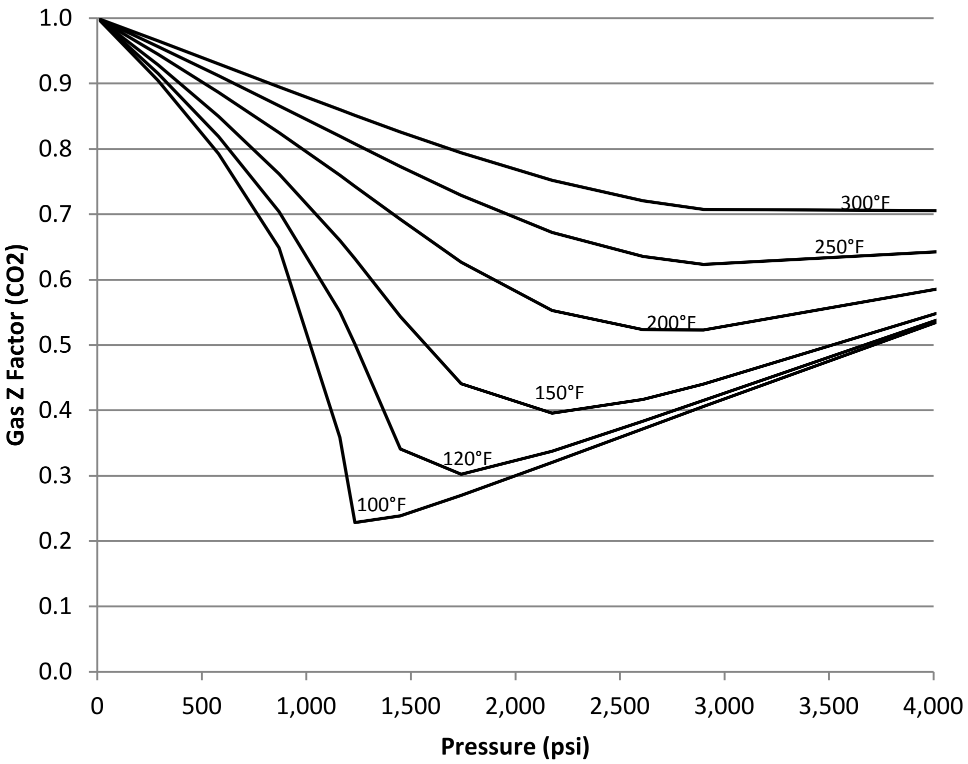
Equation (3) is essentially the same as the first equation on page 3 of Thomas (2009) with two exceptions, the presence of surface density of CO_2, $\rho_{\ CO2,s}$, and the formation factor, B_f, in the numerator. Thomas (2009) does correctly apply $\rho_{\ CO2,}$ in their original calculations using:

$$M_{CO2,t} = \frac{V_{prod} + V_{reserves}}{B_f} * \frac{(53.04 * P_r 60 * 0.9942)}{(14.5 * T_r Z_{CO2,r})} \qquad (4)$$

Where:

$\rho_{\ CO2,s}$ = 53.04 t/Mmcf
$Z_{CO2,s}$ = 0.9942
B_f = 1.2
1 bar = 14.5 psi
T_s = 60° F

The gas factor, $Z_{CO2,r}$, is pressure and temperature dependent:



GAS

Omission of Surface Density of CO_2, $\rho_{CO2,s}$

A similar derivation can be developed for the gas reservoirs. Starting with:

$M_{CO2,t} = V_{NR,r}\rho_{CO2,r}$

and employing the gas law as well as similar substitutions as for oil above, the final equation for the estimation of mass of CO_2 stored in a gas reservoirs should be:

$$M_{CO2,t} = ?_{??2,?} \left(?_{????} + ?_{????????}\right) \frac{(?_{??,?}\ ?_{??2,?})}{(?_{??,?}\ ?_{??2,?})} \qquad (5)$$

Thomas (2009) is missing a factor of $\rho_{CO2,s}$ but applies the correct form (5) in the calculations. The estimates are calculated using:

$$M_{CO2,t} = (V_{prod} + V_{reserves}) \frac{(53.04 * ?_{??,?} * 0.9942)}{(?_{??2,?} * 0.998)}$$

Where:

$Z_{NG2,s} = 0.998$

Hence, no correction is necessary for the estimates for CO_2 storage in gas reservoirs.

TABLE 3

The following is the Table 3 corrected for both errors in the oil estimates and addition errors in the original table. In millions of tons.

Basin	No. Fields	Oil		Gas		Total	
		Low	High	Low	High	Low	High
Central Valley	276	124.19	770.913	1,842.57	3,285.95	1,966.76	4,056.86
Cuyama	9	8.404	43.362	55.24	113.23	63.64	156.59
Eel River	2	<0.01	<0.01	18.15	18.15	18.25	18.25
La Honda	4	0.099	0.121	0.05	0.06	0.15	0.18
Livermore	2	0.088	0.187	28.2	34.82	28.29	35.01
Los Angeles	70	137.643	326.887	705.1	1,076.52	842.74	1,403.41
Orinda	2	<0.01	<0.01	0.12	0.12	0.22	0.22
Salinas	11	4.939	8.085	5.77	6.33	10.71	14.42
Ventura	87	59.906	127.204	380.68	643.77	440.59	770.97
TOTALS	**463**	**335.269**	**1276.759**	**3,035.88**	**5,178.95**	**3,371.35**	**6,455.91**

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ASSESSMENT OF THE POTENTIAL FOR CARBON DIOXIDE SEQUESTRATION BY REACTIONS WITH MAFIC ROCKS AND BY ENHANCED OIL RECOVERY IN NEVADA

Jonathan G. Price, Daniel M. Sturmer, Daphne D. LaPointe,
and Ronald H. Hess

Nevada Bureau of Mines and Geology

DOE Contract No.: DE-FC26-05NT42593
Contract Period: October 1, 2005 - May 11, 2011

Assessment of the Potential for Carbon Dioxide Sequestration by Reactions with Mafic Rocks and by Enhanced Oil Recovery in Nevada

Jonathan G. Price, Daniel M. Sturmer, Daphne D. LaPointe, and Ronald H. Hess

ABSTRACT

This report follows the preliminary assessment of the potential for carbon dioxide (CO_2) sequestration in geological settings in Nevada (Price et al. 2005) by more thoroughly evaluating the potentials for reaction of CO_2 with naturally occurring minerals and for use of CO_2 in enhanced oil recovery (EOR). The results of these two evaluations have been published by the Nevada Bureau of Mines and Geology (Sturmer et al. 2007 for the mineral-reaction work; LaPointe et al. 2007 for the EOR work). This contract report combines those two reports.

One option for decreasing the amount of greenhouse gas that is added to the atmosphere from the burning of fossil fuels is to capture CO_2 and react it with certain minerals found in rocks. Part 1 of this report investigates the potential for such carbon sequestration using rocks in Nevada. There are sufficiently large volumes of basalt (a rock rich in the oxides of magnesium, iron, and calcium) in Nevada to consider reaction of those rocks with CO_2 from coal-fired power plants.

Reaction with minerals has theoretical advantages over many other schemes for carbon sequestration in that it would be essentially permanent disposal (that is, no leakage as could possibly occur from geological storage in deep saline aquifers, oil fields, or other geological environments, and there would be no threat of loss of CO_2 from wildfires, as with terrestrial sequestration in trees or other biomass). Nonetheless, the technology for mineral reaction is unproven. Considerably more research would be needed before a commercial operation could be seriously considered.

When and if commercial viability is demonstrated, those areas most likely to be of interest in Nevada would be ones with large volumes of basalt or chemically similar rock near railroads and major power lines. Those areas would most likely be northwestern Washoe County; southern Washoe and parts of Storey, Lyon, Churchill, and Pershing Counties; the Humboldt lopolith in Churchill and Pershing Counties; the Battle Mountain area in Lander and Eureka Counties; and southwestern Mineral and northwestern Esmeralda Counties.

Part 2 of this report covers the potential for EOR as a means of CO_2 sequestration. Critical factors in Nevada include depth, temperature, and cumulative production. Most Nevada oil reservoirs are considerably hotter than ideal conditions for maintaining a dense CO_2 phase underground. Furthermore, none of the Nevada oil fields is large enough to accommodate all the CO_2 from a large coal-fired power plant. The cumulative volume of oil and associated water

production from all Nevada oil fields is about two orders of magnitude less than what would be needed to sequester a significant amount of CO_2 from a power plant. Therefore, there is not much potential in Nevada for CO_2 sequestration through EOR.

CONTENTS

*** Appendices are available on line at www.nbmg.unr.edu/dox/r52/r52append.htm.**

PART 1

Assessment of the Potential for Carbon Dioxide Sequestration by Reactions with Rocks in Nevada

Daniel M. Sturmer, Daphne D. LaPointe, Jonathan G. Price, Ronald H. Hess

EXECUTIVE SUMMARY

One option for decreasing the amount of greenhouse gas that is added to the atmosphere from the burning of fossil fuels is to capture carbon dioxide (CO_2) and react it with certain minerals found in rocks. This report investigates the potential for such carbon sequestration using rocks in Nevada. There are sufficiently large volumes of basalt (a rock rich in the oxides of magnesium, iron, and calcium) in Nevada to consider reaction of those rocks with CO_2 from coal-fired power plants.

Reaction with minerals has theoretical advantages over many other schemes for carbon sequestration in that it would be essentially permanent disposal (that is, no leakage as could possibly occur from geological storage in deep saline aquifers, oil fields, or other geological environments, and there would be no threat of loss of CO_2 from wildfires, as with terrestrial sequestration in trees or other biomass). Nonetheless, the technology for mineral reaction is unproven. Considerably more research would be needed before a commercial operation could be seriously considered.

Whereas there is plenty of basalt in Nevada to meet the CO_2 sequestration demands for several large power plants, there are insufficient quantities of other rock types (serpentinite, iron and manganese ores, wollastonite, and brucite) considered to be of significance for sequestering CO_2 from a large power plant. However, in-situ reaction of CO_2 with basalt is impractical, because the large volume increases that would result from the creation of carbonates of magnesium, iron, and calcium would plug pore spaces. Basalt would therefore have to be mined. It may make more sense to locate a coal-fired power plant close to the source of basalt than to transport mined basalt to an existing plant that may be located close to a source of coal. Solid waste products from burning the coal and other waste materials brought in by rail could be disposed along with the carbonates created from reacting CO_2 with the basalt, partly in the holes dug to mine the basalt.

When and if commercial viability is demonstrated, those areas most likely to be of interest in Nevada would be ones with large volumes of basalt or chemically similar rock near railroads and major power lines. Those areas would most likely be northwestern Washoe County; southern Washoe and parts of Storey, Lyon, Churchill, and Pershing Counties; the Humboldt lopolith in Churchill and Pershing Counties; the Battle Mountain area in Lander and Eureka Counties; and southwestern Mineral and northwestern Esmeralda Counties.

INTRODUCTION

Large amounts of carbon dioxide (CO_2) are generated from the burning of fossil fuels (coal, natural gas, oil, and derivative products, such as gasoline), wood, and other biomass. Worldwide, humans put approximately 6.5 gigatons of carbon (6.5 billion metric tons—some pertinent conversions regarding carbon and CO_2 are listed in Table 1) into the atmosphere each year from the burning of fossil fuels (Service, 2004). Some of that carbon returns to the Earth's oceans and land, but in recent years, the atmosphere has gained approximately 3.2 gigatons of carbon per year (Intergovernmental Panel on Climate Change, 2001). Because CO_2 is a greenhouse gas (it reflects heat radiated from the Earth, thereby contributing to global warming), and although other factors, both natural and anthropogenic, may be contributing to global climate change, considerable effort (see, for example, Deutch et al. 2007; Friedmann, 2007) has focused on investigating whether CO_2 can be captured (particularly from power plants and cement manufacturers) and sequestered (disposed of effectively and permanently, such that it does not reenter the atmosphere).

The United States alone burns approximately one gigaton of coal per year (Energy Information Administration, 2006a) and has vast resources of coal. In recent years, China has exceeded the U.S. in annual coal production and consumption (Energy Information Administration, 2004). The U.S., Russia, China, and India, in descending order, lead the world in recoverable reserves of coal (Energy Information Administration, 2006b), which are likely large enough to continue as a major energy source for electricity throughout the 21st century. In recent decades, coal has been the major source of energy for electricity in Nevada, with production from a few major power plants (e.g., Figure 1).

The primary sources of energy consumed in the United States and Nevada are fossil fuels. In 2006, collectively fossil fuels accounted for 85% (and coal accounted for 23%) of the energy consumed in the United States; nuclear energy (8%) and renewable sources, including hydroelectric, geothermal, solar, wind, and biomass (collectively 7%) made up the rest (Energy Information Administration, 2006c). In Nevada in 2004, the latest year for which state statistics are available from the Energy Information Administration (2006c), 93% of energy consumption came from fossil fuels (27% from coal), 2% came from hydroelectric power, and 4% came from geothermal power. Nevada's largest coal-fired power plant, the Mohave Generating Station in far southern Nevada, shut down at the end of 2005 because it was unable to meet current pollution-control standards. Most of the deficit from the loss of this plant was made up by more electrical production from burning natural gas.

In 2003, the State of California, in collaboration with the U.S. Department of Energy and the States of Alaska, Arizona, Oregon, and Washington, asked the State of Nevada to join the West Coast Regional Carbon Sequestration Partnership (WESTCARB) and participate in a regional analysis of CO_2 sequestration potential, through both terrestrial and geological approaches. The terrestrial approaches involve growing more biomass (particularly trees), and the geological options include proven technologies, such as using CO_2 to enhance recovery from oil fields and disposal of CO_2 in saline aquifers. Some unconventional approaches are also being evaluated. As the state with the least amount of annual precipitation, Nevada has little potential for growing substantially more biomass relative to states along the Pacific Ocean. The Nevada

Bureau of Mines and Geology (NBMG) reported its findings from a preliminary assessment of the potential for geological sequestration in Nevada (Price et al. 2005). This report follows up with a more detailed evaluation of one of the unconventional approaches—sequestration through reaction with minerals and rocks.

Table 1. Carbon and CO_2.

Carbon, C (12.0111 grams per mole)
Oxygen, O (15.9994 grams per mole)

Burning carbon:

C [in wood, grass, and fossil fuels – natural gas, petroleum (and its products – gasoline, diesel, and heating oil), and coal]
+ O_2 [from the atmosphere] = CO_2 [into the atmosphere]

With this reaction, one ton of C yields 3.664 tons of CO_2; 1 gigaton of C yields 3.664 gigatons of CO_2.

1 gigaton = 10^9 tons = 1 billion tons.

1 gigaton (metric) of water (with a density of 1.0 g/cm^3) occupies a volume of 1 km^3.

The concentration of CO_2 in the Earth's atmosphere is currently approximately 370 parts per million by volume (ppmv), which is equal to approximately 560 parts per million by weight (ppmw). The bulk of the remainder of the Earth's atmosphere is nitrogen (N_2, 78.1% by volume or 75.5% by weight), oxygen (O_2, 20.9% by volume or 23.1% by weight), and argon (Ar, 0.93% by volume or 1.3% by wieght). The total amount of carbon in the Earth's atmosphere is approximately 730 gigatons (Intergovernmental Panel on Climate Change, 2001).

Theoretical Considerations Regarding Reactions with Rocks and Minerals—

Recent research has explored the feasibility and practicality of carbon dioxide sequestration by reaction with common minerals, also known as mineral carbonation (Lackner et al. 1995, 1997a,b,c; Butt and Lackner, 1997, Goff and Lackner, 1998; O'Conner et al. 2002; Voormeij et al. 2004; Mazzotti et al. 2005). Most studies have investigated the conversion of magnesium-iron-calcium silicates (olivine and pyroxenes) to carbonates of magnesium, iron, and calcium, but it is similarly possible to sequester carbon dioxide by reaction with iron oxide ore, manganese oxide ore, or other minerals to form iron and manganese carbonate minerals stable under atmospheric conditions. The reactions most applicable for minerals and rocks in Nevada are listed in Table 2.

Table 2. Theoretical weights and volumes of reactants and products in reactions between CO_2 and various rocks and minerals (data from Weast, 1971, Roberts et al. 1974, and Robie and Hemingway, 1995; modified from Price et al. 2005).

Mineral reactant	Ratio of weights of mineral reactant to C	Volume of mineral reactant (m^3/ton of C)	Ratio of weights of solid products to C	Volume of solid products (m^3/ton of C) assuming 20% porosity	Ratio of volumes of solid products to solid reactants	Heat generated (- Enthalpy of reaction) (kJ mol-^{1} CO_2)	Free energy of reaction (kJ mol-^{1} CO_2)*
1. Mg_2SiO_4 (forsterite)	5.86	1.82	9.52	4.09	2.24	88.65	-36.45
2. Fe_2SiO_4 (fayalite)	8.48	1.93	12.15	4.24	2.19	78.65	-27.00
3. $MgSiO_3$ (enstatite)	8.36	2.62	12.02	5.27	2.01	84.90	-33.10
4. $FeSiO_3$ (orthoferrosilite)	10.98	2.75	14.65	5.42	1.97	77.90	-26.70
5. $CaSiO_3$ (wollastonite)	9.67	3.32	13.34	6.20	1.87	89.80	-41.40
6. $CaAl_2Si_2O_8$ (anorthite)	23.16	8.39	26.83	11.22	1.34	77.00	-21.10
7. $NaAlSi_3O_8$ (albite)	43.66	16.67	47.33	21.18	1.27	5.60	52.20
8. $Mg_6Si_4O_{10}(OH)_8$ (antigorite)	7.69	2.98	10.35	4.49	1.51	64.13	-19.90
9. $Mg(OH)_2$ (brucite)	4.86	2.02	7.02	2.92	1.44	81.10	-38.70
10. MnO (manganosite)	5.91	1.10	9.57	3.23	2.93	114.20	-61.80
11. MnO_2 (pyrolusite)	7.24	1.43	9.57	3.23	2.26	-20.60	40.30
12. Fe_2O_3 (hematite)	6.65	1.26	9.65	3.06	2.42	-50.70	83.80
13. Fe_3O_4 (magnetite)	6.43	1.24	9.65	3.06	2.47	-9.50	49.17
14. Fe (iron)	4.65	0.59	9.65	3.06	5.18	362.40	-288.40
15. Hypothetical basalt	16.32	5.21	19.98	8.50	1.63	74.49	-21.11

1. Mg_2SiO_4 (forsterite in olivine) + $2CO_2$ (gas, captured from power plant) = $2MgCO_3$ (magnesite) + SiO_2 (quartz or other silica compound)
2. Fe_2SiO_4 (fayalite in olivine) + $2CO_2$ (gas) = $2FeCO_3$ (siderite) + SiO_2 (quartz)
3. $MgSiO_3$ (enstatite in pyroxenes) + CO_2 (gas) = $MgCO_3$ (magnesite) + SiO_2 (quartz)
4. $FeSiO_3$ (ferrosilite in pyroxenes) + CO_2 (gas) = $FeCO_3$ (siderite) + SiO_2 (quartz)
5. $CaSiO_3$ (wollastonite in pyroxenes) + CO_2 (gas) = $CaCO_3$ (calcite) + SiO_2 (quartz)
6. $CaAl_2Si_2O_8$ (anorthite in plagioclase) + CO_2 (gas) = $CaCO_3$ (calcite) + Al_2O_3 (alumina or corundum) + $2SiO_2$ (quartz)
7. $2NaAlSi_3O_8$ (albite in plagioclase) + CO_2 (gas) = Na_2CO_3 (sodium carbonate) + Al_2O_3 (alumina or corundum) + $6SiO_2$ (quartz)

8. $Mg_6Si_4O_{10}(OH)_8$ (antigorite) + $6CO_2$ (gas) = $6MgCO_3$ (magnesite) + $4SiO_2$ (quartz) + 4H2O (water)
9. $Mg(OH)_2$ (brucite) + CO_2 (gas) = $MgCO_3$ (magnesite) + 4H2O (water)
10. MnO (manganosite) + CO_2 (gas) = $MnCO_3$ (rhodochrosite)
11. MnO_2 (pyrolusite) + CO_2 (gas) = $MnCO_3$ (rhodochrosite) + $0.5O_2$ (gas)
12. Fe_2O_3 (hematite) + $2CO_2$ (gas) = $2FeCO_3$ (siderite) + $0.5O_2$ (gas)
13. Fe_3O_4 (magnetite) + $3CO_2$ (gas) = $3FeCO_3$ (siderite) + $0.5O_2$ (gas)
14. Fe (iron) + CO_2 (gas) + $0.5O_2$ (gas) = $FeCO_3$ (siderite)

* With the exception of reactions 7, 11, 12, and 13, all reactions are thermodynamically favorable (with respect to calculated negative Gibbs free energies of reaction at 25°C and 10^5 pascals).

15. The composition of this hypothetical basalt is calculated with the following assumptions:

Hypothetical Basalt	Mole fraction of minerals
Mg_2SiO_4 (in olivine)	0.15
Fe_2SiO_4 (in olivine)	0.05
$CaSiO_3$ (in pyroxenes)	0.07
$MgSiO_3$ (in pyroxenes)	0.23
$FeSiO_3$ (in pyroxenes)	0.10
$CaAl_2Si_2O_8$ (in plagioclase)	0.30
$NaAlSi_3O_8$ (in plagioclase)	0.10
TOTAL	1.00

Chemical composition	Weight %
SiO_2	48.6
Al_2O_3	19.2
MgO	11.5
FeO	7.8
CaO	11.2
Na_2O	1.7
TOTAL	100.0

The principal means by which CO_2 is naturally sequestered in rocks is through the alteration of calcium- and magnesium-rich rocks, ultimately forming carbonates (rocks composed primarily of calcite, $CaCO_3$, the major mineral in limestone, and dolomite, $CaMg(CO_3)_2$). The Earth contains abundant calcium and magnesium in basalts and their intrusive equivalents, gabbros. Basalts are volcanic rocks commonly erupted at ocean ridges on the seafloor, in volcanic islands, such as Hawaii, and in certain continental areas, such as the Columbia River Plateau east of the Cascade Range in Oregon and Washington. These rocks are termed mafic to describe their high magnesium and iron (ferrous) contents. Dissolved calcium in the oceans, and that trapped in limestone and dolomite, owes its origin primarily to the weathering and hydrothermal alteration of these mafic rocks, although dissolution of other common, feldspar-, amphibole-, and pyroxene-rich igneous rocks (granites, andesites, etc.) and carbonates undoubtedly contributes to the calcium budget of the ocean.

One approach to permanent CO_2 sequestration would be to speed up the natural process of mineral carbonation. Minerals in these rocks can react with CO_2 to produce various carbonates, silica, and alumina as reaction products. As indicated in Table 2, in terms of volume of material required for the reactions and volume of materials produced, rocks with high concentrations of the mineral forsterite (Mg_2SiO_4), the magnesium end member of the olivine group, would be most favored. These are ultramafic rocks, particularly Mg-rich igneous rocks, including dunite (a rock composed primarily of forsterite) and peridotite (a rock composed mostly of olivine and pyroxenes, minerals composed primarily of $(Mg,Fe,Ca)SiO_3$). Serpentinite, another ultramafic rock, is a rock composed mostly of serpentine minerals, such as antigorite, $Mg_6Si_4O_{10}(OH)_8$, which is nearly as favorable volumetrically as reaction with olivine (Table 2).

Coincidentally, the reaction of CO_2 with Mg_2SiO_4 or $Mg_6Si_4O_{10}(OH)_8$ is favorable thermodynamically and exothermic; heat generated from the reaction could provide energy needed to pulverize the rock, thereby speeding up the kinetics of the reaction. Mazzotti et al. (2005) discussed the status of engineering research on mineral carbonation, including problems of slow reaction kinetics. The reactions with several other minerals in Table 2 are also thermodynamically favorable. The exceptions include albite, the sodium end member of the plagioclase feldspar solid solution, and the oxides for which iron or manganese would have to be reduced to the divalent state (pyrolusite, hematite, and magnetite).

Goff and Lackner (1998) described the potential use of ultramafic rocks for CO_2 sequestration. They proposed a process in which the ultramafic rocks would be reacted with hydrochloric acid to facilitate reactions with CO_2. Unfortunately, although ultramafic rocks are abundant in California, Oregon, and Washington, Nevada contains only small amounts of these types of rocks near the surface. Nevad1a does, however, have abundant basalt and other mafic rocks (Figure 2).

The amount of CO_2 generated during the lifetime of a coal-fired power plant can be immense. A large coal-fired power plant (burning 5 million metric tons of carbon in coal per year and generating on the order of 2,000 megawatts) would burn a quarter of a gigaton of carbon during a 50-year lifespan. We use this figure of 0.25 gigaton of carbon for comparison throughout the report. For example, using the hypothetical basalt composition in Table 2, 1.3 km^3 of basalt would need to be mined to react with 0.25 gigaton of carbon, and 2.1 km^3 of waste would be generated from the reaction, approximately 1.6 times the amount needed to refill the hole from which the basalt would be mined. For dunite and serpentinite, the volumes of reactant rocks would need to be 0.45 and 0.75 km^3, respectively, and the amount of waste would be 1.0 and 1.1 km^3, respectively. These volumes are comparable to the sizes of large-scale copper and gold mines in Nevada (e.g., the Robinson and Yerington copper mines and the Carlin and Betze-Post gold mines) and other parts of the western United States.

A hypothetical scenario for permanent CO_2 sequestration would be to site a CO_2-generating power plant near a large amount of ultramafic rock or basalt, which would be mined and used in chemical reactors. The waste products from the reactions could be used to isolate municipal and other waste materials, which would refill the holes dug in the mining operations. Because of the volume considerations (Table 2), additional landfills would be required, or artificial hills would be constructed near the mining sites of the ultramafic rock or basalt. Ideally, such an industrial ecology facility would be located close to railroads (to bring coal from Wyoming and other sources and waste from cities) or perhaps ports (to bring coal from Alaska and possibly oil or natural gas from any location), electrical transmission lines, and cities that use the electricity and generate the municipal waste.

As outlined by Mazzotte et al. (2005), considerable engineering and environmental research would be necessary to determine whether this hypothetical approach to carbon sequestration (mineral carbonation involving mining of ultramafic or mafic rocks) is practical. Major issues to be resolved, if possible, include overcoming slow reaction kinetics (and the related energy costs of mining and comminution), taking advantage of the energy savings from the exothermic reactions, health concerns if dealing with rocks containing asbestos (as is the case with many serpentinites), and environmental concerns (ecological disturbance, reclamation involving volumes of waste materials that are larger than what was taken from the ground, impacts on groundwater and surface water, etc.) and social concerns (traffic, safety, noise, increased employment, demands on local infrastructure, sustainability, etc.) associated with surface mining operations.

Large outcrops of mafic rocks in Nevada are plotted with current railroads, piplelines, electrical transmission lines, and major CO_2 generators in Figure 2. In this report, we assess the volumes of mafic and ultramafic rocks in Nevada. Recognizing that approximately 87% of the state is managed by federal agencies, we have not evaluated these outcrops in terms of land ownership.

Depending on the chemical reactor design (using supercritical, liquid, or gaseous CO_2 versus an aqueous solution as described by Goff and Lackner, 1998), considerable water may be needed for the process. Interestingly, reaction of CO_2 with serpentinite, which is more abundant in California than in Nevada, would produce approximately one ton of water for each ton of carbon sequestered, thereby perhaps eliminating or significantly reducing the need to consume existing water resources. A further advantage of serpentinite is that it is locally considered a nuisance, because of commonly contained asbestos, which would be destroyed upon reaction with CO_2.

McGrail et al. (2006) investigated in-situ reaction of CO_2 with basalt. This would involve pumping CO_2 into the ground, as with conventional approaches to geological sequestration. We believe that any attempt to achieve substantial permanent sequestration through in-situ mineral carbonation is impractical, because the large volume increase resulting from the chemical reactions (Table 2) would plug available pore space. For the example of the hypothetical basalt in Table 2, the ratio of volumes of solid products to reactants would be at least 1.31 (assuming no change in intergranular porosity) and perhaps as much as 1.63 (assuming a porosity of 20% within the product phases). That is, for the reaction to proceed to completion, with all the key reactants consumed, the in-situ basalt would need to have an initial porosity of 31%, well more than is likely to be found in nature. Whether significant volumes of CO_2 could be stored in a liquid phase within the pore spaces or open fractures in subsurface basalts is a separate question that would require thorough understanding of the hydrogeology (including the seals necessary to prevent escape of CO_2 under pressure). In this report, we restrict our consideration to above-ground reaction with rocks and minerals.

MAFIC AND ULTRAMAFIC ROCKS IN NEVADA

Sufficient volumes of basalt and ultramafic rocks likely occur in the western states to meet the CO_2 sequestration needs of the region (Goff and Lackner, 1998). In Nevada, Tertiary basalts crop out in many parts of the state, and a large gabbroic complex occurs near Lovelock in northern Churchill and southern Pershing Counties. Small bodies of serpentinite, presumably altered pieces of dunite- or peridotite-rich oceanic crust thrust onto the North American continent during Paleozoic and Mesozoic mountain-building events (Stewart, 1980), occur in Mineral, northwestern Nye, and eastern Humboldt Counties.

The mafic and ultramafic rocks exposed in Nevada range in age from Paleozoic to Recent, but the overwhelming majority are post-Early Miocene (Figure 3, Table 3). The magmas

Table 3. Major exposures of mafic and ultramafic rocks in Nevada.

Rock Type	Age	Geologic Setting
Basalt, serpentinite, and dunite	Paleozoic	Oceanic lithosphere
Gabbro and basalt	Mesozoic	Lopolith
Basalt	Cenozoic	Basin-and-range extension

from which these rocks crystallized were formed in the lithospheric mantle and have undergone minor geochemical modification in the crust. The following contains a brief discussion of the tectonic setting of Nevada and the older ultramafic and mafic rocks, followed by geochemical and isotopic heterogeneities in Tertiary and Quaternary basalts. For a more thorough discussion the reader is directed to Dickinson (2001, 2004), DeCelles (2004), et al. cited below.

The oldest lithosphere in Nevada is a promontory of the Archean Wyoming province in northeastern Nevada (Lush et al. 1988). During the Proterozoic, several terranes were accreted to the Archean Wyoming province, including the Mojave (~2.0 billion years ago, or Ga), Yavapai (1.76 Ga) and Mazatzal (1.63 Ga) (Ball and Farmer, 1991; Magnani et al. 2004; Dubendorfer et al. 2006). Initial Proterozoic rifting began locally, and is recorded in deep epicratonal basins in Montana, Idaho (Belt basin), California (Death Valley), and Arizona (Unkar and Chuar). Renewed rifting began ~750-800 million years ago (Ma) with the breakup of Rodinia (Stewart and Suczek, 1977; Stewart, 1991). What is now western North America rifted away from a number of possible land masses, including Antarctica, Australia, China, and Siberia, although Siberia and/or Australia seem to be most likely (Moores, 1991; Dalziel, 1992, 1997; Karlstrom et al. 1999; Sears and Price, 2000, 2003; Stewart et al. 2001; Li et al. 2002).

Subsidence and cooling of the crust began nearly 150 Ma after initial rifting, allowing for deposition of a thick passive margin sequence. Initial deposition in Nevada included a terrigenous detrital sequence in the latest Proterozoic – Lower Cambrian and deeper water carbonate and shale in the Cambrian (Stewart and Szucek, 1977; Stewart, 1991). These rocks crop out in eastern and southern Nevada, and generally thicken to the west (Stewart, 1991). Passive margin deposition continued into the Devonian, when sedimentation was largely disrupted by a series of orogenic events, including the Antler and Sonoma orogenies. During the Devonian to Late Pennsylvanian Antler orogeny, the Roberts Mountains allochthon (composed of generally deep-ocean sediments, some basalts, and rare ultramafic rocks) was thrust eastward above the miogeoclinal sequence (generally shallower ocean sediments). The Sonoma orogeny occurred as another terrane-accretion event in the Late Permian – Early Triassic. Whereas these orogenies have been thought of as discrete events (Nilson and Stewart, 1980; Speed and Sleep, 1982), recent work by Trexler et al. (2004) has documented as many as seven tilting events in Pennsylvanian-Permian time, indicating that contractional deformation was more continuous than discrete during the mid to late Paleozoic. The long period of contraction resulted in stacking of thrust sheets and produced thick crust through much of Nevada, comparable to parts of the contemporary Andes.

Arc-related Sierra Nevada volcanism began in the Late Triassic, with episodes of back-arc spreading occurring intermittently during the Mesozoic and into the Cenozoic (Dickinson, 2002). Major pulses of magmatism occurred during the Middle Jurassic and Middle to Late Cretaceous (Moore, 2000; Ducea, 2001), concurrent with back-arc contraction in an arcuate belt between the Nevada-Idaho border and southeast California. The Laramide orogeny began in the Late Cretaceous. During this time magmatism and contractional deformation migrated eastward to the longitude of Colorado (Christiansen and Yeats, 1991), or ~1000 km east of the subduction zone. This volcanic/orogenic migration has been attributed to the flattening of the Farallon plate slab in the Late Cretaceous (Dickinson and Snyder, 1978).

Over-thickened crust began to locally extend rapidly after the end of the Laramide orogeny, eventually forming a belt of metamorphic core complexes that extends from British Columbia to Mexico (Armstrong, 1972; Coney, 1980; Davis et al. 1980; Wernicke, 1981; Miller et al. 1983; Bartley and Wernicke, 1984; Reynolds and Spencer, 1985; Davis and Lister, 1988; Wernicke, 1992). The plate boundary in southern California began to switch from subduction to a dextral strike-slip transform about 30 Ma, although it did not fully organize into the San Andreas fault as we know it until about 17 or 18 Ma, when basin-and-range extension (with steeply dipping normal faults forming along the edges of many current mountain ranges and adjoining sediment-filled basins) began in Nevada (Atwater 1970, Dickinson, 1997; Atwater and Stock, 1998).

Beginning in the Eocene two volcanic fronts began to migrate towards southern Nevada; one moving southward from Idaho and the other moving west-northwest to northward from New Mexico and Arizona (Christiansen and Yeats, 1991; Faulds et al. 2001). The southward migrating front stalled in central Nevada during late Oligocene-early Miocene time and produced multiple calderas that resulted in the widespread deposition of ash-flow tuffs in Nevada, eastern California, and Utah (Axen et al. 1993). The northward-migrating volcanic front abated just south of Las Vegas ~13 Ma, though no caldera-forming eruptions appear to have been associated with the stall (Christiansen and Yeats, 1991; Faulds et al. 2001). The Las Vegas amagmatic zone lies between the two stalled fronts, between latitudes 36°N and 37°N (Eaton, 1982).

Two types of volcanism dominated after ~18 Ma: dominantly andesitic calc-alkaline volcanism and bimodal (basalt-rhyolite) volcanism. The andesitic volcanism is consistent with derivation from an arc system, whereas the bimodal volcanism is interpreted as related to extension (Christiansen and Yeats, 1991; John et al. 1999; Garside et al. 2000). Large volume basaltic volcanism occurred in Washington and Oregon during the initial stages of the bimodal volcanism (~18-15 Ma) although these events may not be directly related to basin-and-range extension (Dickinson, 1997). Arc volcanism began to shut off as the Mendocino triple junction propagated northward, with andesitic volcanism ending at the latitude of Reno around 7 Ma. Arc volcanism continues locally in northeastern California, with Mount Shasta and the Lassen volcanic fields as prominent features. Locally basaltic and volumetrically less rhyolitic volcanism has occurred in the Quaternary in Nevada (Scott, 1969; Scott and Trask, 1971; Naumann et al. 1991; Rash, 1995; Yogodzinski et al. 1996; Smith et al. 2002; Smith and Keenan, 2005).

Most of the mafic to ultramafic rocks exposed in Nevada are extension-related and were erupted during the past ~18 Ma. The main exceptions are Paleozoic serpentinite and oceanic basalt and a Mesozoic mafic lopolith. The serpentinite is part of the mélange obducted onto North America during Paleozoic-Mesozoic orogenies. Basaltic Pennsylvanian and Eocene dikes crop out in the Independence Mountains in Elko County (Phinisey, 1995), but these occurrences are volumetrically minor. Minor mafic rocks also crop out in Mesozoic metamorphic rocks in western Nevada (Proffett and Dilles, 1984).

The only ultramafic rocks exposed in Nevada are small scattered lenses of Paleozoic serpentinite in the Candelaria area of Mineral and Esmeralda Counties and in northern Nye County (Page, 1959; Stewart and Carlson, 1978; Kleinhampl and Ziony, 1985) and exposures of ultramafic rocks in the Twin Creeks Mine in Humboldt County (Thoreson et al. 2000). These minor occurrences are most likely related to Paleozoic-Mesozoic accretion of Paleozoic crust and upper mantle.

Geochemistry

Throughout Nevada the geochemical and isotopic compositions of basalts vary both temporally and spatially. The temporal variation may be related to the change in type of plate boundary to the west (Farmer et al. 1989; Glazner and Ussler, 1989; Fitton et al. 1991), late Cenozoic asthenospheric upwelling (Fitton et al. 1991), lithospheric delamination (Humphreys, 1995; Ducea and Saleeby, 1998), and/or relative crustal thinning (Glazner and Ussler, 1989). Spatial variations in geochemical and isotopic data probably are due to a combination of crustal (Brandon, 1989; Fitton et al. 1991; Kempton et al. 1991) and mantle lithosphere (Hedge and Noble, 1971; Mark et al. 1975; Leeman, 1982; Menzies, 1989; Fitton et al. 1991; Kempton et al. 1991; Rogers et al. 1995) heterogeneities.

Initial Cenozoic volcanism in Nevada was dominantly intermediate to felsic in composition, though volcanism was more bimodal (felsic plus mafic, without significant intermediate compositions) but primarily basaltic beginning about 18 Ma. This may have been due to the end of subduction and the coalescence of the proto-San Andreas fault off the coast of California at that time (Dickinson, 1997). The northern Nevada rift formed 17–14 Ma; it is a 500 km-long, 4–7 km-wide zone of basaltic dikes that extends from the Nevada-Oregon border to southern Nevada, and is coeval and geochemically similar to the Columbia River flood basalts (Zoback, 1978; Zoback and Thompson, 1978; Hildebrand and Kucks, 1988; Blakely and Jachens, 1991; Zoback et al. 1994; John et al. 2000b; Wallace and John, 2000; Leavitt et al. 2000; Ponce and Glen, 2002; Grauch et al. 2003). Glazner and Ussler (1989) pointed out that at least some of the basaltic volcanism does not directly correlate with basin-and-range extension, because many syn-extensional volcanic rocks are intermediate to silicic in composition. They suggested that the change to dominantly basaltic volcanism is related to crustal thinning due to extension. As the crust thins, magma generated in the mantle will move through the crust faster, and the amount of magma-crustal interaction will decrease.

It appears that variations in major oxide, trace element, and isotopic compositions of basalts could not have possibly been due to crustal interaction alone and must be due, at least in part, to heterogeneities in the lithospheric mantle (Ormerod, 1988; Ormerod et al. 1988; Lum et al. 1989; Menzies, 1989; Rogers et al. 1995). Lum et al. (1989) compared two end member basalts to see if the differences in the basalts could have been due to crustal interaction alone and concluded that there must be heterogeneities in the lithosphere.

Menzies (1989) used seismic tomography, heat flow, and xenolith thermobarometry to map out lithospheric mantle domains in the western United States (Figure 4). He separated the mantle lithosphere into four domains, two domains of enriched mantle, one depleted mid-ocean ridge basalt mantle domain, and one domain similar to mantle underlying ocean island basalts.

One of the enriched mantle domains is restricted to sub-Archean areas in Wyoming, Utah, and northeastern Nevada. The depleted mid-ocean ridge mantle domain (DMM in Figure 4) is below Proterozoic/Phanerozoic crust but not Archean crust. The other enriched mantle domain (EM2) is widespread beneath Proterozoic crust, and it seems to replace depleted mid-ocean ridge mantle in some areas. Formation of the enriched mantle domain may be related to subduction or recycling processes. The ocean island basalt mantle (OIB) area occurs in an area of upwelling beneath the southern Basin and Range, and it partially replaces older mantle. Depleted mid-ocean ridge mantle may represent a sub-Proterozoic lithosphere that existed prior to the subduction-related creation of more enriched mantle. Spatial arrangement of lithospheric mantle domains is representative of the tectonic history that led to their formation. Archean crustal production, and stabilization led to the enriched mantle domain. In the Proterozoic, subduction may have led to the enriched mantle domain. Cenozoic asthenospheric upwelling has led to the ocean-island basalt domain (Menzies, 1989).

Geochemical data (major oxide, minor element and some trace element analyses) were assembled for approximately 450 Nevada rocks (Appendix 1, which is available on line at www.nbmg.unr.edu/dox/r52/r52append.htm). Most of the analyses were found in the NAVDAT (http://navdat.kgs.ku.edu) and PETROS (http://www.ngdc.gov/mgg/geology/petros.html) databases. These databases contain published and unpublished geochemical data from the 1800s through 1980 (PETROS) and since 1980 (NAVDAT). More geochemical data were found in papers and unpublished theses that had yet to be incorporated into the NAVDAT database. For areas where data were scarce, we collected a few samples and analyzed them for major oxide compositions (Table 4). In most other cases, the rocks selected from the geochemical databases had $SiO_2 < 55\%$ by weight.

A helpful way of comparing chemical compositions of igneous rocks is through calculations of normative mineralogy, hypothetical minerals that would form if magma of a given chemical composition crystallized slowly at low pressure (Iddings, 1909). Cross, Iddings, Pirsson, and Washington (CIPW) norms were calculated for 200+ basalt analyses. Calculations were completed using the CIPW, meso- and kata-norm calculator from the Saskatchewan isotope laboratory (http://sil.usask.ca/software.htm). Preferred samples are those with normative olivine greater than 10%, especially with dominantly normative forsterite. A large percentage of forsterite is preferred, because the greater the amount of normative forsterite (e.g., the more mafic), the less waste product produced by the reaction with carbon dioxide (Table 2). The rocks that are highest in normative forsterite are generally dunites, serpentinites, and basalts that are particularly Mg rich. Igenous rocks with high concentrations of Fe and Ca, as well as Mg (basalts), are also favorable, but less so than those with particularly high concentrations of Mg. If and when specific rocks are evaluated for mineral carbonation reactions, careful petrographic work would need to be undertaken to determine actual mineralogy, not relying on the calculated norms.

Of approximately 450 samples for Nevada, 100 had CIPW olivine norms greater than 10% (Appendix 2, which is available on line at www.nbmg.unr.edu/dox/r52/r52.append.htm). Most of these analyses were from the basalt fields of eastern Nye County, southern Mineral County, northern Esmeralda County, eastern Clark County, southern Pershing County, and southern Washoe County (Figures 5 and 6).

Table 4. Major element analyses of selected mafic rock samples from western Nevada.

Major Oxides* (%)	M05-1	M05-2	M05-3	M05-6	M05-7	M05-8
SiO_2	51.3	49.8	58.3	53.7	58.4	55.3
TiO_2	0.96	1.20	1.45	0.85	0.72	1.20
Al_2O_3	19.2	18.2	15.8	16.4	18.2	17.1
Fe_2O_3	9.73	9.92	7.94	8.47	6.58	7.59
MnO	0.15	0.15	0.19	0.15	0.12	0.12
MgO	5.44	5.62	1.16	7.21	2.15	4.02
CaO	9.88	8.30	3.83	10.0	6.01	6.52
Na_2O	2.53	3.40	4.86	2.05	3.98	3.69
K_2O	0.51	1.17	3.62	0.77	2.02	3.00
P_2O_5	0.22	0.40	0.78	0.13	0.30	0.73
LOI	0.92	0.97	1.54	0.14	0.65	0.12
Total	100.8	99.1	99.4	99.9	99.1	99.4

* Analyses of major oxides by x-ray fluorescence at the Nevada Bureau of Mines and Geology (Paul Lechler, Chief Chemist). LOI = loss on ignition.

Sample	Location	UTM (NAD 1983)
M05-1	Western Smoke Creek Desert, Washoe County	11 T 278784/ UTM 4505319
M05-2	Hwy 447, northern Washoe County	11 T 286832/ UTM 4522013
M05-3	Sheldon Antelope Range, northwestern Humboldt County	11 T 286943/ UTM 4634886
M05-6	US 95, north of Winnemucca, Humboldt County	11 T 439450/ UTM 4543640
M05-7	US 95, southeast of Hawthorne, Mineral County	11 S 373409/ UTM 4268302
M05-8	Near Belleville, Mineral County	11 S 395609/ UTM 4229341

Procedure for Evaluating Mafic Volcanic Fields

Basalt outcrops are located in every county in Nevada (Figure 3), but many of these outcrops contain much less than the 1 km^3 necessary to supply a power plant for 50 years. Because a large volume of basalt is needed for carbon dioxide sequestration, we chose to focus this study on the largest basalt fields in Nevada (Figure 3) and disregard areas with only thin basalts exposed (Figure 7). In order to calculate the thickness of basalts in these areas, we combined existing maps and LANDSAT images to estimate aerial extent, and existing geologic maps, air photos, topographic maps, and field observations to estimate thickness and thickness variations (see below).

Basalt fields that met the volume requirement were then combined with geochemical and selected geospatial data in order to determine which field(s) may be favorable for future development. The geochemical data are fairly sparse and are only meant to be used as a broad characterization of the basalts in each field. The geospatial data includes proximity of the basalt fields to existing roads, railroads, and power lines, all of which affect the cost and/or placement of future power plant(s) that could use basalt to sequester carbon dioxide.

Procedure for Assessing Mafic Rock Volume

The first step was to constrain the aerial extent of basalt in the selected fields using the 1:500,000-scale digital state geologic map (Stewart and Carlson, 1978) and 92/93 LANDSAT images (available at http://keck.library.unr.edu/data/landsat/pathrow.html). The state geologic map was converted from a NAD 1927 projection to NAD 1983 projection so that 1:24,000-scale digital orthophotoquads (DOQs) could also be overlaid on the geologic map. The geologic map was set on 60% transparency and laid over the DOQs in ARCMAP 9.1. Mafic and ultramafic areas of interest were then redigitized in ARCMAP 9.1 based on the state geologic map but modified by the color contrasts seen on the LANDSAT images.

Thicknesses were estimated using a combination of existing data, air photos, topographic maps, and field photos. Several control points were chosen for each study area. True dip was taken from existing geologic maps, if available. Estimates for the dip and percentage of basalt at a control point were taken from the air photos and geologic maps, and an apparent thickness was calculated from a topographic map using elevation differences between top and bottom of the basalt flows. Field reconnaissance photography was also done to help estimate basalt thickness. Photos were taken (usually at distance) in order to find estimates of percent basalt and basalt dip at a control point and then combined with data from a topographic map to calculate thickness. Geologic maps were used to help convert apparent dip from photographic angles to true dip (using the relationship $\tan(\delta) = \tan(\delta')\cdot\cos(\gamma)$, where δ = true dip, δ' = apparent dip, and γ = angle of divergence between the direction of the true dip and the apparent dip). At each measurement point, true thickness of mafic rock, t, was estimated using the following formula:
$t = f\cdot a\cdot\cos(\delta)$, where
f = fraction of thickness that is mafic rock (as opposed to, for example, interbedded tuff);
a = apparent thickness measured from topographic elevations; and
δ = true dip of the mafic rocks.

Using the thickness control points, we then contoured the areas containing mafic rocks with a 30-m contour interval, with the exception of the Humboldt lopolith (100-m contour interval). The digitized lines and points were converted into polygons in ARC Catalog, and the newly created shape file with basalt thickness polygons was brought back into ARCMAP 9.1. In order to calculate the volume, the area of each polygon was multiplied by the basalt thickness for that polygon and converted from m^3 to km^3. The thickness values given for each polygon are the average of the bounding thickness contours. When there is only one bounding contour (thickest sections), the thickness used is a preexisting maximum thickness estimate (if one exists) or 15 m greater than the highest contour (if a maximum thickness estimate does not exist).

Our volume estimates are minimum numbers for three major reasons. First, we have not made an attempt to project basalts under alluvial cover. Although it is certain that basalts occur beneath valley-filling alluvium, we have limited our volume calculations to areas of known basalt outcrops in the highlands, as outlined by Stewart and Carlson (1978). Second, for the Humboldt lopolith, we have calculated thicknesses of the mafic units only above the valley floors. That is, volume below the elevations of the valley floors is not considered, with the rationale that deeper mining would be more costly than mining in the hills because of the need to pump groundwater during the mining operation. Third, our volume estimates are minimum numbers for steeply dipping basalts, because we use true thickness, rather than vertical depth, to multiply by surface area. Our volume estimates should be divided by the cosine of the dip to provide more accurate estimates; however, for the purpose of this study (in which an error of a factor of two or three is acceptable), the dip of the basalt only introduces a large underestimation when it exceeds 60° (for which the cosine is 0.5). With the exceptions of steeply dipping basalts that occur locally in the area of southern Washoe, Storey, Lyon, and Churchill Counties, most of the basalts in the areas studied for this report are gently dipping or nearly horizontal.

Because this procedure does not involve actually measuring sections, it probably has a fair amount of error associated with it, such that thickness estimates are probably good to one significant figure. This error will propagate through to the volume calculation so that the volumes are only accurate to one significant figure. That is acceptable for the purposes of this report, but the field should be studied in greater detail to generate more accurate volume estimates if and when basalt is going to be used to sequester CO_2 in Nevada,.

Description of Selected Mafic Rock Fields

Nine mafic rock fields in Nevada were studied, and all meet the volume requirement for carbon dioxide sequestration (Table 5). Polygon volume data can be found in Appendix 3, which is available on line at www.nbmg.unr.edu/dox/r52/r52append.htm. Each field is briefly described below.

Table 5. Estimated volumes of mafic rocks for the studied fields.

Field	Estimated Volume (km^3)	Volume requirement met?
Northwestern Washoe County	139	Yes
Owyhee Plateau	177	Yes
Battle Mountain area	29	Yes
Southern Washoe/Storey/ Lyon/Churchill/Pershing Counties	176	Yes
Humboldt lopolith	31	Yes
Southwestern Mineral/ Northwestern Esmeralda Counties	41	Yes
Reveille/Pancake Ranges*	9	Yes
San Antonio Mountains	13	Yes
Southern Clark County	3+	Not necessarily

* Estimate from Yogodzinski et al. (1996).

Northwestern Washoe County

The area studied in northwestern Washoe County extends from west of the Smoke Creek desert on the south to southern Long Valley on the north, and includes portions of the Hays Canyon Range, Granite Range, Buffalo Hills (Figure 8), Buffalo Meadows, and Poodle Hills (Figure 9). Rocks in this area were grouped into the Canyon Assemblage by Bonham and Papke (1969). The geomorphology in the area is dominated by flat-lying plateaus to gently dipping fault blocks bounded by basin-and-range normal faults. Cenozoic and Quaternary rocks comprise ~90% of all outcrops. Lithologies are dominantly volcanic, mostly basalt with lesser andesite, dacite, rhyolite, and intercalated tuffaceous sediments (Bonham and Papke, 1969).

Mafic rocks are exposed throughout much of northern Washoe County, especially in the Hays Canyon and Granite Ranges, and in the Buffalo and Poodle Hills. The most common type of basalt in the area is reddish-brown to black weathered, dark-gray fresh, augite-plagioclase-olivine aphyric basalt (Bonham and Papke, 1969). Relatively little published geochemical data exist from this area. Our samples from this area (M05-1 and M05-2, Table 2) were hypersthene-normative and did not contain normative olivine. However, based on rock descriptions and hand samples, olivine is present in most of these basalts.

Basalt thickness is extremely variable from ~30 m near the Oregon border to ~300 m at Poodle Mountain and in the Hays Canyon Range (Bonham and Papke, 1969). Individual flows are commonly 3-7 m thick. Because the basalt in this area covers such a large area, the thickness required for 1 km^3 is minimal. Based on the estimated thicknesses (Appendix 3) the volume of basalt in this area is ~139 km^3.

Owyhee Plateau

These basalts are located in northeastern Humboldt and northwestern Elko Counties, as well as extending north into Oregon and Idaho (Figure 10). This 17–11 Ma basalt plateau (Shoemaker and Hart, 2004) is a center of volcanism on the Yellowstone hotspot track. On the state geologic map, the basalts in this area are part of the Banbury Volcanics (Stewart and Carlson, 1978), though the basalts were renamed the Big Island Formation by Coats (1985). The Big Island Formation includes ~100 m of boulder gravel, covered by ~6 m of rhyolitic tuff, and ~60 m of tholeiitic olivine basalt. Above the plateau surface are scattered small shield volcanoes and cinder cones, none of which is more than ~90 m above the plateau (Coats, 1985). Basalts are fairly uniform in phenocryst assemblage, geochemistry, and age throughout the plateau (Coats, 1985). CIPW norm values reported by Coats (1985) range from 0 to 14.7 % normative olivine, although all but one analysis had greater than 5% normative olivine. This field is the most voluminous mafic field, with an estimated 177 km^3 of mafic rock.

Battle Mountain Area

A thick section of northern Nevada rift basalts occupies the southern Sheep Creek and northern Shoshone Ranges (Argenta Rim) of northern Lander and Eureka Counties (Figure 11). The basalts range in age from 15.85 Ma to 14.7 Ma (John et al. 2000a) and have an estimated volume of 29 km^3. The northern Nevada rift related rocks have been divided into five units, including (from oldest to youngest) the Mule Canyon sequence (basalt and andesite), the andesite of Horse Heaven, porphyritic dacite, trachydacite, and olivine basalt (John et al. 2000a). If deep surface mining were considered, additional volumes of basalt presumably could be mined from feeder dikes for the basalt flows exposed in this area. One possible area to consider initially would be the Mule Canyon gold mine, where a basalt-andesite volcanic center, including dikes and flows of basalt, was mined (John et al. 2000a, 2003), and sufficient mafic rock may be available for pilot testing of mineral carbonation.

Southern Washoe/Storey/Lyon/Churchill Counties

Mafic rocks crop out throughout southern Washoe, Storey, Lyon, Churchill, and parts of Pershing Counties (Figures 12-17). Basalts in this area are post-~12-18 Ma. The most voluminous basalt package is the 16-12 Ma Pyramid sequence (Bonham and Papke, 1969; Garside et al. 2000; Faulds et al. 2003a, b; Henry et al. 2004; Drakos, 2007). More recent lava flows, including the Lousetown (11-6 Ma, John et al. 1999; Schwartz, 2001) and McClellan Peak (1.5-1.44 Ma, Silberman and McKee, 1972; Morton et al. 1980; John et al. 1999; Schwartz, 2001) Basalts, are thinner and less widespread than the Pyramid sequence basalts. Basalt caps most of the ranges and locally is up to 1 km thick. The mafic rock in this field has a volume of 176 km^3, though the outcrops are spread over a large area.

Humboldt Mafic Lopolith, Churchill and Pershing Counties

The Jurassic Humboldt igneous complex is exposed in the West Humboldt and Stillwater Ranges, the Clan Alpine Mountains, the Carson Sink area, and ranges bordering Dixie Valley (Figure 18). The plutonic sequence includes, from the bottom, olivine gabbro (35 % olivine), melatroctolite (10 % olivine), hornblende gabbro (10 % olivine), microgabbro and diorite, and more felsic intrusions (Speed, 1962). Published ages for the complex include 165±5 Ma and 145±5 Ma, which are K-Ar ages on hornblende and biotite from a gabbro in the West Humboldt Range (Willden and Speed, 1974) and 157±4 Ma, K-Ar on hornblende from diorite in the Stillwater Range (Dilek and Moores, 1995). However, these ages may be anomalously young as the entire complex has been hydrothermally altered (Vanko and Bishop, 1982). The sequence is probably Middle Jurassic (Dilek and Moores, 1995; Johnson and Barton, 2000b).

The olivine gabbro-hornblende gabbro section of the plutonic complex is only exposed locally. The microgabbro-diorite unit is the most extensively exposed plutonic unit. A 100-m-wide basaltic dike swarm intrudes the microgabbro at Cottonwood Canyon and farther south (Dilek and Moores, 1991). Basaltic lavas related to the plutonic complex are exposed at the top of the extrusive segment of the igneous complex. The estimated volume of this unit is 31 km^3, more than an order of magnitude smaller than the ~1,300 km^3 estimate of Willden and Speed (1974). We believe that our volume estimate is considerably smaller because we only include mafic units within the complex and because we only include material above the elevation of the valley floors.

Southwestern Mineral/Northwestern Esmeralda Counties

Late Tertiary (post 5 Ma) basalts are exposed throughout southwestern Mineral and northwestern Esmeralda Counties (Figure 19), especially prevalent east of Aurora, between Candelaria and Teel's Marsh, along the border with California, and in the Garfield, Anchorite, and Volcanic Hills (Ross, 1961; Albers and Stewart, 1972; Brem, 1978; Ormerod, 1988). Thicknesses of basalt approach ~300 m (Ross, 1961), and the estimated volume is 41 km^3. The mafic rocks here are usually dark-gray to gray-black fresh, vesicular, and aphyric with small phenocrysts of olivine, hypersthene, and/or augite. Mafic rocks in this area are generally highly potassic, and as such are classified as trachybasalts, trachyandesites, and quartz latites (Figures 20 and 21; Ross, 1961).

Reveille/Pancake Ranges, Eastern Nye County

Some of the youngest basalts in Nevada are in the Lunar Crater volcanic field (LCVF) in the southern Pancake Range. This is at the northern end of NNE-trending zone of Pliocene-Holocene (?) mafic volcanism that extends from Death Valley to the southern Pancake Range (Vaniman et al. 1982; Farmer et al. 1989; Yogodzinski et al. 1996; Smith et al. 2002; Smith and Keenan, 2005). While volcanism at the LCVF is the youngest in eastern Nye County, older basalts to the south in the Reveille Range are more voluminous (Figure 22). Yogodzinski et al. (1996) estimate that ~9 km^3 of Pliocene basalt occurs in the Reveille Range. Basaltic volcanism reached a peak during the Pliocene, becoming more localized and sporadic during the Quaternary (Yogodzinski et al. 1996).

Mafic volcanism began ~14 Ma in the Reveille Range and continued until ~3 Ma (Rash, 1995; Yogodzinski et al. 1996). The initial mafic volcanism was basaltic and is exposed in the northwest Reveille Range with an estimated volume of ~0.05 km^3 and a thickness of up to 30 m where exposed (Rash, 1995). The next episode of basaltic volcanism (episode 1 of Naumann et al. 1991) occurred between 5.9 and 5.1 Ma. These are porphyritic olivine basalts (hawaiites) with plagioclase megacrysts. They erupted from 52 vents with an estimated volume of 8 km^3 (Naumann et al. 1991; Rash, 1995; Yogodzinski et al. 1996). Following the eruption of 4.24-4.39 Ma trachytes (Naumann et al. 1991) a second package (episode 2) of basalts was erupted between 4.24(?) and 3.00 Ma. These are porphyritic plagioclase-clinopyroxene-olivine basalts (mostly basanites with lesser hawaiites). They erupted from 14 vents with an estimated volume of 1 km^3 (Naumann et al. 1991; Rash, 1995; Yogodzinski et al. 1996). Because published volume estimates are based on detailed study of the mafic field, those estimates are used for this report.

More recent mafic volcanism has occurred in the Quaternary-Holocene (?) in the southern Pancake Range at the LCVF, which contains numerous cinder cones and lava flows (Figures 23 and 24; Scott, 1969; Scott and Trask, 1971; Smith et al. 2002, Smith and Keenan, 2005). These flows cover ~250 km^2 but are fairly thin. Many of the flows contain mafic and ultramafic xenoliths of olivine ± pyroxene ± plagioclase (Scott, 1969; Scott and Trask, 1971). Because the mafic rocks in the Pancake Range are thin, they are not included in the volume estimate for the field.

Based on geochemical and isotopic data, Yogodzinski et al. (1996) found that these basalts were derived from asthenospheric melts. The episode 2 basalts have ^{87}Sr/^{86}Sr of 0.7035 and ε_{Nd} of +4.2, but the episode 1 basalts have more variable ^{87}Sr/^{86}Sr (up to 0.7060) and ε_{Nd} (+0.8 to +4.5). Additional variations in Sr/Nd and Pb/La require that the episode 1 basalts have a crustal component, probably carbonate wall-rock. Because basanites only were erupted during episode 2, these eruption episodes were probably caused by separate melting events (Yogodzinski et al. 1996).

San Antonio Mountains, western Nye County

Most of the San Antonio Mountains and Thunder Mountain in the Monitor Range consist of basalt (Figure 25). Basaltic volcanism in this area came at the end of volcanic activity in the Tonopah area, and the basalt caps much of the San Antonio Mountains. Red Mountain, which is north of Tonopah, was one source of the basalt. Another volcanic center occupies the northern end of the San Antonio Mountains at the San Antone mining district (Kleinhampl and Ziony, 1985). Estimated basalt volume is 13 km^3.

Southern Clark County

Basaltic rocks are exposed in Clark County between Las Vegas and Searchlight (Figure 26). Those considered for this study are in the McCollough Range (Figure 27) and Eldorado Mountains. More basalt is exposed in the Black, River, and South Virgin Mountains, but because these ranges are in the Lake Mead National Recreation Area, they were not considered for this study. The volcanic units in this area were divided into three main members by Anderson (1971); those are 1) the Patsy Mine Volcanics, 2) the tuff of Bridge Spring, and 3) the Mount Davis Volcanics. Faulds et al. (2001) show eight episodes of volcanism in the Lake Mead area, including 1) mafic to intermediate 21-18.5 Ma “Pre-Patsy Mine Volcanics”, 2) 18.5 Ma Peach Springs Tuff (Glazner et al. 1986; Nielson et al. 1990), 3) 18.5-15.2 Ma basaltic andesite to rhyolite of the Patsy Mine Volcanics (Anderson, 1971; Anderson et al. 1972; Faulds et al. 1995;

Faulds, 1996), 4) 15.2 Ma tuff of Bridge Spring (Anderson et al. 1972; Morikawa, 1994; Faulds et al. 1995) and the 15.0 tuff of Mount Davis (Faulds 1995; Faulds et al. 2002), 5) 15-~12 Ma basalt to basaltic andesite of the Mount Davis Volcanics (Anderson et al. 1972; Faulds, 1995), 6) local 11.9-8.7 Ma tholiitic basalt fields, including Malpais Flattop Mesa in the northern Black Mountains, 7) local 10.6-8.0 Ma basaltic andesites, including those at Callville Mesa, and 8) 6.0-4.5 Ma alkalic Fortification Hill basalts (Feuerbach et al. 1993).

Whereas basalt is present in southern Clark County, the overwhelming majority of the volcanic rocks are andesites, basaltic andesites, and dacites (Anderson, 1977; 1978). The Tertiary volcanic section in this area is on the order of ~5 km thick, but basalt only comprises 10-150 m of the section (Anderson, 1977; Faulds et al. 2001). The final stage of volcanism is basaltic, but that is confined to eastern Clark County (in the Lake Mead National Recreation Area) and northwestern Arizona (Faulds et al. 2001). Structural complexity (especially in the Eldorado Mountains) makes obtaining an accurate “above valley-fill” basalt volume estimate exceedingly difficult. Additionally, much of this area is part of the newly formed McCollough Mountains Wilderness Area and would therefore be off limits for mining. Nonetheless, a range of basalt volumes was calculated by multiplying the area of volcanic rocks (Figure 26) by the basalt thicknesses. The basalt volume ranges between 3.4 and 50.6 km^3, though the majority of this is not exposed at or near the surface. More work would need to be done to determine the amount of basalt outside the wilderness area.

OTHER NEVADA MINERAL RESOURCES THAT COULD BE AMENABLE TO SEQUESTRATION OF CO_2

We have made a literature survey of iron and manganese deposits in an effort to determine the extent of remaining reserves of iron and manganese ore in Nevada that might be amenable for use in carbon sequestration by mineral carbonation. Significant deposits of iron and manganese in Nevada with sufficient reserves to use in carbon dioxide sequestration are summarized in Table 6 showing their names, location, land status, predominant mineralogy, past production, and estimated remaining reserves.

A location map of iron and manganese deposits and other minerals amenable to mineral carbonation in Nevada is shown in Figure 28 illustrating proximity to railways, highways, and existing power plants. Other considerations of iron and manganese deposits besides reserve tonnage are:

- proximity of the deposits to rail transport or to existing or future coal-fired power plants
- amenability of the mineralogy of the deposits to carbonate formation
- land status (public or private)
- depth and geometry of the deposits (cost of extraction)

Significant Iron Deposits of Nevada

Total tonnage of resources remaining in Nevada iron deposits was estimated in 1964 at between 0.5 billion and 1.0 billion metric (approximately the same as long) tons of material grading more than 40% iron (Reeves, 1964). Nevada’s iron production dropped off sharply in the 1960s and

Table 6. Significant deposits of iron, manganese, and other minerals in Nevada with sufficient reserves to be considered for use in carbon dioxide sequestration.

Site Name	District Name	County Northing	UTM Easting	UTM (NAD 27)	Latitude (NAD 27)	Longitude	Ore Minerals	Land Status	Past Production	Estimated Remaining Reserves
IRON DEPOSITS										
Buena Vista Hills, Churchill & Pershing Counties										
Buena Vista Mine	Mineral Basin	Churchill	4425400	400000	39-58-29N	118-10-16W	magnetite, hematite	patented and BLM-administered land	Collectively, the mines of the Buena Vista Hills produced over 4 million tons of iron ore averaging over 50% Fe over a production history that peaked in the 1950s and dwindled in the 1980s.	Collectively the Buena Vista Hills mines contain an estimated 1.5 million tons grading 50–60% Fe plus a significant tonnage of lower grade material.
Segerstrom-Heizer Mine	Mineral Basin	Pershing	4432890	402220	40-02-32N	118-08-51W	magnetite, hematite, pyrite, marcasite	patented and BLM-administered land		
Thomas Mine	Mineral Basin	Pershing	4438100	398680	40-05-20N	118-11-19W	magnetite, hematite	patented and BLM-administered land		
American Ore Co. Mine	Mineral Basin	Pershing	4433225	403040	40-02-49N	118-08-12W	magnetite	patented and BLM-administered land		
American Ore Co. Mine (North)	Mineral Basin	Pershing	4437570	399060	40-05-11N	118-11-17W	magnetite	patented and BLM-administered land		
American Ore Co. Mine (South)	Mineral Basin	Pershing	4431650	401550	40-01-52N	118-09-14W	magnetite	patented and BLM-administered land		
Cortez Mountains, Eureka County										
Barth Mine (West Mine)	Safford	Eureka	4492025	561832	40-34-43N	116-16-10W	Hematite, magnetite, specular hematite	patented and BLM-administered land	Collectively the Cortez Mountains area mines produced about two million tons of iron ore. The main periods of production were 1903–1918 and 1950s–1960s, with sporadic production into the 1980s.	Collectively the Cortez Mountains area mines and prospects contain an estimated 3.5 million tons of material grading about 50% Fe plus a significant tonnage of lower grade material.
Unnamed Iron Deposit	Safford	Eureka	4496500	565813	40-37-07N	116-13-19W	magnetite, hematite	patented and BLM-administered land		
Modarelli (Amarilla) Iron Mine	Modarelli-Frenchie Creek	Eureka	4468474	562640	40-21-59N	116-15-44W	martite, magnetite	BLM-administered land		
Sheep Creek Prospect	Modarelli-Frenchie Creek district	Eureka	4461505	558779	40-18-14N	116-18-30W	magnetite, hematite	BLM-administered land		
Big Pole Creek	Modarelli-Frenchie Creek	Eureka	4465880	558320	40-20-36N	116-18-48W	magnetite, hematite	BLM-administered land		
Jackson Prospect	Modarelli-Frenchie Creek	Eureka	4468342	557688	40-21-56N	116-19-14W	hematite, magnetite	BLM-administered land		
Imperial Prospect	Modarelli-Frenchie Creek	Eureka	4467959	559979	40-21-43N	116-17-37W	magnetite, hematite	BLM-administered land		
Frenchie Creek Prospect	Modarelli-Frenchie Creek	Eureka	4467345	560338	40-21-23N	116-17-22W	magnetite, hematite	BLM-administered land		
Frenchie Canyon Prospect	Modarelli-Frenchie Creek	Eureka	4466719	559187	40-21-03N	116-18-11W	hematite, magnetite	BLM-administered land		
Jackson Mountains, Humboldt County										
Iron King (DeLong) Mine	Jackson Mountains District; Jackson Creek	Humboldt	4573700	381000	41-18-36N	118-25-22W	magnetite, hematite	patented and BLM-administered land	Collectively the three main Jackson Mountains mines produced probably less than a million tons of iron ore, mainly in the 1950s.	Collectively the three main Jackson Mountains mines contain an estimated 750,000 tons of material grading between 15–40% Fe.
Black Jack (Humboldt) Mine	Jackson Mountains District; Jackson Creek	Humboldt	4572800	380300	41-17-29N	118-26-22W	magnetite, hematite	patented and BLM-administered land		
Redbird Mine	Jackson Mountains District; Jackson Creek	Humboldt	4573120	381000	41-18-10N	118-25-17W	magnetite	patented and BLM-administered land		

continued

Table 6 (continued). Significant deposits of iron, manganese, and other minerals in Nevada with sufficient reserves to be considered for use in carbon dioxide sequestration.

Site Name	District Name	County	UTM Northing	UTM Easting	Latitude (NAD 27)	longitude (NAD 27)	Ore Minerals	Land Status	Past Production	Estimated Remaining Reserves
IRON DEPOSITS (continued)										
Dayton area, Lyon & Storey Counties										
Dayton Iron Deposit (Rosetta Mine)	Red Mountain	Lyon	4360095	288936	39-21-25N	119-25-41W	magnetite, pyrite	patented and BLM-administered land	The Dayton iron deposits have not produced any appeciable amount of iron.	The Dayton iron deposits contain an estimated 7.5 million short tons of ore grading from >40% Fe to >50% Fe, plus 100 million tons of lower grade material.
Iron Blossom Prospect	Red Mountain	Lyon	4358363	285276	39-20-60N	119-29-31W	magnetite	patented and BLM-administered land		
Gabbs area, northwest Nye County										
Phelps Stokes (Iron Mountain) Mine	Gabbs	Nye	4304600	428000	38-53-34N	117-49-30W	magnetite, hematite, pyrite, pyrrhotite	patented and BLM-administered land	The Phelps-Stokes Mine produced about a half million tons of iron ore from 1949 through the 1950s with sporadic small production into the 1970s.	There is an estimated 500,000 tons of material grading between 50% Fe remaining in the mine area.
Yerington Area, Douglas & Lyon Counties										
Minnesota Mine	Buckskin	Douglas	4326600	298000	39-04-08N	119-20-03W	magnetite, pyrite	patented and BLM-administered land	The Minnesota Mine produced nearly 4 million tons of iron ore, mainly in the 1950s and 1960s.	There is an estimated 2–3 million tons of ore grading about 50% Fe remaining in the mine area.
Pumpkin Hollow deposit (Lyon Prospect)	Yerington	Lyon	4311400	321000	39-04-01N	119-20-05W	magnetite, chalcopyrite	patented and BLM-administered land	The Pumpkin Hollow deposit remains unmined.	Up to 440 million short tons of ore grading 24% to 40% Fe.
TOTAL									Total production of iron ore from Nevada iron mines is about 12 million tons of ore grading over 50% Fe.	A conservative estimate of Nevada's total remaining iron-bearing resource is about 558 million tons of material grading up to 50% Fe, with a possibility of as much as 1.5 billion tons of material of grade varying between 15% and 50% Fe.
MANGANESE DEPOSITS										
Las Vegas Area, Clark County										
Three Kids Deposit (Manganese Inc. Mine)	Las Vegas	Clark	3995000	688000	36-05-29N	114-54-43W	manganite, pyrolusite	patented and BLM-administered land	More than 2.2 millon tons of manganese ore was mined from the Three Kids deposit, mainly from the 1950s through the 1960s.	There are about 3.3 million tons grading 5% to 18% Mn plus more lower grade material remaining in the Three Kids Mine area.
Boulder City Deposit	Las Vegas	Clark	3980000	699350	35-56-45N	114-47-24W	manganite, pyrolusite	patented and BLM-administered land	No production was reported from the Boulder City manganese deposit.	The Boulder City deposit contains approximately one million tons of material grading 7.5% Mn or 15 million tons with an average grade of 3% Mn.
TOTAL										A conservative estimate of Nevada's total remaining manganese-bearing resource is about 4.3 million tons of higher grade material grading between 5% and 18% Mn, plus about 20 million tons of lower grade manganese-bearing material with an average grade of up to 3% Mn.
WOLLASTONITE DEPOSITS										
Gilbert Wollastonite Deposit	Gilbert	Esmeralda	4222000	441000	38-08-45N	117-40-23W	wollastonite	BLM-administered land	No wollastonite has been produced.	The Gilbert wollastonite deposit is estimated to contain a resource of about two million tons of material containing 50–70% wollastonite.
BRUCITE DEPOSITS										
Gabbs Brucite Deposit	Gabbs	Nye	4302100	422500	38-51-58N	117-53-36W	brucite	patented and BLM-administered land	About 3 million tons of brucite ore was mined from the Gabbs brucite deposit beginning in the late 1930s and continuing into the 1980s. The high-grade brucite ore was mostly mined out in the early days, but mining of magnesite continues today.	The Gabbs Brucite deposit contains an estimated 200,000 tons of remaining brucite ore.

dwindled to near zero by the 1980s leaving most of these reserves unmined. That estimate was made, however, before reports of the reserves of the Pumpkin Hollow (Lyon) iron skarn deposit were public. Inclusion of this additional deposit would increase the total estimated amount of unmined iron ore in Nevada to approximately 1.5 billion metric tons.

There are six known areas of Nevada that host significant iron deposits with total endowment (past production plus reserves and resources) in excess of a million metric tons of iron ore:

- The Buena Vista Hills, located on the Pershing –Churchill County line in west-central Nevada (Reeves and Kral, 1958; Nylen, 1998; Johnson and Barton, 2000a, 2000b).
- The Cortez Mountains of Eureka County (Shawe et al. 1962; Roberts et al. 1967).
- The Jackson Mountains of Humboldt County (Shawe et al. 1962)
- The Dayton area near the Lyon-Storey County line (Roylance, 1965; 1966; Reeves et al. 1958).
- The Gabbs area in northwest Nye County (Reeves et al. 1958).
- The Yerington area in Lyon and Douglas Counties (Reeves et al. 1958; Dilles et al. 2000a, 2000b; Matlock and Ohlin, 1996).

Buena Vista Hills

Although iron was discovered in the Buena Vista Hills in 1898, there was no appreciable production from the deposits before World War II. Iron ore was mined from several deposits in the Buena Vista Hills beginning in 1952 and was shipped to Japan for use in post-World War II reconstruction. The area had produced more than 560,000 long metric tons of ore by the end of 1952. The grade of the ore shipped at this time was about 57% Fe or higher. Production continued throughout the 1950s at a rate of 2,500 to 3,000 metric tons of iron ore per day. Production dwindled throughout the 1960s (Reeves and Kral, 1958; Johnson, 1977), and ended completely by the early 1980s. The mines of the district were estimated to have produced a total of more than 4 million metric tons of iron ore with an average grade of over 50 weight percent iron (Moore, 1969, 1971; Johnson and Barton, 2000b).

There were four main producing iron mines in the Buena Vista Hills area: the Buena Vista Mine, the Segerstrom-Heizer Mine, the Thomas Mine, and the American Ore Company Mine (Stoker-Marker, Parker Brothers). Remaining reserves from the combined mines were estimated to be several hundred thousand metric tons plus an additional million tons of inferred material, all grading from 50% to more than 60% Fe. There may be a considerable tonnage of material in these deposits of too low a grade for iron ore, but which would be amenable for use in mineral carbonation.

Most of the Buena Vista Hills iron mine area is underlain by a large composite intrusion of Mesozoic (Jurassic) age and basaltic composition, which intruded and metamorphosed Upper Paleozoic to mid-Mesozoic volcanic and sedimentary rocks. The intrusive rock in the mined areas is a diorite that has undergone intense sodium-rich hydrothermal alteration forming a medium- to coarse-grained rock consisting almost entirely of scapolite and hornblende (Johnson and Barton, 2000a, 2000b). This scapolitized diorite is the main host rock for the iron deposits. The deposits occur as steeply dipping irregular replacement bodies in brecciated areas at fault intersections and as stratabound orebodies. The mineralogy of the deposits is predominantly magnetite with partial minor replacement by hematite (Reeves and Kral, 1958). Minor gangue minerals constitute a small fraction of the ore material and include calcite, apatite, chlorite, scapolite, and hornblende.

An order-of-magnitude, liberal estimate of the amount of magnetite available in the Buena Vista Hills is 1.4 million metric tons of Fe_3O_4 (equivalent to two million metric tons of ore grading 50% Fe) or 2.7×10^5 m^3 (2.7×10^{-4} km^3) of magnetite.

Cortez Mountains

Major deposits in the Cortez Mountains include those at the Barth Mine and Modarelli Mine, and the Frenchie Creek prospects. The Barth iron mine is located on formerly Southern Pacific Railroad land 10 km west of Palisade, on the Humboldt River, southwest of Elko in Eureka County. The Barth deposit is a replacement of Mesozoic-age andesitic volcanic rocks by magnetite subsequently replaced by hematite. Quartz monzonite intrudes similar rock about 550 m west of the Barth pit. The ore mineralogy of the deposit is predominantly hematite with some magnetite (Shawe et al. 1962; Cornwall, 1965).

The deposit was recognized in the 1860s, and mined in the 1900s. From 1903 to 1918, 761,000 metric tons of iron ore were mined from the Barth deposit and shipped by rail to Salt Lake City for use as smelter flux ore (Nylen, 1998). Exploration in the 1950s discovered that the iron deposit was approximately 370 by 90 m and up to 75 m thick, and extended to the north underneath alluvium in the river bed. The Humboldt River channel was diverted and the mine was reopened in 1961, producing approximately 600,000 metric tons of ore grading 63-64% Fe by 1964 (Shawe et al. 1962). The Barth Mine continued minor production of iron ore through 1988 (Nevada Bureau of Mines and Geology, 1981, 1982, 1983, 1984, 1987, 1988, and 1989).

The Modarelli Mine deposit, about 40 km south of the Barth deposit, was discovered in 1903 and mined sporadically throughout the 1950s into the 1960s (Nylen, 1998). By 1961 the mine had shipped nearly 400,000 metric tons of iron ore concentrate grading 58% Fe. The deposit was wedge-shaped with dimensions of approximately 430 by 300 by 270 m. It consisted of a replacement of Mesozoic rhyodacitic volcanic rocks by magnetite, in turn partially replaced by hematite. The deposit was developed both by an open cut and by underground workings on eight levels. The southeast half of the deposit was described as consisting of ore with the rest of lower grade material, so one can assume considerable tonnage (perhaps half a million metric tons) of iron-rich material grading less than 58% Fe remaining as a resource in the Modarelli Mine area (Shawe et al. 1962).

In the same general area are the Frenchie Creek prospects, a series of about nine sub-ore grade lenses or pods of iron oxides replacing rhyodacitic tuff along a northeast-striking shear zone. These range from a few tens of m in diameter up to a 120-by-120-m pod, grading 34% to 53% Fe. Iron is in the form of magnetite and hematite in varying proportions (Shawe et al. 1962). Exact tonnage of these lenses and pods is unknown, but collectively they could constitute up to a few million metric tons of iron-rich material amenable to mineral carbonation.

An order-of-magnitude, liberal estimate of the amount of hematite available in the Cortez Mountains is 1.5 x 10^6 metric tons of Fe_2O_3 (approximately equal to past production) or 2.9 x 10^5 m^3 (2.9 x 10^{-4} km^3) of hematite.

Jackson Mountains

The Jackson Mountains in west-central Humboldt County host three sizeable deposits of iron ore: the Iron King (DeLong), Red Bird, and Black Jack Mines, which were developed together beginning in the 1950s. Combined total production for the Jackson Mountains deposits was more than 780,000 metric tons of massive magnetite ore with few impurities, grading more than 50% Fe (Shawe et al. 1962). The amount of ore remaining in the deposits is unknown but may be estimated to be at least equivalent to the amount produced, probably at a somewhat lower grade (15% to 40% Fe). The orebodies are lenticular replacements of metavolcanic rocks within a north-striking shear zone near a contact with intrusive diorite. An order-of-magnitude, liberal estimate of the amount of magnetite available in the Cortez Mountains is 1.0 million metric tons of Fe_3O_4 (equivalent to two million metric tons of ore grading 50% Fe) or 1.9 x 10^5 m^3 (1.9 x 10^{-4} km^3) of magnetite.

Dayton Area

The Dayton iron deposits are about 35 km southeast of Reno, 19 km northwest of Dayton, and 3 km northwest of U.S. Highway 50 on a pediment along the southeast base of the Flowery Range. There are two exposures of iron oxide about 300 m apart, which are connected at depth forming the main Dayton deposit, with several smaller satellitic magnetite bodies (Roylance, 1965, 1966). The Dayton iron deposit was first discovered and patented between 1903 and 1908, and was further explored in the 1940s by the U.S. Bureau of Mines (USBM), which did trenching and drilling of the area to delineate the areal extent of the deposit. Utah Construction and Mining Company bought the property in 1951 and explored it with 11,000 m of rotary drilling through 1961 (Roylance, 1965, 1966).

The Dayton deposit is composed predominantly of magnetite partially oxidized to hematite to a depth of about 30 m. The southern part of the deposit is exposed at the surface, whereas the northern half is overlain by 1.5 to 9 m of colluvium. The mineralized zone covers an area at least 610 m long by 460 m wide, extends to a depth of 180 m, and is exposed at the surface. Reserve tonnages are estimated at 6.8 million metric tons of iron ore grading more than 40% Fe, much of it more than 50% Fe. The total resource of lower grade iron-bearing material could be as much as 100 million metric tons.

Regionally metamorphosed Mesozoic carbonate sediments and mafic volcanic rocks were intruded by Jurassic diorite to granodiorite. Magnetite ore formed mainly at the contact between carbonate sedimentary rocks and the granodiorite. Ore-forming fluids are thought to have accompanied the intrusion of the granodiorite. A later quartz monzonite intrusion is post-mineral in age, possibly Cretaceous. The entire package was tightly folded in an anticline overturned to the northeast, and subsequently faulted into segments (NBMG mining district files available at www.nbmg.unr.edu/scans/3870/38700001.pdf, www.nbmg.unr.edu/scans/3870/38700003.pdf, www.nbmg.unr.edu/scans/3870/38700005.pdf,

www.nbmg.unr.edu/scans/3870/38700007.pdf, and
www.nbmg.unr.edu/scans/3870/38700010.pdf. An order-of-magnitude estimate of the amount of magnetite available in the Dayton area is 60 million metric tons of Fe_3O_4 (equivalent to 110 million metric tons of ore grading 40% Fe) or 1.2×10^7 m^3 (1.2×10^{-2} km^3) of magnetite.

West-Central Nevada

Approximately 20 iron deposits and prospects in west-central Nevada have had variable amounts of production, but of these, only three contained more than a few thousand metric tons of iron ore: 1) the Phelps-Stokes Mine near Gabbs, 2) the Minnesota Mine northwest of Yerington, and 3) the Pumpkin Hollow deposit (Lyon prospect) southeast of Yerington.

Gabbs Area

The Phelps Stokes Mine in northwestern Nye County near Gabbs was discovered in 1902 and was mined mainly between 1949 and 1954, producing more than 400,000 metric tons of iron ore grading up to 55% Fe during that time period. It was sporadically active during the 1960s and 1970s (Cornwall, 1965). The mineralogy of the deposit is primarily magnetite with some hematite. The deposit formed as a replacement of Triassic Luning Formation dolomite, probably associated with the intrusion of Tertiary dikes (Reeves et al. 1958). Remaining reserves are not published but are conservatively estimated to be about equal to the amount mined – approximately one-half million metric tons of material grading up to 50% Fe. This equates to 3.5×10^5 metric tons of Fe_3O_4 or 6.7×10^4 m^3 (6.7×10^{-5} km^3) of magnetite.

Yerington Area

The Minnesota Mine is located in the Buckskin Mountains in the extreme northeast corner of Douglas County, a few kilometers northwest of Yerington. It is a skarn (contact metamorphic hydrothermal) deposit, and was first worked in the early 1900s as a copper mine. Although sporadic iron ore production began in the 1940s, Standard Slag Company began large-scale production of iron ore from the mine in 1952. By 1969, the Minnesota Mine had produced more than 3.7 million metric tons of iron ore averaging about 50% Fe in grade, mainly for shipment to Japan during reconstruction. There may be as much as two to three million metric tons of iron ore remaining in the deposit. The iron skarn deposit formed in Triassic and Jurassic metasedimentary (dolomite) and metavolcanic rocks intruded by granodiorite and pyrite-bearing quartz monzonite porphyry. Magnetite is the predominant ore mineral present in the deposit, with lesser disseminated chalcopyrite and minor molybdenite (Reeves et al. 1958).

Pumpkin Hollow Deposit

The Pumpkin Hollow deposit (Lyon prospect) is reportedly the largest iron skarn deposit in Nevada. It is located in the Wassuk Range about 8 km southeast of Yerington in Lyon County. The estimated aggregate tonnage of the several Pumpkin Hollow orebodies is at least 250 million metric tons of ore grading from 24% to 40% iron and containing up to a few percent copper and up to 0.7 parts per million gold by weight (0.02 troy ounces of gold per short ton of ore), but the deposit may be as large as 400 million metric tons (Sherlock et al. 1996; Nevada Bureau of

Mines and Geology, 2000, 2001). Smaller reserves have been reported for the higher-grade copper-gold portion of the deposit. The Pumpkin Hollow deposit is similar to many other Nevada iron skarns in its geology, but is much larger and remains totally unmined. The deposit does not crop out at the surface and is covered by 90 to 400 m of alluvium. It was first located in 1960 by an aeromagnetic survey, followed by extensive ground geophysical surveys and drilling in the early 1960s to delineate the size and extent of the orebodies (Smith, 1984; NBMG mining district files available at www.nbmg.unr.edu/scans/5430/54300039.pdf and www.nbmg.unr.edu/scans/5430/54300043.pdf).

The Pumpkin Hollow deposit was formed when Upper Triassic to Jurassic carbonate and siliceous sedimentary rocks were intruded by Jurassic plutonic rocks ranging in composition from quartz monzonite to granite porphyry. The mineralizing intrusion is part of the northern Yerington batholith associated with the Yerington porphyry copper deposit. Contact metasomatic replacement mineralization occurred in the metasedimentary rocks adjacent to the igneous contact. The orebodies are irregularly shaped masses greater than 300 m long, 150 m wide, and 520 m thick vertically. Metallic minerals include magnetite, pyrite, chalcopyrite, and pyhrrotite. Gangue minerals are silica, calcite, actinolite, tremolite, garnet, epidote, chlorite, and talc (Ohlin et al. 1995; NBMG Yerington mining district file, available on line through http://www.nbmg.unr.edu/mdfiles/mdfiles.htm).

An order-of-magnitude, liberal estimate of the amount of magnetite available in the Yerington area is 250 million metric tons of Fe_3O_4 (equivalent to 450 million metric tons of ore grading 40% Fe) or 4.8×10^7 m^3 (4.8×10^{-2} km^3) of magnetite.

Significant Manganese Deposits of Nevada

The Three Kids Mine area of southern Clark County, located just southeast of Las Vegas, is the only significant manganese resource in Nevada with the potential for use in mineral carbonation. The manganese ore at the Three Kids Mine occurs as a bedded deposit concordant with layering of the enclosing sedimentary rocks, formed by the replacement of volcanic tuff and volcaniclastic sediments. Tabular beds of manganese oxide minerals pyrolusite (MnO_2), psilomelane ($Ba(Mn^{2+}, Mn^{4+})_5O_{10}\ H_2O$), and manganite ($Mn^{3+}O\ (OH)$) are found in a persistent zone about 30 m above the base of the sedimentary sequence of gypsum and other sedimentary rocks (Hewett and Weber, 1931; Hunt et al. 1942; Hewett et al. 1963; Longwell et al. 1965).

The Three Kids deposit was estimated to contain at least 500,000 metric tons of manganese ore grading 30% Mn, with the possibility of an additional half million tons of the same when it was first explored in the 1930s. In 1942, after detailed mapping and sampling work, Hunt et al. (1942) estimated the reserves of the Three Kids deposit at about 5.0 million metric tons of material averaging 10% Mn, of which about a 0.9 million metric tons averaged 20% Mn. Total Nevada production of manganese ore to 1964 was about 800,000 metric tons of ore and concentrates grading mostly over 35% Mn. Most of the production was from the Three Kids Mine, where more than 2.0 million metric tons of 18% Mn ore was processed to yield more than 540,000 metric tons of concentrate grading 45% Mn. Total resource tonnage remaining in the deposit could be estimated at about 3.0 million metric tons of ore averaging between 5% and 18% Mn, plus an unknown additional tonnage at lower grades. In addition, the nearby Boulder

City deposit # 7 was estimated in 1964 to contain resources of one million metric tons of material grading 7.5 % Mn or 15 metric million tons averaging 3% Mn (McKelvey and Wiese, 1949; Trengove, 1959).

An order-of-magnitude, liberal estimate of the amount of manganese available in the Three Kids deposit area is one million metric tons of Mn. Apart from psilomelane, the ore minerals in this area contain relatively oxidized ions, making the reactions with CO_2 thermodynamically unfavorable. If the estimated amount of Mn occurred as the reduced mineral, manganosite, it would occupy a volume of approximately 2.4×10^5 m^3 (2.4×10^{-4} km^3).
A significant amount of manganese-bearing ore in Nevada also remains in the mines of the Pioche District in Lincoln County (Bell, 1911; Gemmill, 1968; Tschanz. and Pampeyan, 1970; Westgate and Knopf, 1932). The mineralogy of the Pioche ore, however, is predominantly manganoan siderite, a carbonate mineral which would not be amenable to carbon dioxide sequestration because it has no capacity to combine with additional CO_2.

Other Minerals Amenable to Carbonation

There are sizeable deposits in Nevada of other industrial minerals that might prove to be compatible with carbon dioxide sequestration by mineral carbonation. Notable among these are wollastonite ($CaSiO_3$) and brucite ($Mg(OH)_2$).

Gilbert Wollastonite Deposit

Reaction of CO_2 with wollastonite is thermodynamically attractive (Table 2). There is at least one area in Nevada that hosts a resource of wollastonite large enough to possibly have potential for use in CO_2 sequestration. The Gilbert wollastonite deposit is located in the Gilbert mining district in Esmeralda County, about 48 km north of Tonopah. The Anaconda Company first identified the wollastonite in the 1970s during gold exploration. Mapping and drilling in the 1980s identified at least three wollastonite zones in a skarn, and an unsuccessful attempt was made in 1994–1995 to develop, process, and market wollastonite from the property (Nevada Bureau of Mines and Geology, 1990; 1991; 1995; 2001; 2003). Recent reports indicate that the Gilbert deposit contains a resource of more than 1.8 million metric tons grading more than 50% wollastonite with zones averaging over 70% wollastonite. Mineralization extends to depths as much as 150 m, and overburden in the area is reported to be negligible. Slightly more than doubling the known resource to estimate total potential of the deposits in the area results in two million metric tons of wollastonite (a volume of 6.9×10^5 m^3 (6.9×10^{-4} km^3).

The Pinson Mine property in the Potosi mining district of Humboldt County hosts scattered veins and small lenses of wollastonite, but no significant tonnage of wollastonite material has been reported (Willden, 1964).

Gabbs Brucite Deposit

Brucite ($Mg(OH)_2$) is one of the minerals that have been mined at Premier Chemical Company's Gabbs magnesite mine (formerly Basic Refractories) near Gabbs in Nye County. There is an abandoned brucite pit on the mine property which still contains an estimated resource of 180,000 metric tons or more of brucite ore (Adam Knight, mine manager, personal commun., 2006). This is the only known brucite deposit of any size in the state. Most of the material currently mined from the property consists of magnesite (magnesium carbonate), which is not amenable to mineral carbonation. If the ore were pure brucite, it would occupy a volume of approximately 8.3×10^4 m^3 (8.3×10^{-5} km^3).

DISCUSSION

There is plenty of mafic rock (mostly basalt) in Nevada to meet the CO_2 sequestration demands for several large power plants (Table 7). However, it is clear from the estimated volumes (Table 7) that Nevada lacks sufficient quantities of other rock types for sequestering CO_2 from a large power plant. Even the locality with the largest amount of material (magnetite from the Yerington area) has only 15% of what would be needed for a large power plant. Furthermore, the oxidized iron and manganese ores found in Nevada are not thermodynamically favorable for the reactions (endothermic and positive free energies of reaction for magnetite, hematite, and pyrolusite in Table 2). Although wollastonite or brucite would be thermodynamically favorable, the amounts available from known deposits are three to four orders of magnitude smaller than what would be needed.

Table 7. Estimated volumes of potential rock and mineral reactants available in Nevada, compared with what is needed for a large power plant.

Rock type	Volume required for power plant that burns 0.25 gigaton of C (km^3)	Locality	Volume of rock or mineral (km^3)
Basalt	1.3	Northwestern Washoe Co.	139
		Southern Washoe area	176
		Humboldt lopolith	31
		Owyhee Plateau	177
		Battle Mountain area	29
		Southwestern Mineral area	41
		San Antonio Mountains	13
		Reveille/Pancake Ranges	9
		Southern Clark County	3+
Magnetite	0.31	Buena Vista Hills	0.00027
		Jackson Mountains	0.00019
		Dayton area	0.012
		Gabbs area	0.000067
		Yerington area	0.048
Hematite	0.32	Cortez Mountains	0.00029
Manganosite*	0.28	Three Kids Mine area	0.00024
Wollastonite	0.83	Gilbert deposit	0.00069
Brucite	0.51	Gabbs	0.000083

* The actual Mn ore minerals are thermodynamically less favorable for reaction with CO_2 than manganosite, which has not been reported in this area.

Commercial-scale sequestration by reaction with rocks, although highly attractive as a means of permanently disposing of the CO_2, is likely to be far in the future, because the chemical reactors and overall power generation-mining-waste disposal systems would need to be designed, perfected, and demonstrated to be cost-effective. Mazzotti et al. (2005) discussed industrial and environmental hurdles to a commercial enterprise, including standard issues involved with mining. Unfortunately, judging from rates of chemical weathering of these rocks and some experiments (e.g., Carroll and Knauss, 2006), the kinetics of the reactions are generally slow (Intergovernmental Panel on Climate Change, 2005; Mazzotti et al. 2005).

Mazzotti et al. (2005) noted that several industrial waste products, including various ashes from coal-fired power plants and municipal solid-waste incinerators, stainless steel slag, and waste cement, may be attractive for reactions with CO_2, as they contain high concentrations of CaO and MgO. In addition, scrap iron could be ideal, because its reaction with CO_2 to form iron carbonate is thermodynamically highly favorable (Table 2). These waste products could be incorporated into an industrial complex that included a coal-fired power plant located near a substantial source of basalt. The resultant carbonate minerals could be used to isolate other municipal and industrial waste products, much of it refilling the holes dug in the ground to mine the basalt. Substantial new mounds would be created as well, because of the large volume increases from the chemical reactions.

Although the need for sites for CO_2 sequestration may ultimately be so great that industrial sites could be chosen in remote areas, in an initial screening, the most favorable sites are likely proximal to both a major electric power transmission line and to a railroad. Coal would be transported to the site by rail, and the power plant would be located near the source of material to react with the CO_2 waste. The rail lines would also be used to bring other waste materials to the site, either for additional reaction with CO_2 or for burial with the iron, magnesium, and calcium carbonate reaction products. The major mafic rock localities, railroads, and major power grid in Nevada are shown on Figure 2. There do appear to be possible sites that are close to railroads and the major power grid in the following six areas: northwestern Washoe County; southern Washoe, Storey, Lyon, Churchill, and Pershing Counties; the Humboldt lopolith in Churchill and Pershing Counties; the Battle Mountain area in Lander and Eureka Counties; and southwestern Mineral and northwestern Esmeralda Counties. The basalts on the Owyhee Plateau in northern Elko and Humboldt Counties are several tens of kilometers farther from railroads than the other sites. Locations with sufficient amounts of basalt in two other areas (the San Antonio Mountains in Nye County; and the Reveille and Pancake Ranges in Nye County) are far from existing railroads.

CONCLUSIONS AND RECOMMENDATIONS

There are sufficiently large volumes of basalt near railroads and major power lines in Nevada to consider reaction of those rocks with CO_2 from coal-fired power plants as a possible means of disposing of the CO_2. Reaction with minerals has theoretical advantages over many other schemes for carbon sequestration in that it would be essentially permanent disposal. That is, there would be no leakage as possible from geological storage in deep saline aquifers, oil fields, or other geological environments, and there would be no threat of loss of CO_2 from wildfires, as with terrestrial sequestration in trees or other biomass. Nonetheless, the technology for mineral reaction is unproven. Considerably more research would be needed before a commercial operation could be seriously considered. When and if commercial viability is demonstrated, those areas of greatest interest in Nevada would contain large volumes of mafic rock near railroads and major power lines. Those areas would most likely be northwestern Washoe County; southern Washoe, Storey, Lyon, Churchill, and Pershing Counties; the Humboldt lopolith in Churchill and Pershing Counties; the Battle Mountain area in Lander and Eureka Counties; and southwestern Mineral and northwestern Esmeralda Counties.

PART 2

Assessment of the Potential for Carbon Dioxide Sequestration with Enhanced Oil Recovery in Nevada

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ABSTRACT

This report follows the preliminary assessment of the potential for carbon dioxide sequestration in geological settings in Nevada (Price et al. 2005) by compiling data on the 15 oil fields that have had historical production. Critical factors in assessing the potential for enhanced oil recovery as a means of carbon dioxide sequestration in Nevada include depth, temperature, and cumulative production. Most Nevada oil reservoirs are considerably hotter than ideal conditions for maintaining a dense CO_2 phase underground. Furthermore, none of the Nevada oil fields is large enough to accommodate all the CO_2 from a large coal-fired power plant. The cumulative volume of oil and associated water production from all Nevada oil fields is about two orders of magnitude less than what would be needed to sequester a significant amount of CO_2 from a power plant. Therefore, there is not much potential in Nevada for CO_2 sequestration through enhanced oil recovery.

INTRODUCTION

In recent years, the prospect of using carbon dioxide (CO_2) injection as an enhanced oil recovery (EOR) technique has gathered much interest, not only as a way of improving oil recovery, but also as a method of sequestering CO_2 generated by coal-burning power plants. In a typical oil field, less than 15 percent of the oil present in the reservoir is recovered during the primary recovery phase, when the initial natural pressure of the reservoir or gravity helps drive oil into the wellbore, where it is generally pumped to the surface. Secondary recovery techniques may extend the oil field's productive life and increase recovery to 20 to 40 percent by injection of water or gas to displace oil and drive it to a production wellbore. With much of the easily produced oil already recovered from U.S. oil fields, some producers have attempted tertiary or EOR techniques that offer the possibility of converting up to 60 percent or more of the reservoir's original oil reserves to production.

Gas injection is the most commonly used EOR technique, accounting for nearly 50 percent of EOR production in the United States. Large volumes of gas such as CO_2, natural gas, or nitrogen are injected into a mature oil reservoir, where the gas pushes additional oil to a production wellbore. The gas also dissolves in the oil, lowering its viscosity and improving its flow rate. CO_2 injection has been used successfully to enhance oil recovery throughout the Permian Basin of West Texas and eastern New Mexico, and is now being pursued to a limited extent in many other states.

In 2003, the State of California, in collaboration with the U.S. Department of Energy and the States of Alaska, Arizona, Oregon, and Washington, asked the State of Nevada to join the West Coast Regional Carbon Sequestration Partnership (WESTCARB) and participate in a regional analysis of CO_2 sequestration potential, through both terrestrial and geological approaches. The terrestrial approaches involve growing more biomass (particularly trees), and the geological options include proven technologies, such as using CO_2 in EOR and disposal of CO_2 in saline aquifers. Some unconventional approaches are also being evaluated. The Nevada Bureau of Mines and Geology (NBMG) reported its findings from a preliminary assessment of the potential for geological sequestration in Nevada (Price et al. 2005). This report follows up with detailed information on Nevada oil fields.

DATA COMPILED

To aid in the evaluation of Nevada oil fields as potential targets for CO_2 EOR, we researched available literature on 15 commercially productive oilfields in Nevada for information pertinent to the suitability of these oil fields for sequestration of CO_2. Nevada's commercially productive oil fields are Bacon Flat, Currant, Duckwater Creek, Eagle Springs, Ghost Ranch, Grant Canyon, Kate Spring, Sand Dune, Sans Spring, and Trap Spring in Railroad Valley, Nye County; Blackburn, North Willow Creek, Three Bar, and Tomera Ranch in Pine Valley, Eureka County; and Deadman Creek in Toano Draw, Elko County. Their locations and relative approximate sizes are shown in Figure 29. Additional fields have been explored and identified within Nevada, but as yet, none of these has had significant commercial production of petroleum, so they were not included in this compilation. Nearly all Nevada oil production has come from fields in Railroad Valley (89.27%) and Pine Valley (10.73%; Davis, 2007).

Because Nevada's 15 commercially producing oil fields are either one-reservoir fields or consist of communicating reservoirs, the field and reservoir level data are essentially the same and are combined on a single data spreadsheet for the 15 oil fields, shown here as Table 8. The data presented in Table 8 are included in a geographic information system (GIS) coverage which accompanies the electronic version of this open-file report. Table 9 is an annotated list of the data field labels and a description of the data contained in each of the fields on Table 8. Field locations in Table 8 and on Figure 29 are based on the point locations of the discovery wells for each field as shown on the petroleum data map of Garside and Hess (2007). The oil field GIS coverage was generated in a shape file format, in UTM zone 11 projection, North American Datum (NAD) 1927. This is the same projection and NAD as the UTM coordinates listed in Table 8. The GIS coverage that accompanies the map of Garside and Hess (2007), available at http://www.nbmg.unr.edu/dox/zip/m162d.zip, includes locations of all oil and gas exploration and production wells in the state.

Table 8. Data compiled for each commercially productive oil field in Nevada. See Table 2 for descriptions of the data fields.

Oil field name	Discovery well name	NV permit number	Discovery well API number	Location	County
OILFIELDNA	DISCO_WELL	PERMIT	API	LOCATION	COUNTY
Eagle Springs	Eagle Springs Unit No. 1-35	4	27-023-05011	Railroad Valley	Nye
Kate Spring	Kate Spring No. 1	436	27-023-05365	Railroad Valley	Nye
Trap Spring	Trap Spring No. 1	180	27-023-05220	Railroad Valley	Nye
Currant	Currant No. 1	241	27-023-05265	Railroad Valley	Nye
Bacon Flat	Bacon Flat No. 1	316	27-023-05305	Railroad Valley	Nye
Blackburn	Blackburn No. 3	324	27-011-05210	Pine Valley	Eureka
Grant Canyon	Grant Canyon No. 1	353	27-023-05318	Railroad Valley	Nye
Tomera Ranch	Foreland-Southern Pacific Land Co. No. 1-5	492	27-011-05235	Pine Valley	Eureka
North Willow Creek	Foreland-Southern Pacific Land Co. No. 1-27	503	27-011-05239	Pine Valley	Eureka
Three Bar	Three Bar Federal No. 25-A	556	27-011-05246	Pine Valley	Eureka
Duckwater Creek	Duckwater Creek No. 19-11	542	27-023-05413	Railroad Valley	Nye
Sans Spring	Federal No. 5-14	635	27-023-05466	Railroad Valley	Nye
Ghost Ranch	Ghost Ranch Springs No. 58-35	789	27-023-05544	Railroad Valley	Nye
Deadman Creek	Deadman Creek No. 44-13 (formerly SP No. 3-13)	342	27-007-05228	Toano Draw	Elko
Sand Dune	Sand Dune Federal No. 88-35	816	27-023-05561	Railroad Valley	Nye

Table 8 (continued).

Oil field name	Township	Range	Sections	Quarter section	Depth to top of field
OILFIELDNA	T	R	S	QTRSEC	DEPTHTOTOP
Eagle Springs	9N	57E	35	SE/4 NE/4 NW/4	5780 feet (1,762 meter)
Kate Spring	08N	57E	2	NW/SW	4450 feet (1,356 meters)
Trap Spring	9N	56E	27	SE/SE	3210 feet (978 meters)
Currant	10N	57E	26	SW/SE	6850 feet (2088 meters)
Bacon Flat	07N	57E	17	C/SW	4960 feet (1512 meters)
Blackburn	27N	52E	8	C NE/4 SW/4 SW/4	5776 feet (1761 meters)
Grant Canyon	07N	57E	21	C E/2 SW/4 NW/4 Sec. 21, T 7N, R 57E	4374 feet (1333 meters)
Tomera Ranch	30N 31N	52E 53E	5; 33	SE/NE/NE	1150 feet (351 meters)
North Willow Creek	29N	52E	27	NW/SE	6290 feet (1917 meters)
Three Bar	28N	51E	25	C NE/4	5720 feet (1743 meters)
Duckwater Creek	09N	057E	19	NW/NW	5680 feet (1731 meters)
Sans Spring	07N	056E	14	SW/NW	5640 feet (1710 meters)
Ghost Ranch	08N, 09N	057E, 057E	02; 34, 35	NE/NW 02; SE/SW 35	4350 feet (1326 meters)
Deadman Creek	39N	65E	13	SE/SE	8165 feet (2489 meters)
Sand Dune	09N	057E	35	SE/SE/SE	5970 feet (1820 meters)

Table 8 (continued).

Oil field name	Depth of producing zone in discovery well	Average depth of production zone in all producing wells	Average depth of production zone in all producing wells (meters)	Cumulative production through 2006 (barrels)
OILFIELDNA	PRODDEPTH	AVDEPTHPRO		CUMPROD2006
Eagle Springs	5,780-7,360 feet	6508 feet	1984	5,218,259
Kate Spring	4450-4820 feet	4598 feet	1401	2,256,573
Trap Spring	3210-4950 feet	4005 feet	1221	13,753,356
Currant	6850-7080 feet	7059 feet	2152	1,523
Bacon Flat	4960-5350 feet	5163 feet	1574	997,509
Blackburn	5776-7140 feet	6902 feet	2104	5,183,966
Grant Canyon	4374-4426 feet	3979 feet	1213	20,938,790
Tomera Ranch	1150-1950 feet	1670 feet	509	36,472
North Willow Creek	6290-6470 feet	6093 feet	1857	50,529
Three Bar	5720-7070 feet	5448 feet	1661	23,837
Duckwater Creek	5680-5830 feet	5755 feet	1754	18,310
Sans Spring	5640-5770 feet	5766 feet	1757	265,457
Ghost Ranch	4350-4620 feet	4474 feet	1364	502,023
Deadman Creek	8165-8850 feet	8508 feet	2593	367
Sand Dune	5970-6200 feet	6178 feet	1883	116,626

Table 8 (continued).

Oil field name	Zone status (currently producing, shut-in, or abandoned wells) 2006 data	Number of producing wells (2006)	Number of inactive wells (2006)	Depth to base of fresh water
OILFIELDNA	ZONESTATUS06	NUMPRODWEL	NUMINACTWE	DEPTHFRESH
Eagle Springs	15 producers, 6 shut-in, 1 injection	15	5	not known
Kate Spring	4 producers, 2 shut-in	4	2	not known
Trap Spring	33 producers, 10 shut-in, 1 P&A	33	11	not known
Currant	1 past producer, now shut-in	0	1	not known
Bacon Flat	1 active producer, 2 shut-in	1	2	not known
Blackburn	5 producers, 2 shut-in	5	2	not known
Grant Canyon	2 producers, 4 shut-in	2	4	not known
Tomera Ranch	2 shut-in, 1 P&A, 1 injection	2	1	not known
North Willow Creek	1 producer, 1 shut-in, 1 P&A	1	2	not known
Three Bar	2 shut-in, 1 P&A	2	1	not known
Duckwater Creek	1 producer	1	0	not known
Sans Spring	1 producer, 2 shut-in, 1 abandon	1	3	not known
Ghost Ranch	4 producers; 1 shut-in	4	1	not known
Deadman Creek	1 P&A	0	1	not known
Sand Dune	1 producer	1	0	not known

Table 8 (continued).

Oil field name	Host rost age/formation/rock type	Average thickness of reservoir rock units in producing wells
OILFIELDNA	HOSTROCK	AVEUNITTHI
Eagle Springs	Oligocene Garrett Ranch Group; Eocene Sheep Pass Formation lacustrine carbonates; Pennsylvanian Ely Limestone carbonate (minor production)	1500 feet
Kate Spring	Neogene Horse Camp Formation breccia and Devonian Guilmette Formation (carbonate, dolomite)	413 feet of Pennsylvanian carbonate breccia; 560 feet of Devonian dolomite & limestone
Trap Spring	Oligocene Tuff of Pritchards Station, ash flow tuff (ignimbrite)	2490 feet
Currant	Eocene Sheep Pass Formation calcareous shale and shaly limestone	439 feet
Bacon Flat	Devonian Guilmette Formation carbonate, dolomite; possibly also Sheep Pass Fm	73 feet
Blackburn	Devonian Telegraph Canyon Formation dolostone; Mississippian Chainman Shale and Dale Canyon Formation shale, sandstone & siltstone; Oligocene Indian Well Formation tuff and tuffaceous sandstone	1275 feet
Grant Canyon	Devonian Simonson and Guilmette Formation vuggy brecciated dolomite	448 feet
Tomera Ranch	Oligocene Indian Well Formation chert and tuffaceous sandstone	189 feet
North Willow Creek	Mississippian Chainman Shale	604 feet
Three Bar	Miocene Humboldt Formation sandstone and volcanic rock; Oligocene Indian Well Formation, and Cretaceous Newark Formation sandstone and carbonate	6000 feet
Duckwater Creek	Oligocene Garrett Ranch Group volcaniclastic rocks and ignimbrites	3125 feet
Sans Spring	Oligocene Garrett Ranch Group volcaniclastic rocks and ignimbrites	933 feet
Ghost Ranch	Late Tertiary landslide breccia blocks of Devonian Guilmette Formation limestone and dolomite	265 feet
Deadman Creek	Miocene Humboldt Formation	685 feet
Sand Dune	Permian and Pennsylvanian limestones	465 feet

Table 8 (continued).

Oil field name	Field area (from literature)	Porosity	Permeability
OILFIELDNA	FIELDAREA	POROSITY	PERMEABILI
Eagle Springs	640 acres	volcanics - 13.5%; Sheep Pass - 16%	volcanics - 10 md; Sheep Pass - 4 md
Kate Spring	Tertiary - 60 acres, Devonian - 200 acres	average 10-12%, up to 17 % in Devonian rock	2000-4100 md possible
Trap Spring	2440 acres	overall, <3%, but 5-15 % matrix porosity in isolated vesicles	highly variable
Currant	40 acres	5.80%	up to 24.6 md
Bacon Flat	80 acres	< 4 %	very high- interconnected fractures, vugs & caverns
Blackburn	400 acres	8%	high - open fractures
Grant Canyon	320-400 acres	< 4 %	very high- interconnected fractures, vugs & caverns
Tomera Ranch	80 acres	up to 24 % but average 6-15 %	<2 md
North Willow Creek	<120 acres	15 - 26% in discovery hole	.05 - 78 md in discovery hole (7.35 md)
Three Bar	<120 acres	unknown	unknown
Duckwater Creek	~40 acres	< 2%	highly variable
Sans Spring	160 acres	18%	1688 md
Ghost Ranch	1500 acres	huge	huge permeabilities
Deadman Creek	~40 acres	unknown	unknown
Sand Dune	~40 acres	10%	0.39 - 1.3 md

Table 8 (continued).

Oil field name	Initial pressure	Initial temperature	Formation water salinity
OILFIELDNA	INITPRE	INITIALTEM	FMSALINITY
Eagle Springs	3000 psi at 6400 feet	200° F (93°C) at 6400 feet	24,298 ppm Cl; 7476-27,912 ppm TDS in oil field waters of 6 wells
Kate Spring	unknown	150° F (66°C)	TDS 239 ppm; 914-2,952 ppm TDS in oil field waters of 5 wells
Trap Spring	1645 psi at 1000 feet	100°-120° F (38-49 °C)	3000-6000 ppm TDS; 2633-3378 ppm TDS in oil field waters of 3 wells
Currant	2944 psig	194° F (90°C)	2264 mg/l TDS
Bacon Flat	2273 psig	250° F (121°C)	4380 ppm TDS; 4662-4943 ppm TDS in oil field waters of 3 wells
Blackburn	3233 psig at 7196 feet	250° F (121°C)	1984-3684 ppm TDS in oil field waters of 3 wells.
Grant Canyon	1,885 psig at 4,400 feet; 1,735 psig at 4,000 feet	239° F (115°C)	4382-4487 ppm TDS in oil field waters of 5 wells
Tomera Ranch	unknown	120° F (49°C)	543-580 mg/l TDS
North Willow Creek	2,798.5 psi	180°-185° F (82-85°C)	7000 ppm to 9000 ppm salt water chlorides in re-entry well
Three Bar	unknown	unknown	530-939 ppm chlorides
Duckwater Creek	unknown	140° F, (60°C) estimated	10,200 ppm TDS
Sans Spring	2410 psig	200° F (93°C)	10,000-17,000 ppm TDS
Ghost Ranch	2179 psig	unknown	TDS concentration 17,500 to 21,000 mg/L.
Deadman Creek	unknown	154° F (68°C)	11,260 to 52,917 ppm TDS
Sand Dune	2866 psig	149° F (65°C)	unknown

Table 8 (continued).

Oil field name	Seal type	Seal thickness	Trap type
OILFIELDNA	SEALTYPE	SEALTHICK	TRAPTYPE
Eagle Springs	Indurated valley fill (Horse Camp Formation) and altered basal volcaniclastic-rich valley fill sediments	169-2680 feet	paleotopographic & stratigraphic, structural-stratigraphic; erosional unconformity pinch-outs
Kate Spring	Indurated clay-rich Tertiary valley fill above unconformity	4371-4738 feet	structural/unconformity; clay-richvalley fill trap
Trap Spring	Alluvial valley fill, argillized clay-rich non-welded tuff layer, unfractured clays, and devitrified ash	271-4854 feet	fault block, structural-stratigraphic
Currant	altered basal volcaniclastic-rich valley-fill sediments; Tertiary volcanic rocks	2995 feet	structural-stratigraphic
Bacon Flat	altered Tertiary basal volcaniclastic-rich valley fill sediments	153-5355 feet	structural; structural-stratigraphic; valley fill trap
Blackburn	pre-Tertiary unconformity; altered Tertiary basal volcaniclastic-rich valley fill sediments	1200-2768 feet	structural
Grant Canyon	altered Tertiary basal volcaniclastic-rich valley fill sediments	910-4020 feet	structural; structural-stratigraphic; valley fill trap
Tomera Ranch	valley fill clays	800-1850 feet	structural fault block; structural-stratigraphic
North Willow Creek	range-bounding fault of the Pinon Range and Devonian Woodruff Fm.	1500 -3000 feet	structural fault block
Three Bar	Tertiary valley fill and volcanic rocks	3000-5000 feet	probably structural
Duckwater Creek	Tertiary valley fill and volcanic rocks	5500 feet	structural - fault block
Sans Spring	Tertiary valley fill and volcanic rocks	5000 feet	fault-bounded structure; structural-stratigraphic
Ghost Ranch	altered basal volcaniclastic-rich valley fill sediments	unknown	Structural high with four-way closure
Deadman Creek	Ash member, Humboldt Formation	2365 feet	unknown
Sand Dune	Tertiary valley fill and volcanic rocks	5900 feet	unknown

Table 8 (continued).

Oil field name	Stimulation (history of secondary and tertiary recovery efforts)	Logs available (discovery hole)
OILFIELDNA	STIMULATIO	LOGS
Eagle Springs	2,000 gallon (7,571 liter) mud acid wash	Lithologic 0 - 10,358 feet; IES 1,018 - 10,358 feet; GR/N 30 - 10,358 feet; ML 1,500 - 10,354 feet; DM 3,460 - 8,205 feet; Section Gauge 1,016 - 10,356 feet.
Kate Spring	Worked over after 1521 BO produced; plugged original perfs; perforated and acidized 4500-1625 feet (1372-1410m)	FIL 4,864-7,495 feet; DM 4,864-7,495 feet; DLL/ML 4,864-7,487 feet; BHCS 4,864-7,497 feet; CBL 3,490-4,814 feet; Directional 4,864-7,495 feet; CN/FDC 4,864-7,495 feet; GR 3,400-7,495 feet; lithologic 60-7500 feet.
Trap Spring	A few attempts to acidize or fracture have been mostly unsuccessful.	Lithologic 1,000 - 6,137 feet; DIL 1,008 - 5,982 feet; CNL/FDC 1,008 - 5,990 feet; BHCS 1,008 - 5,970 feet; FIL 4,000 - 5,600 feet
Currant	none	Lithologic 60-7,800 feet, 6,720-7,115 feet; FIL 2,200-7,790 feet; DIL 427-7,789 feet; GR 6,800-7,118 feet; BHCS 429-7,791 feet; CNL/FDC 428-7,793 feet; DM 436-7,793 feet
Bacon Flat	acidized with 1000 gallons (3,785 liters) 15 % HCl	Lithologic 515-5,441 feet; DI 519-5,451 feet; BHCS 519-5,433 feet; CNL/FDC 3,404-5,439 feet; DM 612-5,450 feet; Dip log 3,414-5,419 feet; CBL 3,350-5,394 feet
Blackburn	Devonian - none, Mississippian & Oligocene - sand/oil fracture treatment	Lithologic 80-7,950 feet; FDL 4,800-7,867 feet; CBL 5,200-7,900 feet; TS 58-7,909 feet; Cal 1,548-5,550 feet; CNL/FDC/DI 95-7,954 feet; BHCS 95-7,943 feet; FIL/GR 4,800-7,956 feet; DM 1,608-7,956 feet; DLL 5,800-7,523 feet
Grant Canyon	none	Lithologic 400 - 4,040 feet; DLL/ML 392 - 3,949 feet; BHCS 392 - 3,957 feet; DI 3,931 - 4,297 feet; LSS 3,931 - 4,300 feet; FIL 3,931 - 4,300 feet; CNL/FDC 392 - 4,300 feet; DM 3,931 - 4,300 feet; Temp/press/gradient 3,900 - 4,150 feet
Tomera Ranch	none	Lithologic 1007 - 5786 feet; DLL 980 - 5774 feet; FDC/N 1018 - 5772 feet; BHCS 988 - 5755 feet; DM 1000 - 5570 feet; DM/computed 1000 - 5570 feet; CBL 1000 - 4567 feet
North Willow Creek	none	CBL 4200 - 6393 feet; FDC/N 980 - 7672 feet; BHCS 950 - 7666 feet; ML 5600 - 7662 feet; DLL 950 - 7650 feet; DM 980 - 7672 feet; Perf. Rec. 6200 - 6393 feet; lithologic 0 - 7678 feet
Three Bar	unknown	Lithologic 57-7217 feet; GR 950-7217 feet; DI 950-7213 feet; DM 950-7216 feet; EM 950-7201 feet; FDC/N 950-7217 feet; S 950-7203 feet; CBL 750-7213 feet
Duckwater Creek	none	DI/GR, 716-5754; BHCS/GR, 716-5750; DM, 3737-5754
Sans Spring	none	lithologic 900-8,463 feet ; CBL-5,000-6,087; DM 4,000-8,459 feet; DI 4,000-8,460 feet; BHCS 4,000-8,462 feet; FDC/N 4,000-8,464 feet; Drift survey 4,000-8,459 feet; Water Flow 5,690-5,910 feet
Ghost Ranch	unknown	lithologic log 515 feet-4570 feet; BHCS/GR 512 feet-4530 feet; Directional Plot 512 feet-4580 feet; DLL 512 feet-4562 feet; FDL/N 3550 feet-4530 feet
Deadman Creek	unknown	Lithologic 90 - 10,930 feet; DM 916 - 10,918 feet; CBL 7,818 - 8,745 feet; BHCS 897 - 10,926 feet; DI 898 - 10,926 feet; FIL 1,500 - 10,923 feet; FDC/N 898-8,638; DM 898 - 8,639 feet; DL 898 - 10,923 feet; GR 898-8,607 feet
Sand Dune	unknown	Lithologic log 642 feet-6411 feet; BHCSGR 642 feet-6366 feet; Directional 636 feet-6400 feet; DMGRCal 3000 feet-6400 feet; IESGR 642 feet-6398 feet; MLGRCal 2400 feet-6407 feet; NGRCal 2400 feet-6407 feet

Table 8 (continued).

Oil field name	Location of logs	Samples available (discovery hole)	Reservoir fluid (oil, gas, water)
OILFIELDNA	LOGLOC	SAMPLES	RESFLUID
Eagle Springs	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 140 - 10,345 feet; Core 4,710 - 9,960 feet.	oil, gas, water
Kate Spring	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 60 - 7,500 feet	oil, water, gas
Trap Spring	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 1,800 - 6,100 feet; Core 4,375 - 4,444 feet	oil, water
Currant	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 430-7,800 feet	oil
Bacon Flat	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 520-5,450 feet	oil, water
Blackburn	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 1,600 - 7,930 feet	oil, water
Grant Canyon	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 390 - 4,040 feet	oil, water
Tomera Ranch	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 900 - 5786 feet	oil, gas, water
North Willow Creek	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 3000 - 7678 feet	oil, water (none initially), some gas initially
Three Bar	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 57 - 7,217 feet	oil, water
Duckwater Creek	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 718-5835 feet	oil, water
Sans Spring	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 900-8,463 feet	oil, water
Ghost Ranch	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings: 500 feet - 4570 feet	oil, small amount of gas, (no) water
Deadman Creek	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings 0 - 10,930 feet. Core analysis is available at NBMG for 9440-9475 feet.	oil, gas, water
Sand Dune	NBMG & U. S. Geological Survey Core Research Center, Well Reports, Data on cuttings and core available online at: http://geology.cr.usgs.gov/crc/data/NV/	Cuttings: 642-6411 feet	oil, water

Table 8 (continued).

Fracture intensity	Main reference, number 1	Main reference, number 2	Main reference, numbers 3+
FRACINTENS	REF1	REF2	REF3
fractured	Bortz (1994a and b)	Bortz and Murray (1979)	Nevada Petroleum Society (1989)
fractured carbonate	Herring (1994a and b)	Nevada Petroleum Society (1989)	
unknown	French (1994b and c)	French and Freeman (1979)	Duey (1979)
unknown	Duey (1994a and b)		
high concentration of interconnected fractures, vugs, and caverns	Johnson and Schalla (1994a)	Hulen and others (1994)	Johnson (1994); MCCutcheon and Zogg (1994)
strong	Flanigan (1994)		
intense; high concentration of interconnected fractures, vugs, and caverns	Johnson and Schalla (1994b)	Hulen and others (1994)	Read and Zogg (1988); Johnson (1994); McCutcheon and Zogg (1994)
strong	Hansen and others (1994a)	Ransom (1994b)	
unknown	Hansen and others (1994b)	Ransom (1994a)	
fractured limestone	Schalla and Grabb (1994)		
unknown	French (1994a)	French and Kozlowski (1994)	Hess and others (2004)
unknown	Grabb (1994a and b)	Hess and others (2004)	
intense fracturing of dolomite	Montgomery and others (1999)	Hansen and Schaftenaar (2005)	
unknown	Frerichs and Pekarek (1994)	Hess and others (2004)	
unknown	Nevadd Bureau of Mines and Geology oil well files		

Table 8 (continued).

Oil field name	Current operator	Approximate UTM northing	Approximate UTM easting	Cumulative water production through 2006 (barrels)
OILFIELDNA	OPERATOR	APROX_UTMN	APROX_UTME	H2OCUMPROD
Eagle Springs	Meritage Energy Company	4273342	627676	5,121,534
Kate Spring	Western General Incorporated	4270858	627193	6,255,046
Trap Spring	Apache Incorporated	4273931	617249	32,908,982
Currant	Makoil, Inc.	4283509	627560	0
Bacon Flat	Equitable Res. Energy Co., Balcron Oil Div.	4257863	622670	729,680
Blackburn	Amoco Production Co.	4453568	573279	33,116,941
Grant Canyon	Makoil, Inc.	4256785	624173	4,856,303
Tomera Ranch	Foreland Corp.	4485300	574050	498,612
North Willow Creek	Deerfield Production Corporation	4468420	576920	3,210
Three Bar	The Gary-Williams Company	4459310	571050	5,958
Duckwater Creek	Makoil, Inc.	4276600	620800	66,225
Sans Spring	Double D Nevada, LLC	4258450	617700	3,716,058
Ghost Ranch	Eagle Springs Production LLC	4272120	627980	2,619,324
Deadman Creek	Foreland Corp.	4570112	703709	0
Sand Dune	Meritage Energy Company	4272050	627800	298,659

Table 9. Data field labels and description of the data contained in each of the fields on Table 1 and in the accompanying GIS coverage of Nevada's commercially producing oil fields.

OILFIELDNA	Name of the oil field
DISCO_WELL	Name of the discovery well for the oil field
PERMIT	Nevada permit number for the discovery well for the oil field
API	API number of the discovery well for the oil field
LOCATION	General location of the oil field
COUNTY	County in which the oil field is located
T	Township in which the oil field is located
R	Range in which the oil field is located
S	Section(s) in which the oil field is located
QTRSEC	Quarter section in which the discovery well for the oil field is located
DEPTHTOTOP	Depth to top of the oilfield in the discovery well for the oil field
PRODDEPTH	Range of depth of the producing zone in the discovery well for the oil field
AVDEPTHPRO	Average depth of the production zone in all producing wells for the oil field
CUMPROD2006	Cumulative production of the oil field through 2006 (in barrels)
ZONESTATUS06	Zone status of all wells in the oil field as of the end of 2006: currently producing, shut-in, or abandoned (P&A)
NUMPRODWEL	Number of producing wells in the oil field at the end of 2006
NUMINACTWE	Number of inactive wells in the oil field at the end of 2006
DEPTHFRESH	Depth to base of fresh water in oil field wells (not known)
HOSTROCK	Host rock (reservoir) ages, name of formations, and rock types for oil fields
AVEUNITTHI	Average thickness of reservoir rock units in producing wells for each field (this may not be the average potential thickness of reservoir rocks in the surrounding area.)
FIELDAREA	Field area as reported in or inferred from literature. A minimum value of 40 acres was used for small fields with no area reported.
POROSITY	Porosity of reservoir rocks
PERMEABILI	Permeability of reservoir rocks
INITPRE	Initial pressure at TD in discovery well
INITIALTEM	Initial temperature at TD in discovery well
FMSALINITY	Formation water salinity
SEALTYPE	Type of seal for reservoir
SEALTHICK	Seal thickness if known or thickness of formation that acts as the seal to the reservoir
TRAPTYPE	Type of trap; structural, stratigraphic, lithologic, other
STIMULATIO	Stimulation, history of secondary and tertiary recovery efforts
LOGS	Logs available for the discovery hole in each oil field
SAMPLES	Samples available for discovery hole in each oil field
LOGLOC	Location of logs and samples for discovery hole and other producing wells of the oil field
RESFLUID	Reservoir fluid (oil, gas, water)
FRACINTENS	Intensity or presence of fracturing of reservoir rock
REF1	Main reference, number 1
REF2	Main reference, number 2
REF3	Main reference, numbers 3+
OPERATOR	Current or most recent operator for the oilfield
APROX_UTMN	Approximate UTM northing of the discovery well for the oilfield
APROX_UTME	Approximate UTM easting of the discovery well for the oilfield
H2OCUMPROD	Cumulative water production of the oil field through 2006

Sources of data for Table 1 include well, core, sample, and log repositories of the Nevada Bureau of Mines and Geology and the U.S. Geological Survey. The Nevada Bureau of Mines and Geology Information Office archives the most complete records and samples. Companies drilling oil and gas wells are required by Nevada state law to give the state copies of logs and two sets of cuttings for each oil and gas well drilled. The logs and sample sets are kept confidential for six months. The Information Office is also the repository for other well cuttings (from geothermal and some other wells) and core. All cuttings, core, and well logs described in the accompanying database of producing Nevada oil fields are housed at NBMG and available for examination. The collection is electronically indexed and may be examined during NBMG business hours. There are also logs for 115 Nevada oil and gas exploration wells available from the USGS as part of the Basin and Range Carbonate Aquifer System Study. They are available online at http://nevada.usgs.gov/barcass/geo_logs/nye_county.htm

DISCUSSION

Critical factors in assessing the potential for enhanced oil recovery as a means of CO_2 sequestration in Nevada include depth of oil production (with a minimum depth of 800 m, so that the CO_2 stays in a liquid state under hydrostatic pressure), temperature (so that the density of CO_2 is preferably greater than 0.6 g/cm^3), volume of pore space available (as estimated from the resource potential or, for fields with declining production, cumulative production), permeability of the oil reservoir, and thickness of the seal that kept the oil in place. These factors, along with others, are listed in Table 1. With one exception (the Tomera Ranch field in Pine Valley), the Nevada oil fields meet the minimum depth criterion. Most fields, however, are so hot that densities of the CO_2 would likely to be less than 0.6 g/cm^3 within the reservoirs (Figure 30). Exceptions, where CO_2 may be denser, include two insignificant producers (Duckwater Creek in Railroad Valley and Deadman Creek in Toano Draw) and one major producer (Trap Spring field in Railroad Valley).

Davis (2007) provided the most recent update on Nevada oil production. Nevada's total oil production in 2006 was 425,705 barrels (0.023% of total U.S. production), from nine fields located in Railroad Valley, Nye County, and from two fields in Pine Valley, Eureka County. Nevada's four other past-producer oil fields were shut in throughout 2006. Nevada ranked 26 out of the 31 oil producing states in the country in 2006 oil production. Nevada's 67 productive oil wells yielded between 3 and 166 barrels of oil and up to 2,503 barrels of water per day. Nevada's cumulative oil production from 1954 through 2006 from all commercial oil fields totaled just less than 50 million barrels, and annual production has steadily declined since 1992 (Figure 31). Cumulative production for each oil field during this time period is shown in Table 1, and cumulative production for each field is shown in Figure 32. Each of the major Nevada oil fields – ones that have produced over 1 million barrels (Grant Canyon, Trap Spring, Eagle Spring, and Kate Spring in Railroad Valley and Blackburn in Pine Valley) – experienced substantial declines in production since peaking in the 1990s or earlier (Figure 33). For more detailed information on Nevada's petroleum resources, please refer to Garside and Hess (2007); their petroleum data map shows current and past oil production and exploration wells in Nevada, as well as "seeps" or surface shows of oil, gas or solid bitumen.

Price et al. (2005) concluded that there does not appear to be much potential in Nevada for CO_2 sequestration through enhanced oil recovery, in part because the oil fields in Nevada tend not to have much associated natural gas, implying that gas originally associated with the fields has escaped. Injected CO_2 would likely leak to the surface as well. In addition, the oil fields in Nevada are small relative to fields in many other parts of the United States, and most Nevada fields are considerably hotter than ideal conditions for maintaining a dense CO_2 phase underground. A large coal-fired power plant that burned 250 million tons of carbon over its lifetime would generate 0.916 gigaton of CO_2, which would occupy a volume of 7.7 billion barrels at a CO_2 density of 0.75 g/cm^3 (typical of areas with low geothermal gradients) or 19 billion barrels at a density of 0.30 g/cm^3. The lower density of CO_2 is applicable for the largest oil fields in Nevada, which are hot (Figure 30; 120 to 130°C at 1,625 m in the Bacon Flat-Grant Canyon oil fields; Hulen et al. 1994). Cumulative oil production from Nevada, through 2006, is slightly less than 50 million barrels, and cumulative water production has been approximately 90 million barrels. The cumulative volume of oil and water production from all Nevada oil fields, approximately 140 million barrels, is about two orders of magnitude less than what would be needed to sequester a significant amount of CO_2 from a power plant. Therefore the conclusion still stands: there is not much potential in Nevada for CO_2 sequestration through enhanced oil recovery.

ACKNOWLEDGMENTS

The research leading to this report was supported by a grant from the U.S. Department of Energy through the University of California and by the State of Nevada through the Nevada Bureau of Mines and Geology. We thank John Clinkenbeard, California Geological Survey, Curt Oldenburg, Lawrence Berkeley National Laboratory, and James Faulds, Nevada Bureau of Mines and Geology, for their reviews of a draft of Part 1 of the report. We also thank Jack Hursh, Kris Pizarro, and Jordan Hastings for assistance with figures and layout and Dick Meeuwig for editing both parts. The authors accept full responsibility for the content of this report. The information in Part 2 of the report should be considered preliminary. It has not been thoroughly edited, peer reviewed, or checked for completeness or accuracy.

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Figure 1. The Valmy coal-fired power plant in Humboldt County, Nevada.

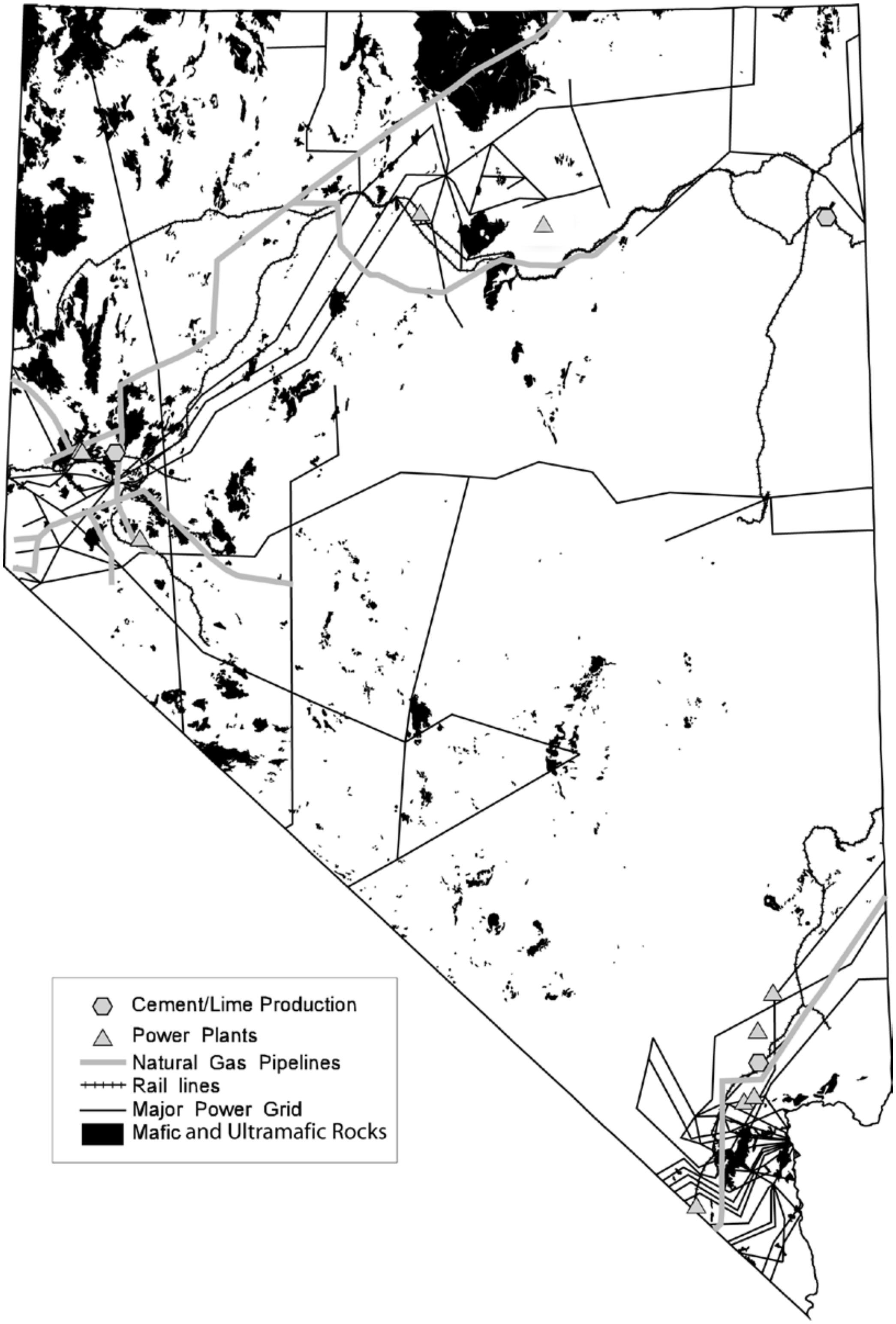

Figure 2. Distribution of mafic (magnesium- and iron-rich) and ultramafic rocks (black), major power plants (gray triangles), cement and lime plants (gray hexagons), major electric power transmission lines, pipelines, and rail lines in Nevada. Outcrop extents are taken from Stewart and Carlson (1978).

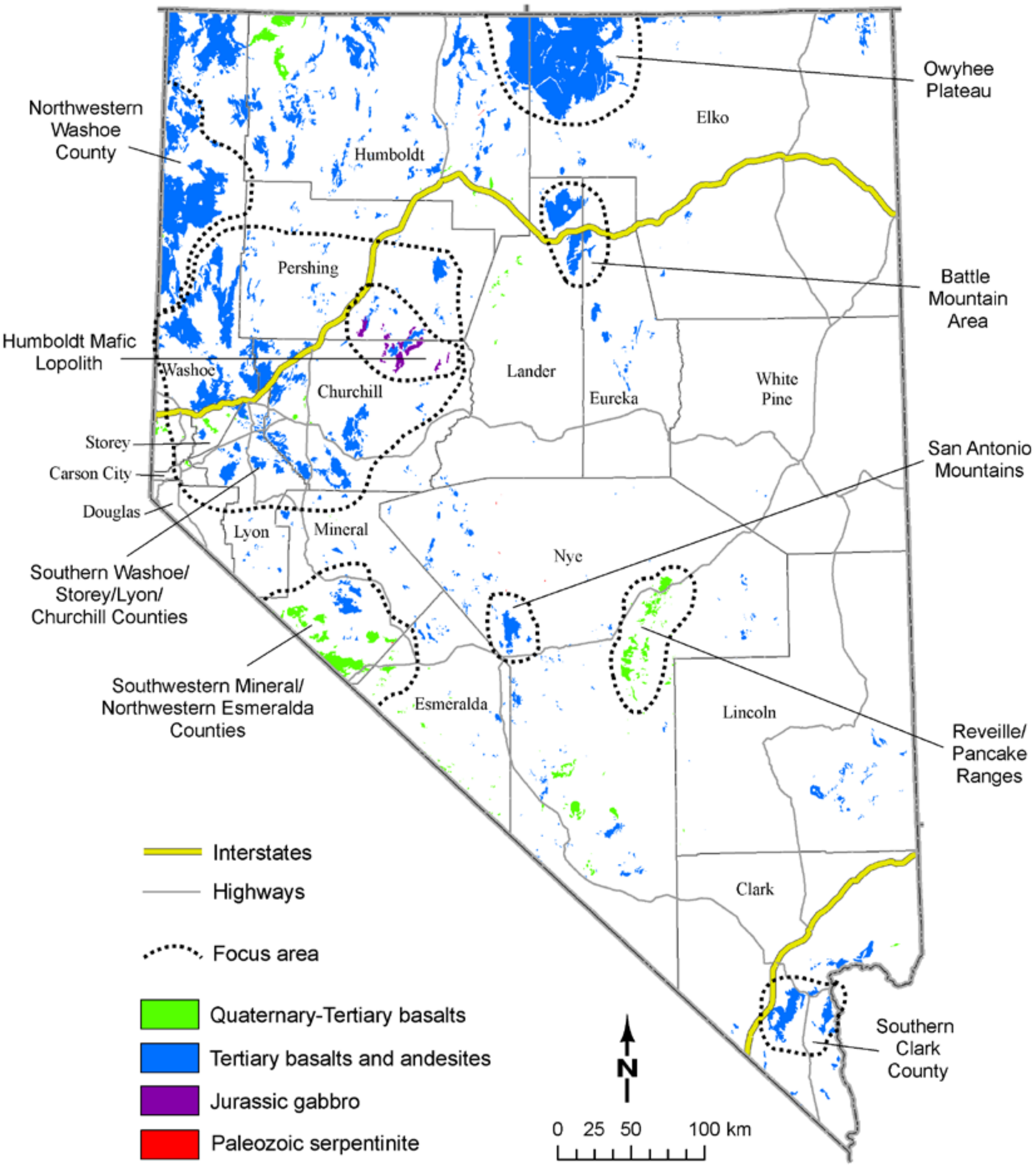

Figure 3. Mafic and ultramafic rocks in Nevada outlining the nine focus areas for this study. Outcrop extents are taken from Stewart and Carlson (1978).

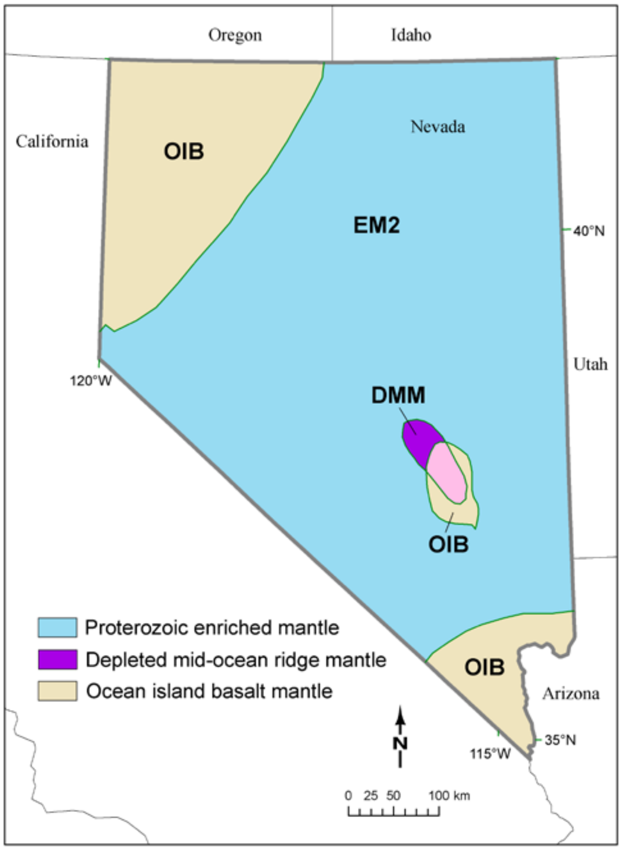

Figure 4. Lithospheric mantle domains in Nevada, based on seismic tomography, heat flow, and xenolith thermobarometry. Locally domains are overprinted. DMM = depleted mid-ocean ridge basalt mantle; EM2 = enriched mantle domain; OIB = ocean island basalt mantle. The sub-Archean lithospheric mantle domain does not appear on this map, because the area of exposed Archean rocks in Nevada is too small to be portrayed. Modified from Menzies (1989).

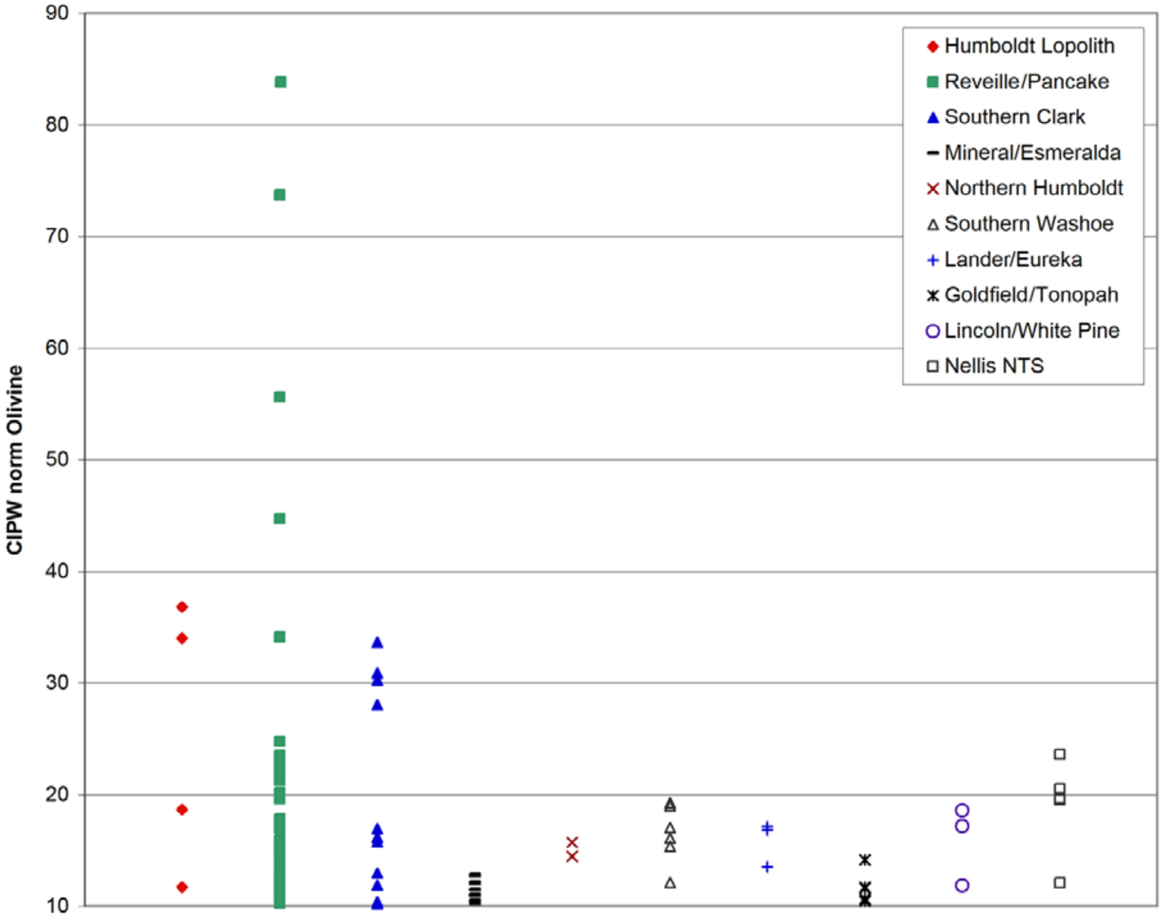

Figure 5. CIPW normative olivine values for some mafic rocks in Nevada (with olivine greater than 10%).

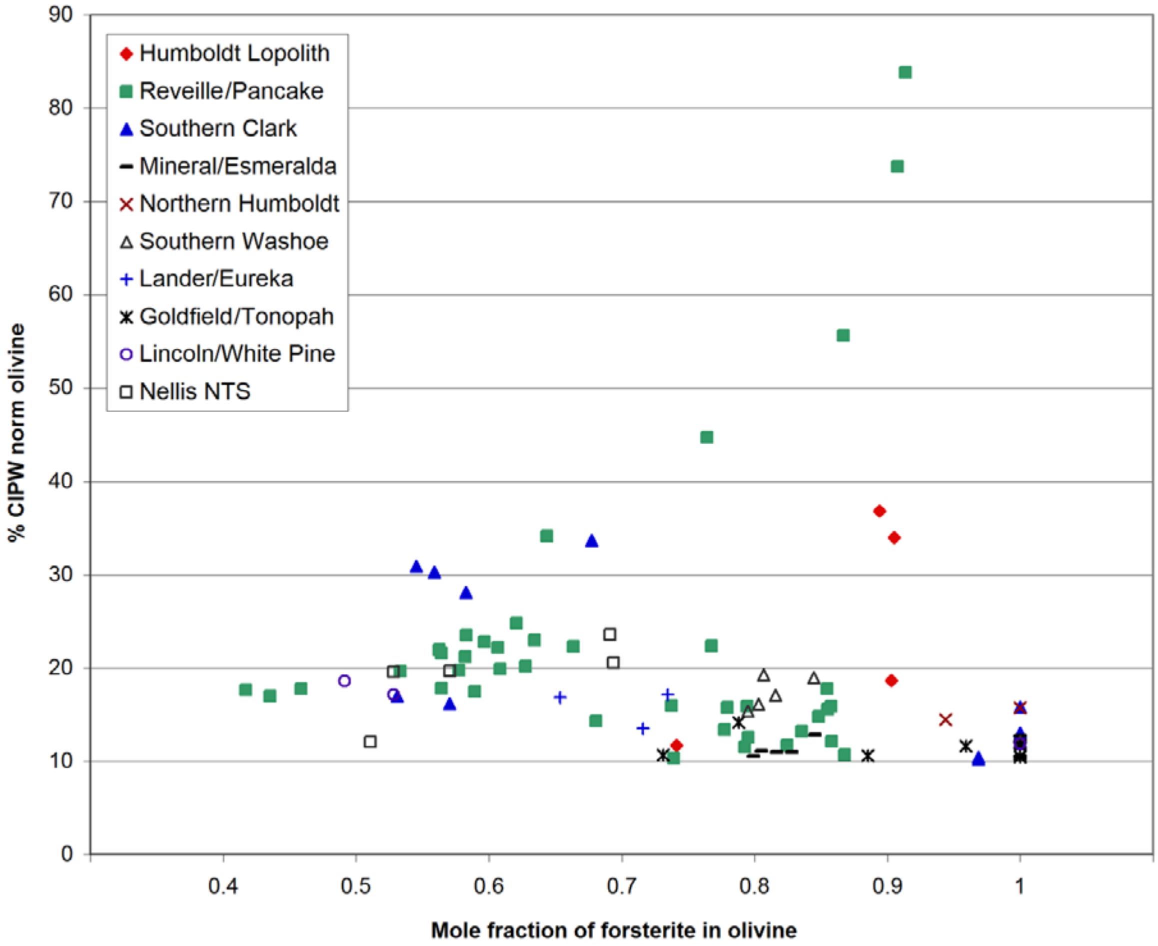

Figure 6. Normative forsterite vs. normative olivine for some mafic rocks in Nevada with normative olivine greater than 10%.

Figure 7. Example of thin (only a few m thick) basalts, not considered in this study, from the Sheldon National Wildlife Refuge in northern Washoe County. Thicker basalts may occur at depth.

Figure 8. Thick (hundreds of meters) sequence of basalt flows in the Buffalo Hills, Washoe County (looking to the northwest).

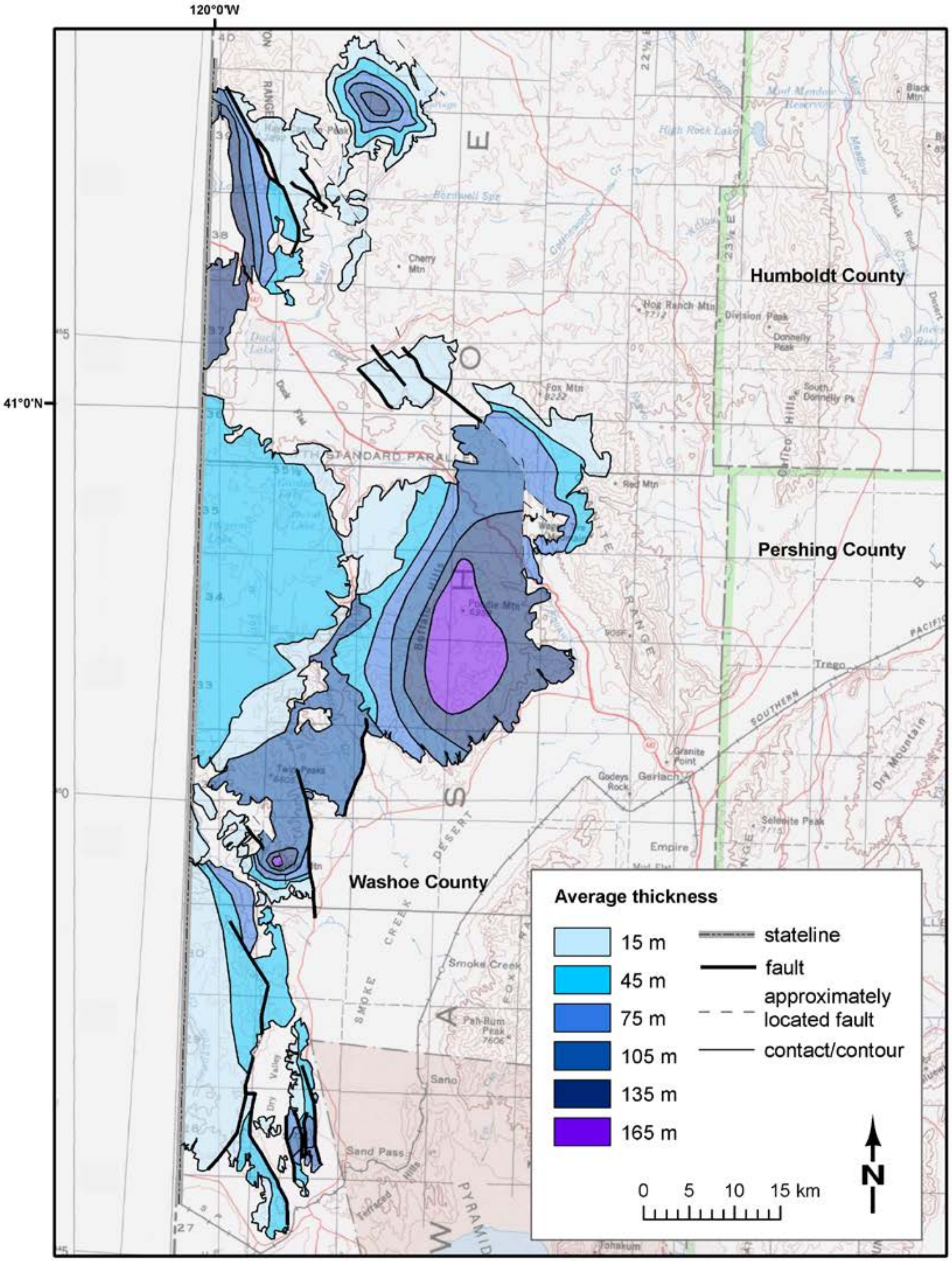

Figure 9. Mafic rock isopach map of northwestern Washoe County.

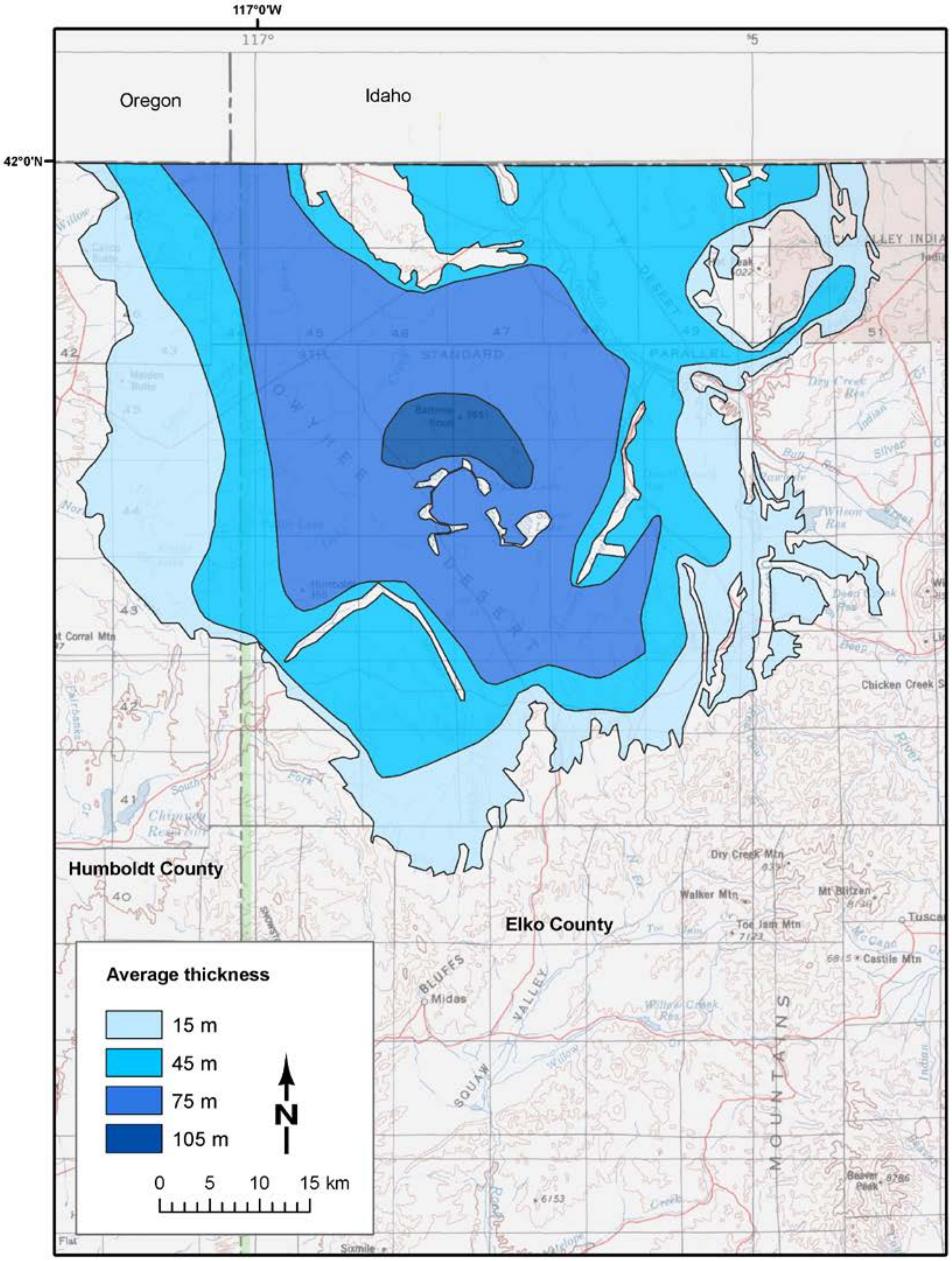

Figure 10. Mafic rock isopach map of the Owyhee plateau area, Humboldt and Elko Counties.

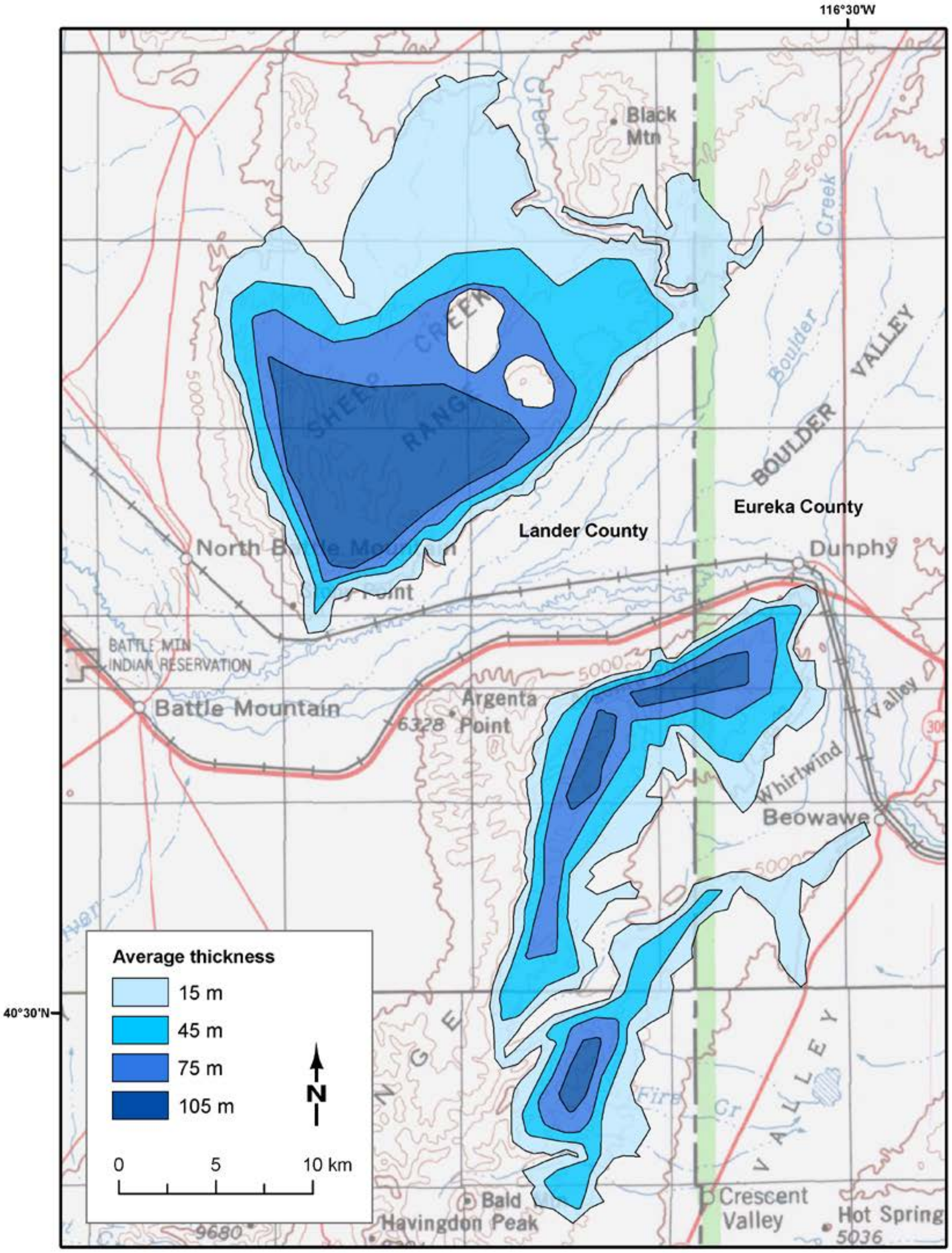

Figure 11. Mafic rock isopach map of the Battle Mountain area, Lander and Eureka Counties.

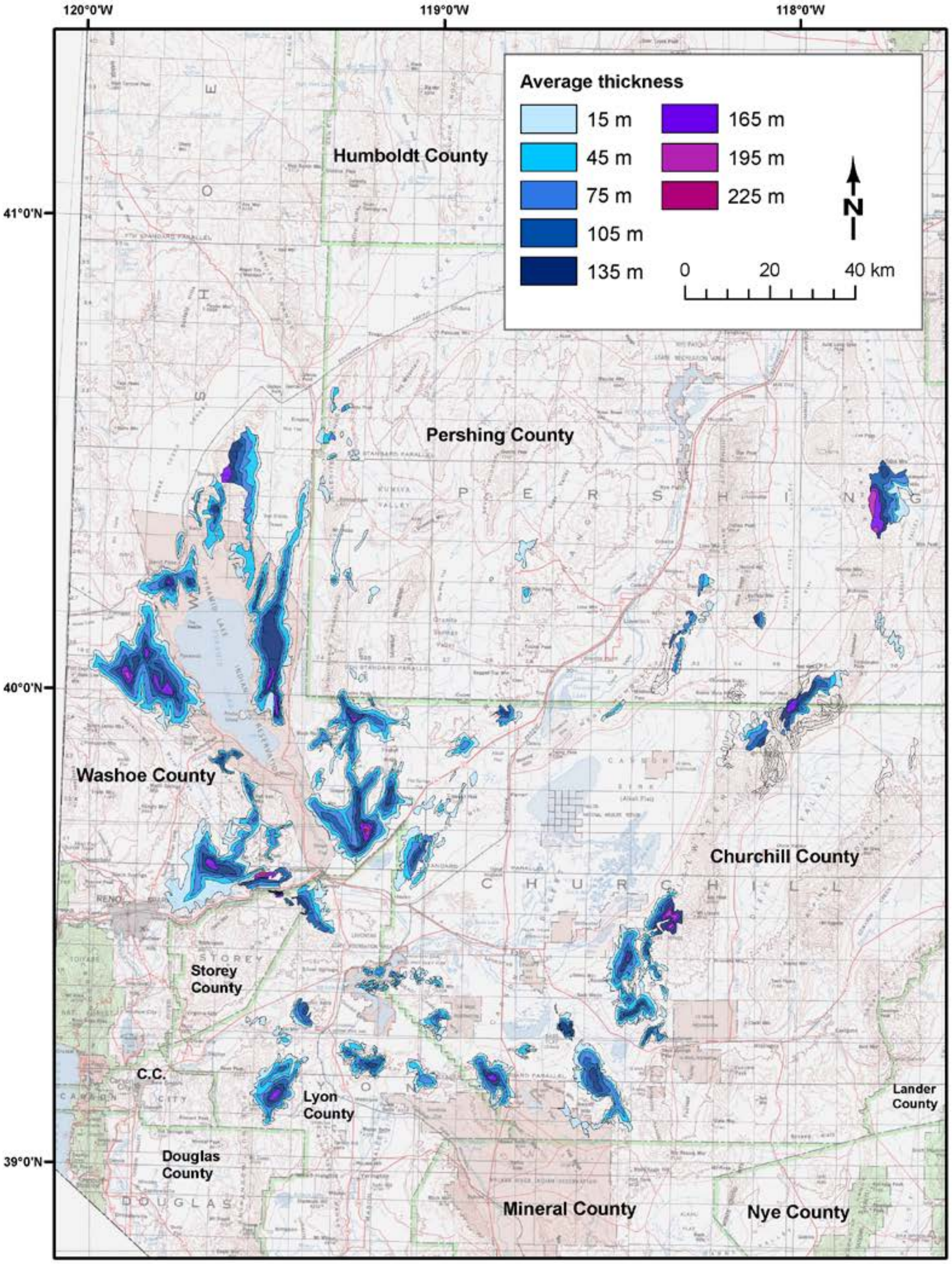

Figure 12. Cenozoic mafic rock isopach map of western Nevada, including southern Washoe, Storey, Lyon, Churchill, and Pershing Counties. Zoomed-in views are presented in Figures 13, 14, 15, and 17.

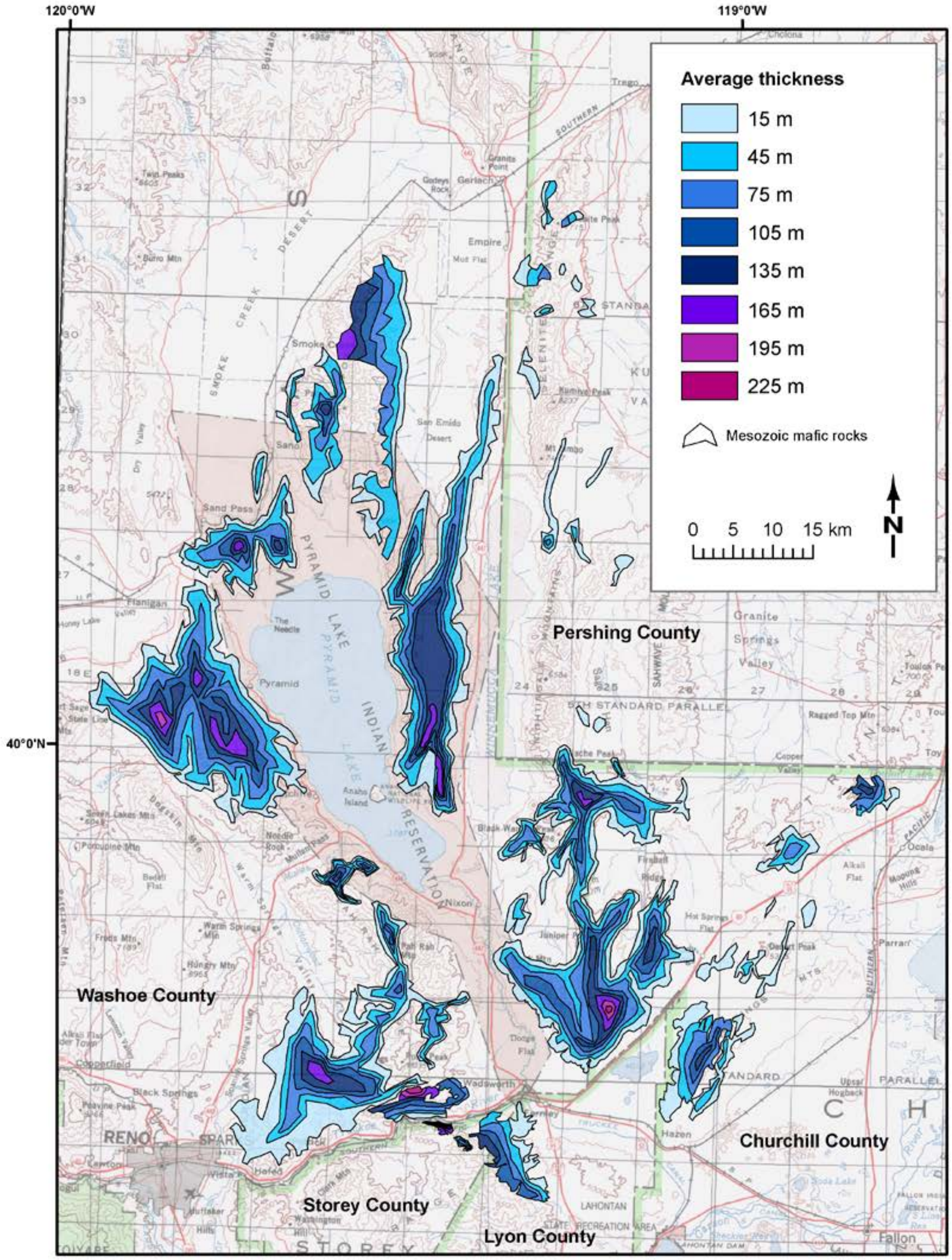

Figure 13. Cenozoic mafic rock isopach map of southern Washoe, Storey, northern Lyon, northwestern Churchill, and southwestern Pershing Counties.

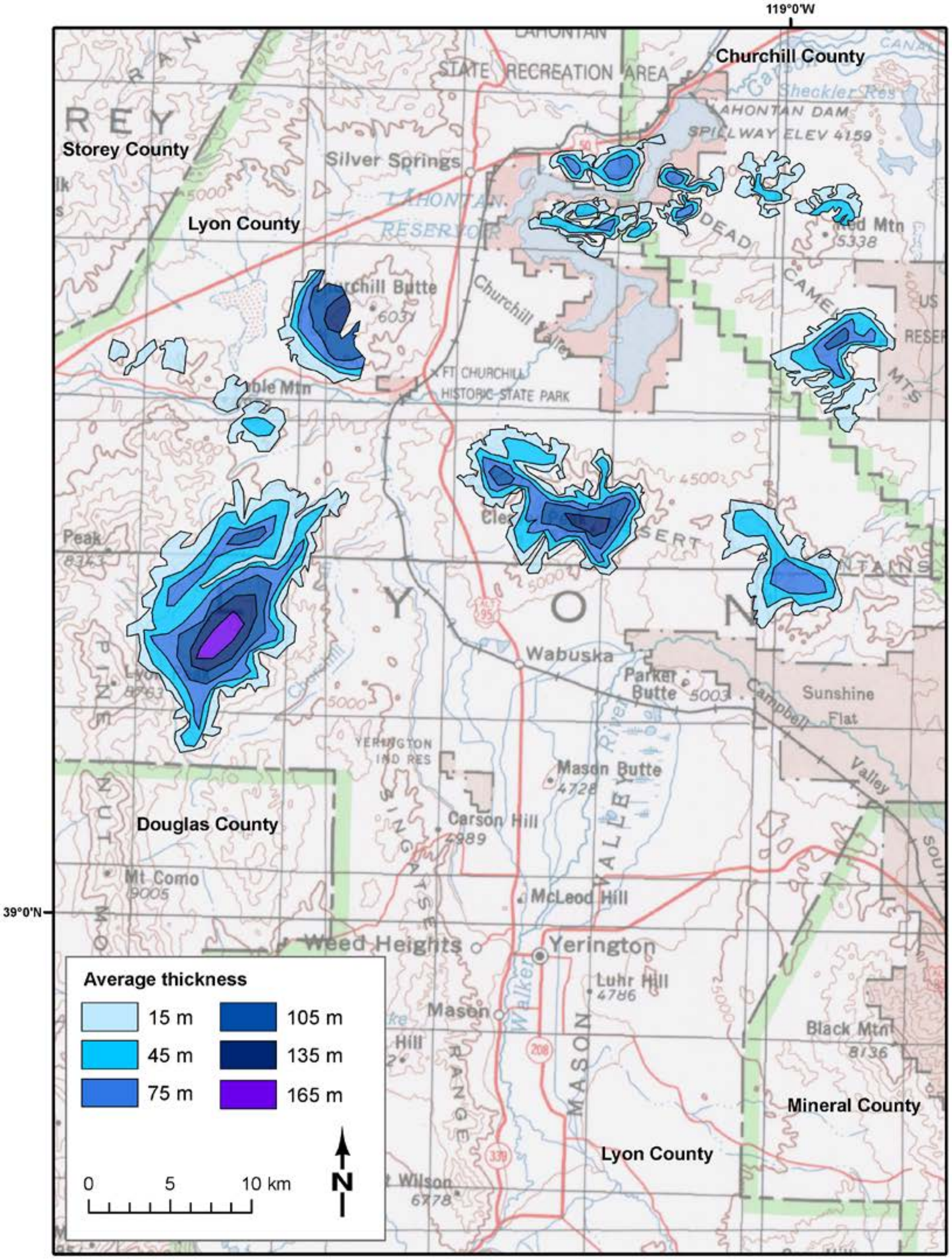

Figure 14. Cenozoic mafic rock isopach map of central Lyon and western Churchill Counties.

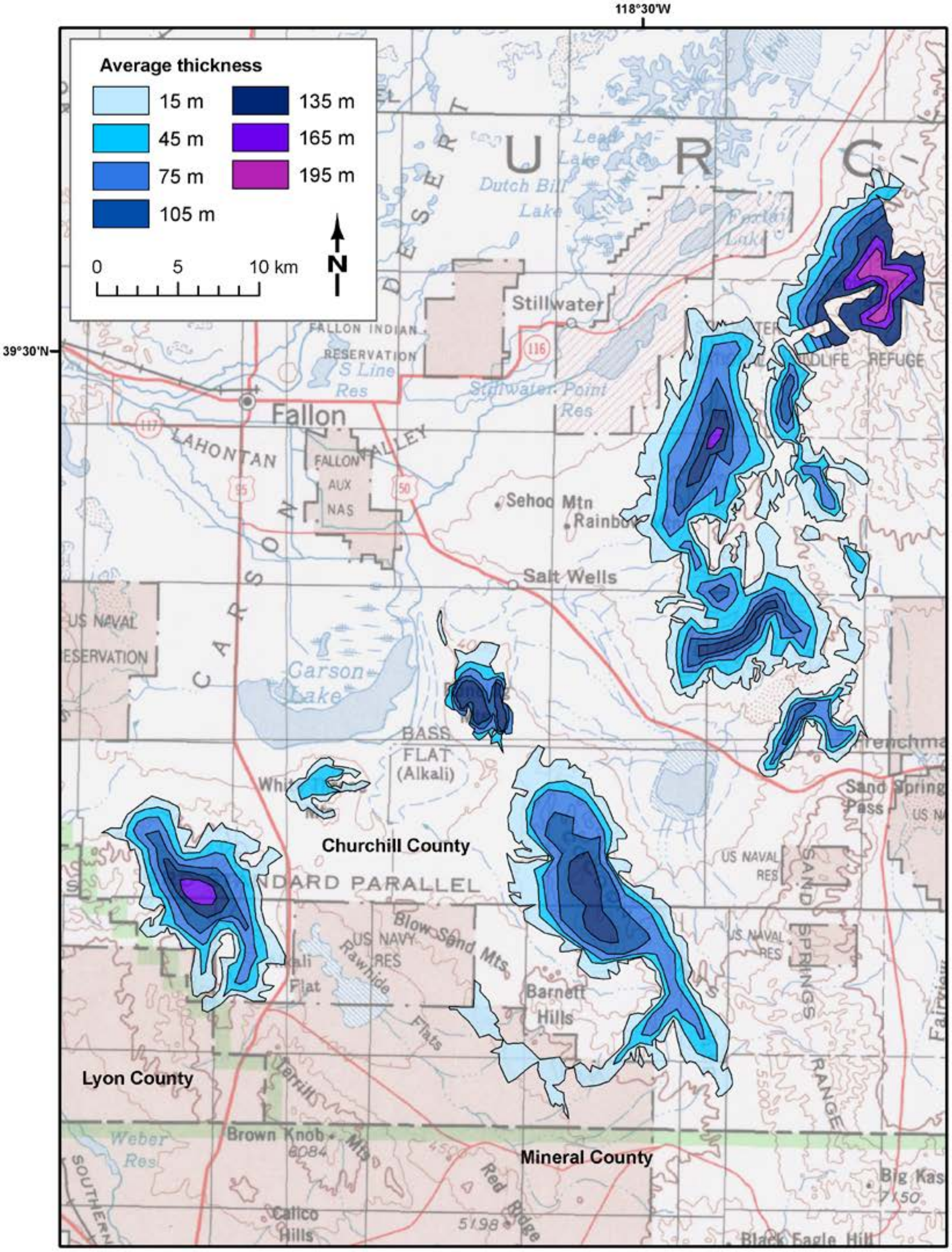

Figure 15. Cenozoic mafic rock isopach map of southwestern and central Churchill Counties.

Figure 16. Thick sequence of basalt flows east of Sand Mountain in Churchill County (looking to the northeast).

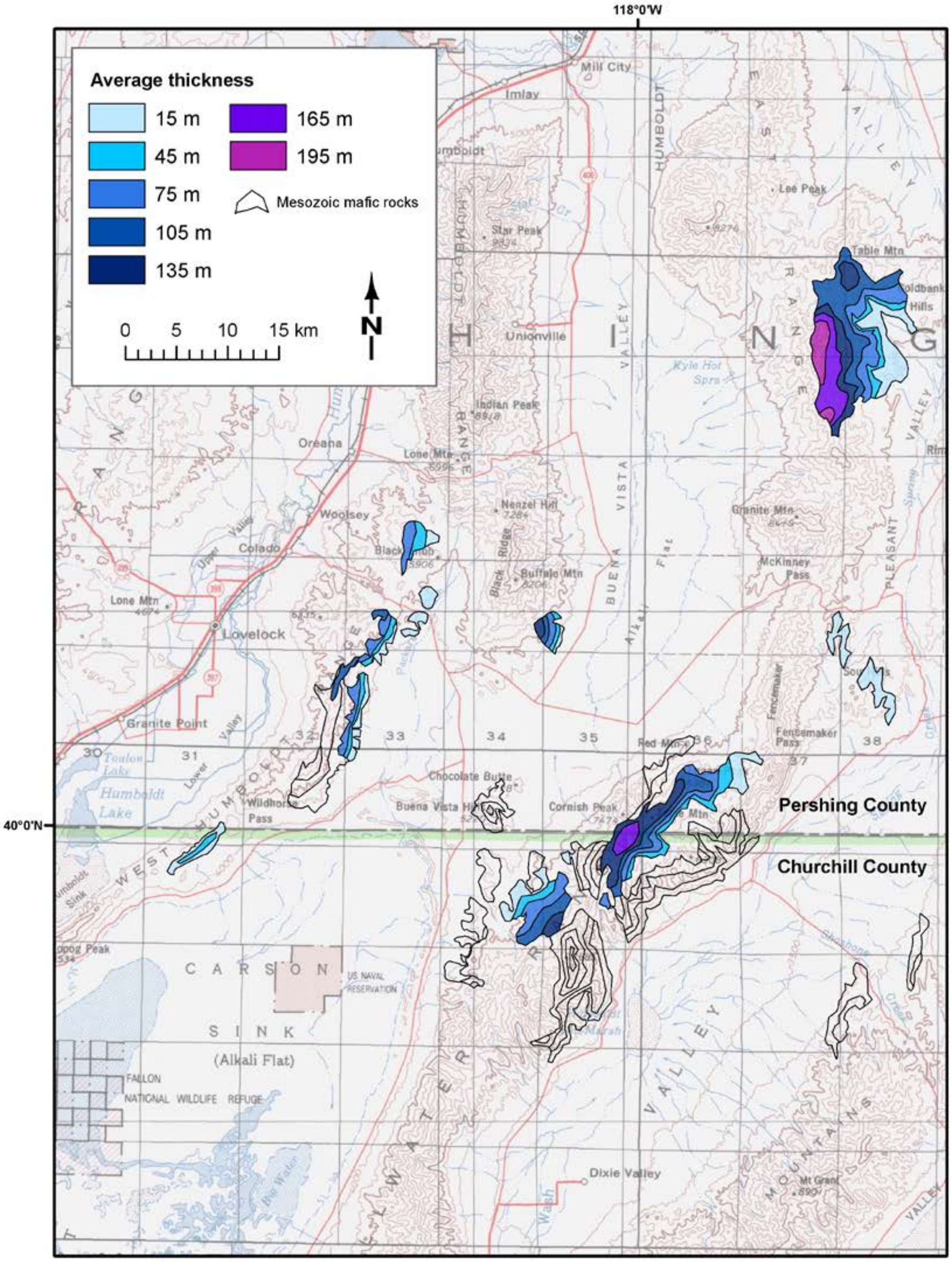

Figure 17. Cenozoic mafic rock isopach map of southern Pershing and northern Churchill Counties.

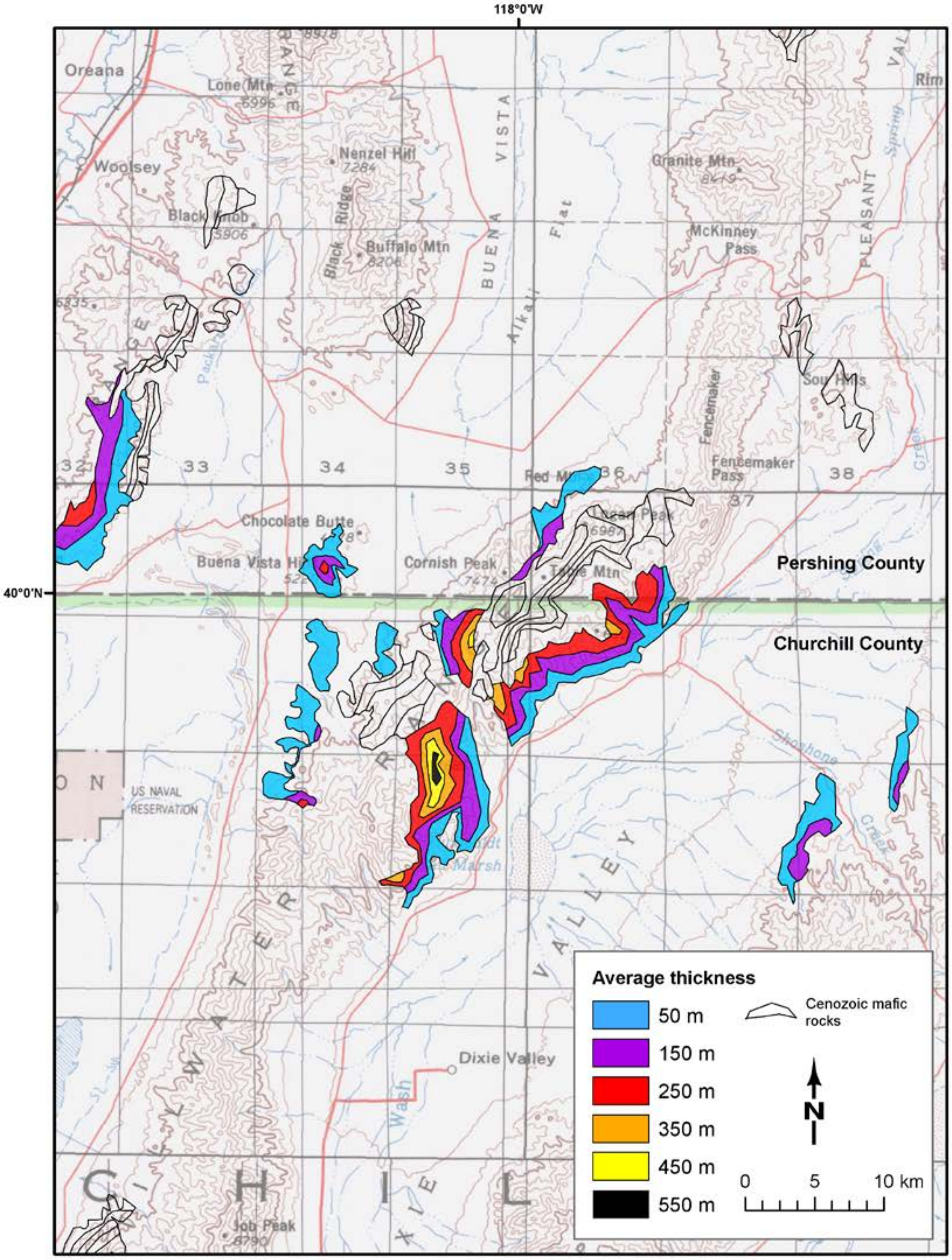

Figure 18. Mafic rock isopach map of the Humboldt lopolith, Churchill and Pershing Counties.

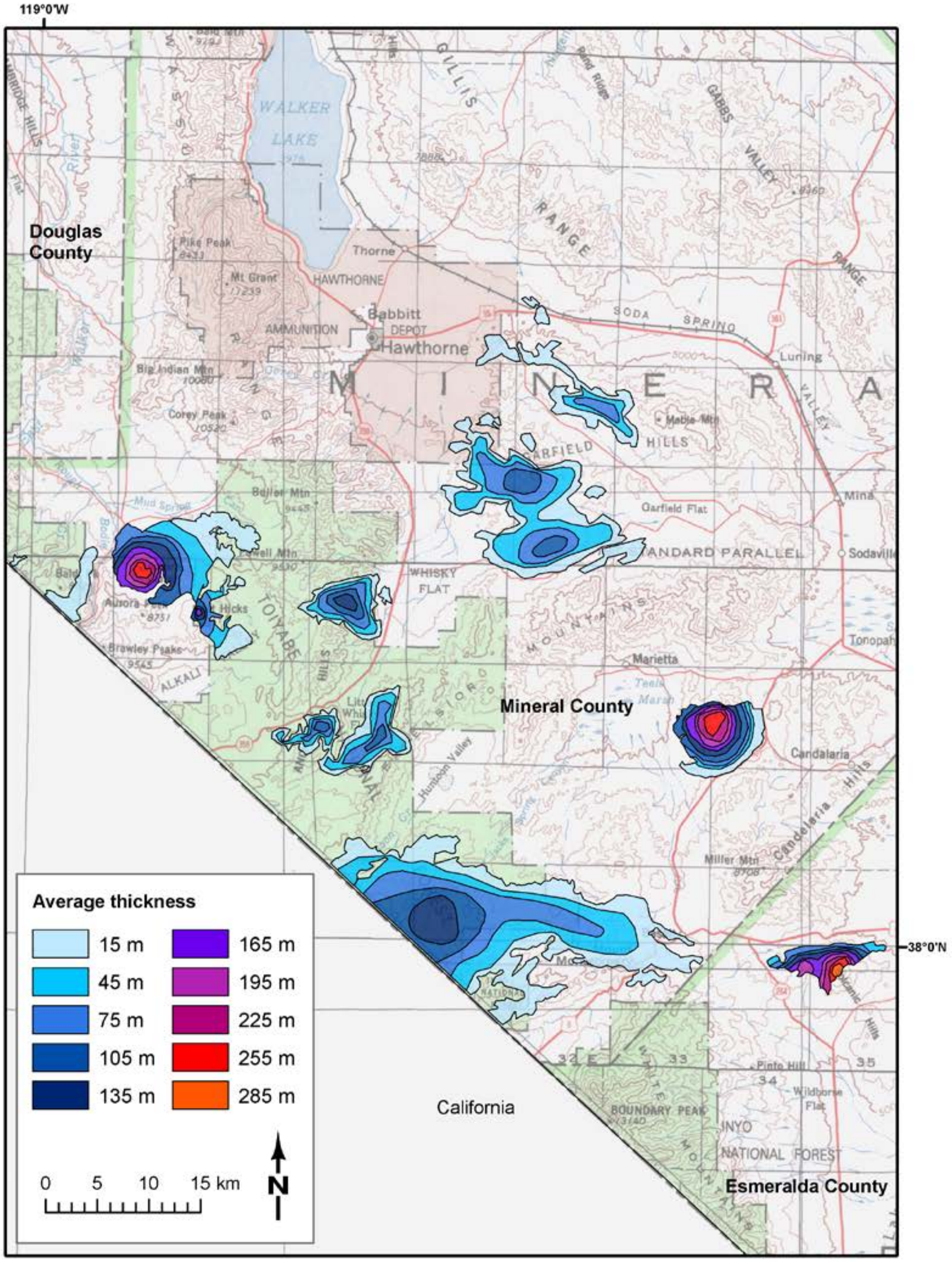

Figure 19. Mafic rock isopach map of southwestern Mineral and northwestern Esmeralda Counties.

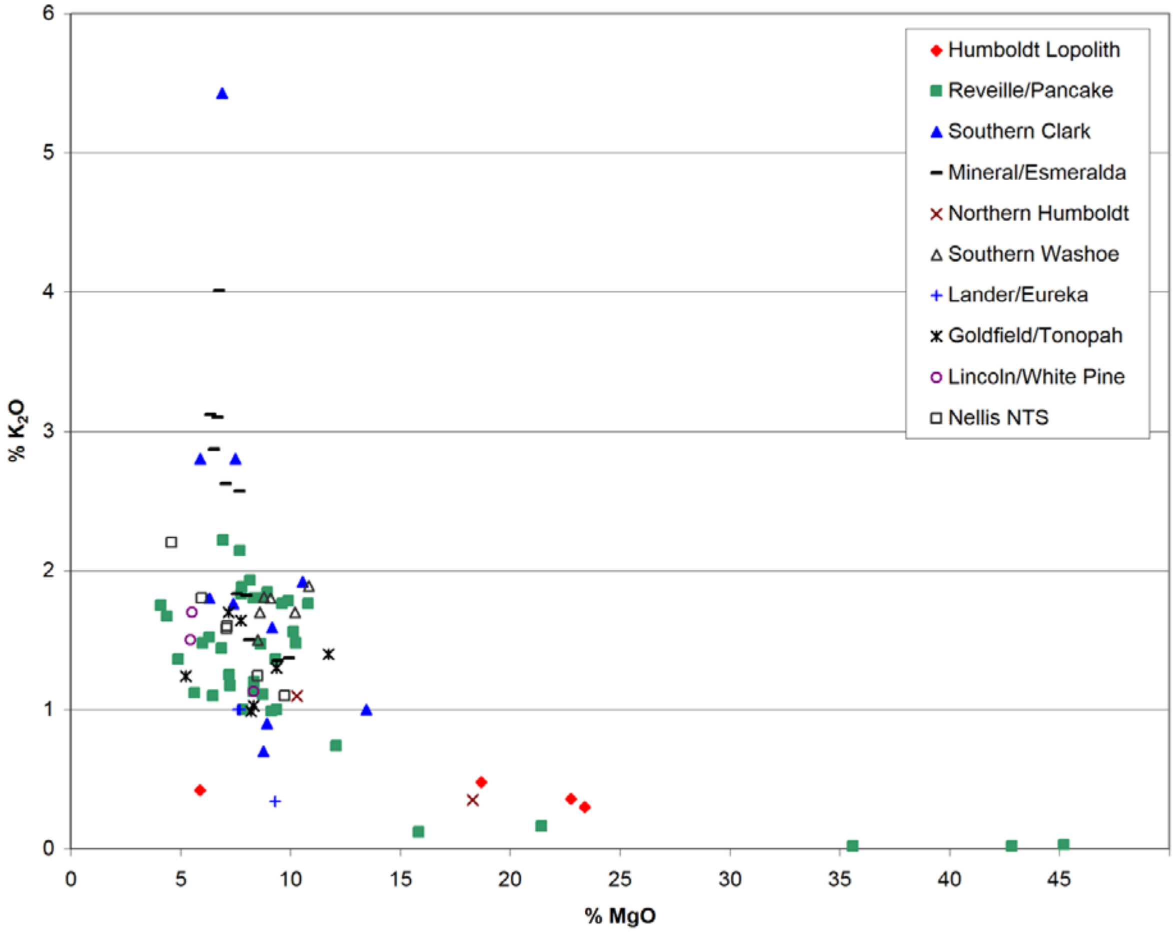

Figure 20. MgO versus K_2O for mafic rocks with CIPW normative olivine greater than 10%. Note that Mineral County mafic rocks have some of the highest K_2O values.

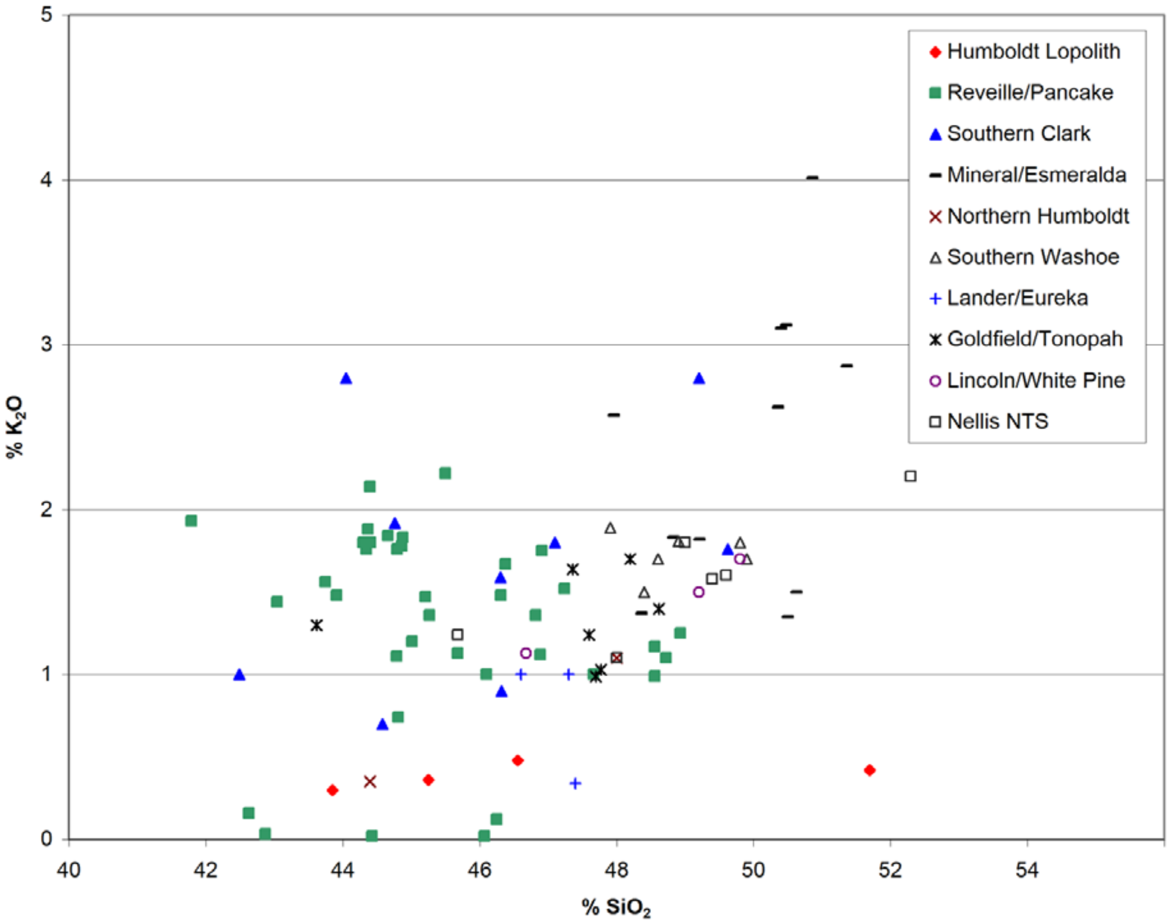

Figure 21. SiO_2 versus K_2O for mafic rocks with CIPW normative olivine greater than 10%.

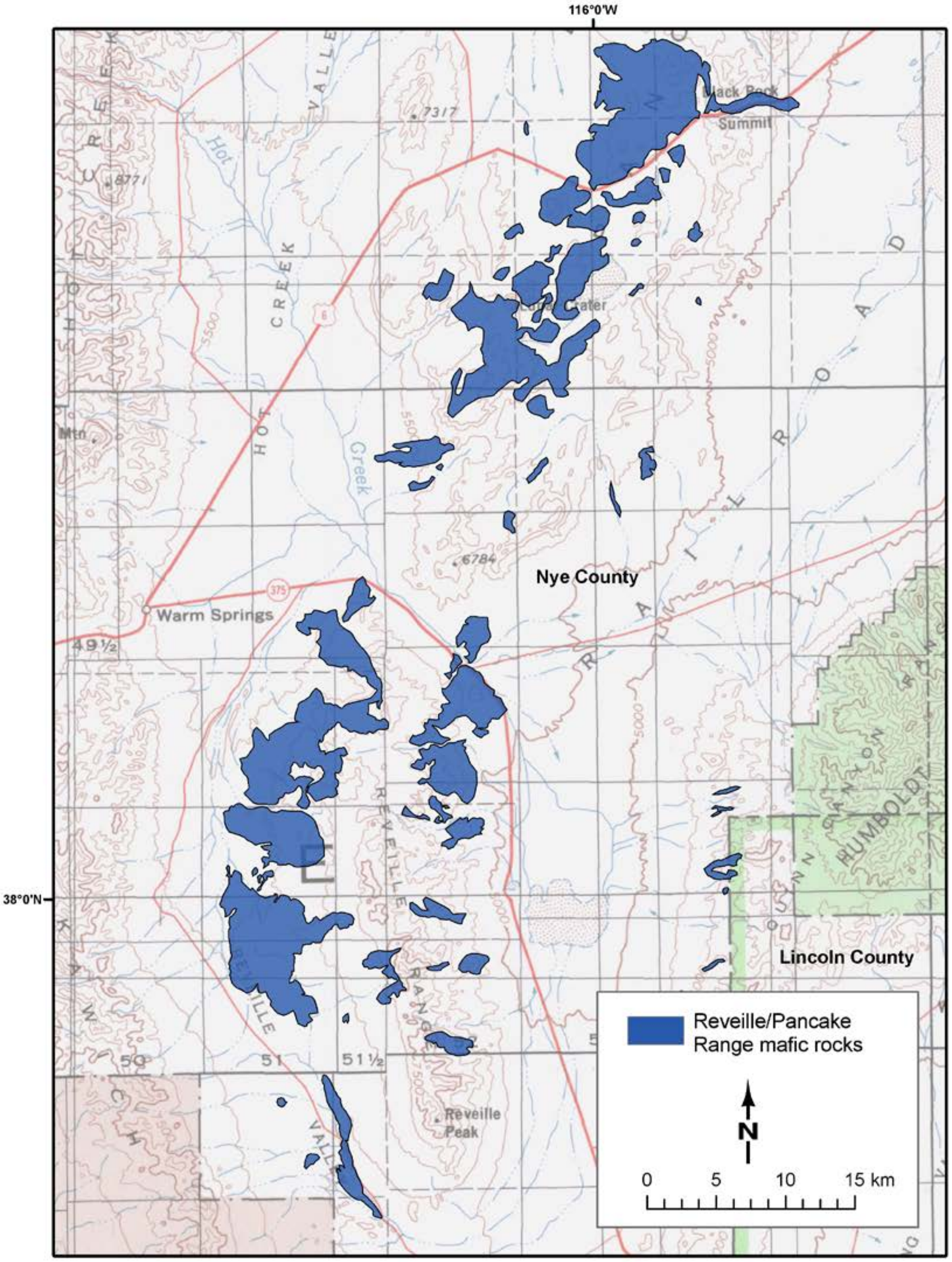

Figure 22. Mafic rock outcrops in the Reveille and southern Pancake Ranges, Nye County.

Figure 23. Easy Chair Crater, one of the Quaternary basalt cinder cones in the Lunar Crater field, Nye County (looking to the east).

Figure 24. Edge of the Black Rock lava flow, with one of the Quaternary basalt cinder cones of the Lunar Crater field in the background (looking to the northeast).

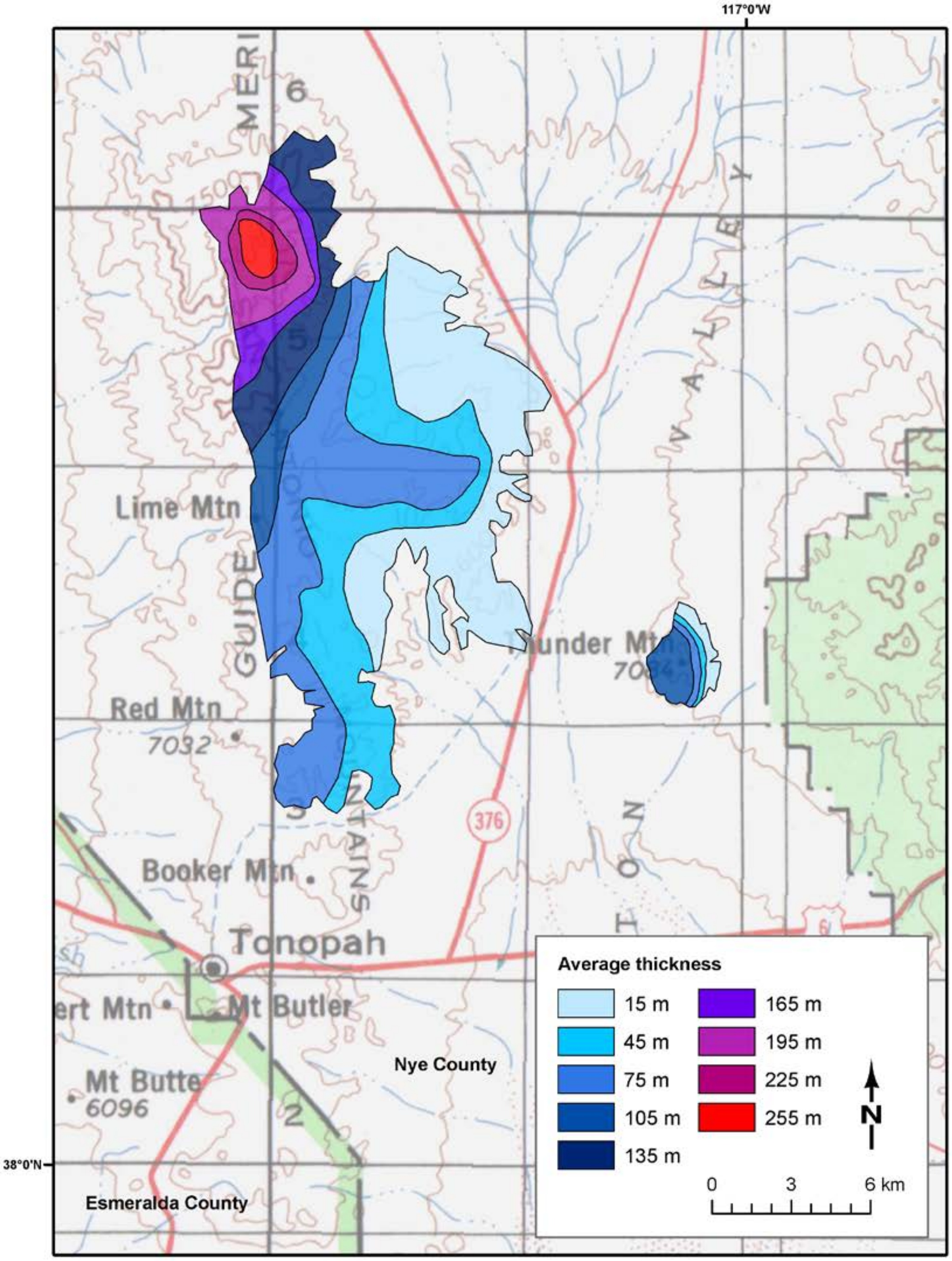

Figure 25. Mafic rock isopach map of the San Antonio Range, Nye County.

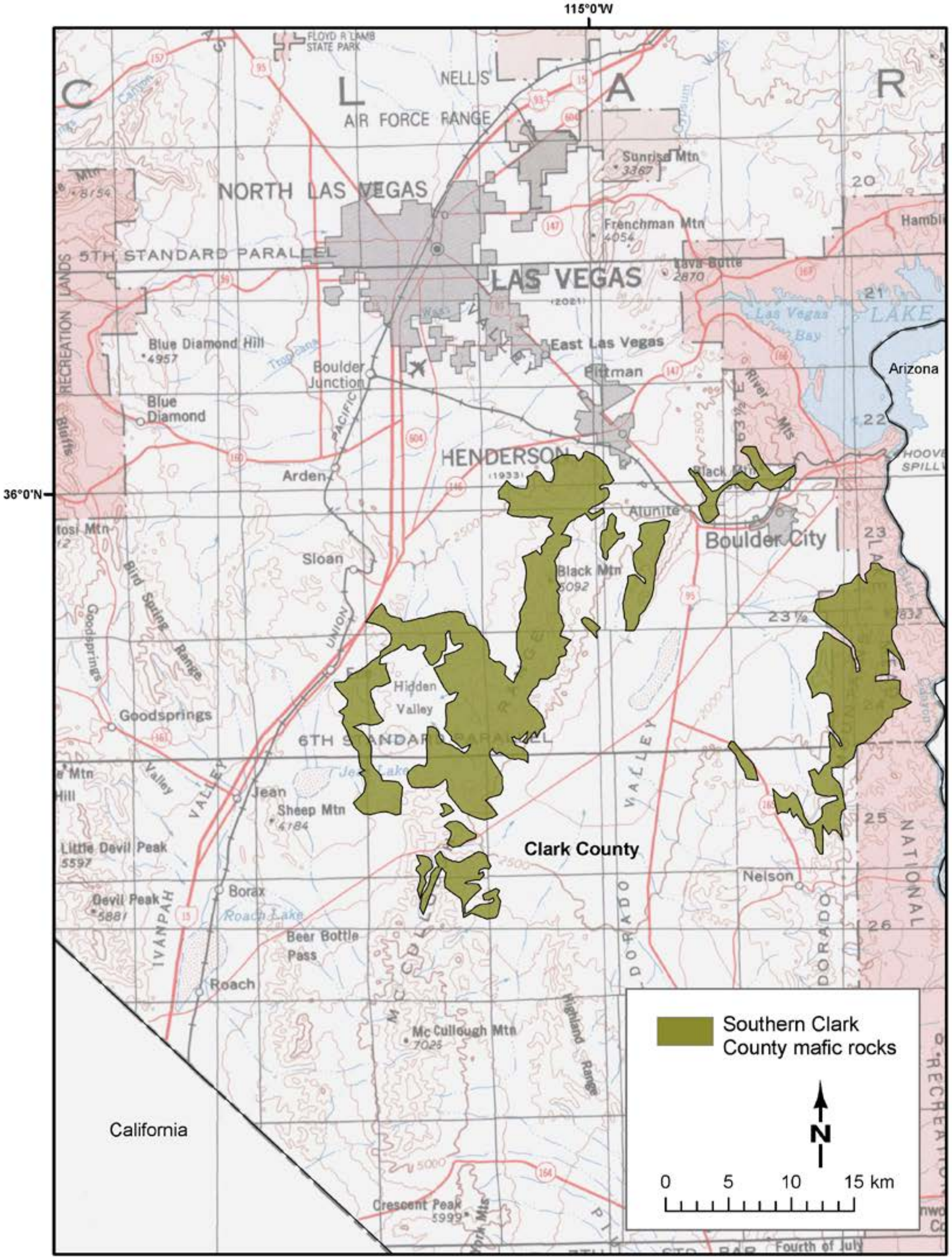

Figure 26. Mafic rock outcrops in southern Clark County.

Figure 27. Basalt flows capping the McCullough Range south of Las Vegas (looking to the northwest).

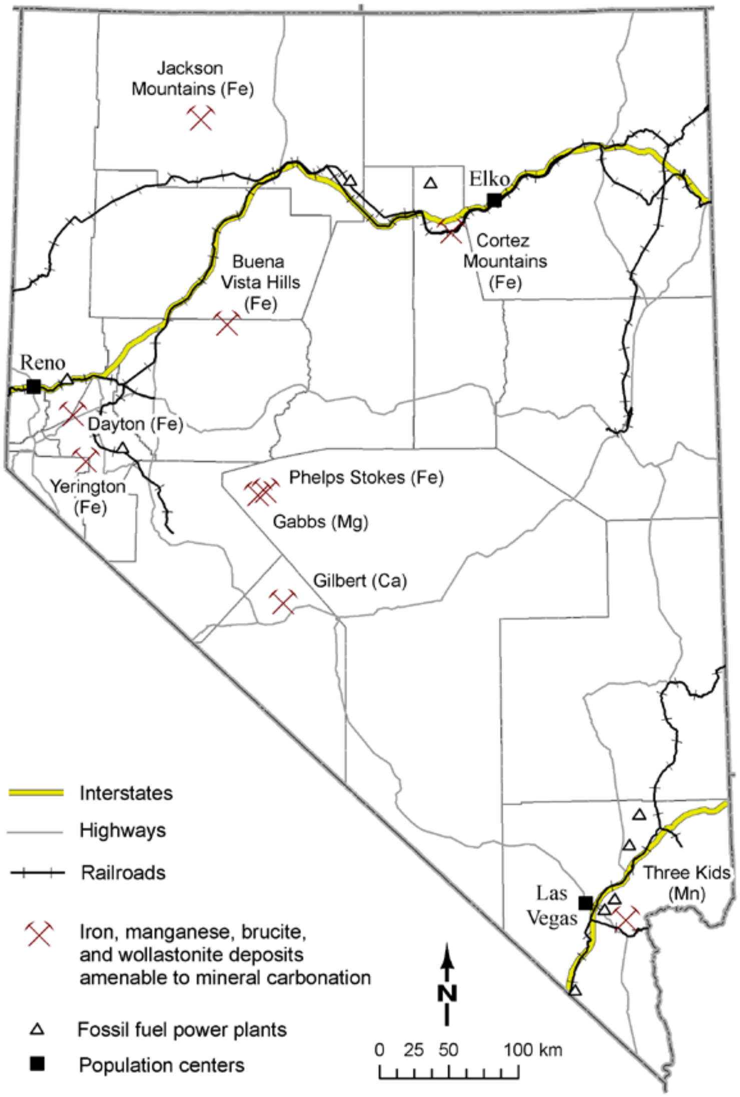

Figure 28. Location map of iron, manganese, and other mineral deposits amenable to mineral carbonation in Nevada, showing proximity to railways, highways, and existing power plants. Deposits include iron in the Buena Vista Hills, in the Cortez Mountains, near Dayton, in the Jackson Mountains, at the Phelps-Stokes Mine, and near Yerington; manganese at the Three Kids Mine; brucite near Gabbs; and wollastonite at the Gilbert deposit.

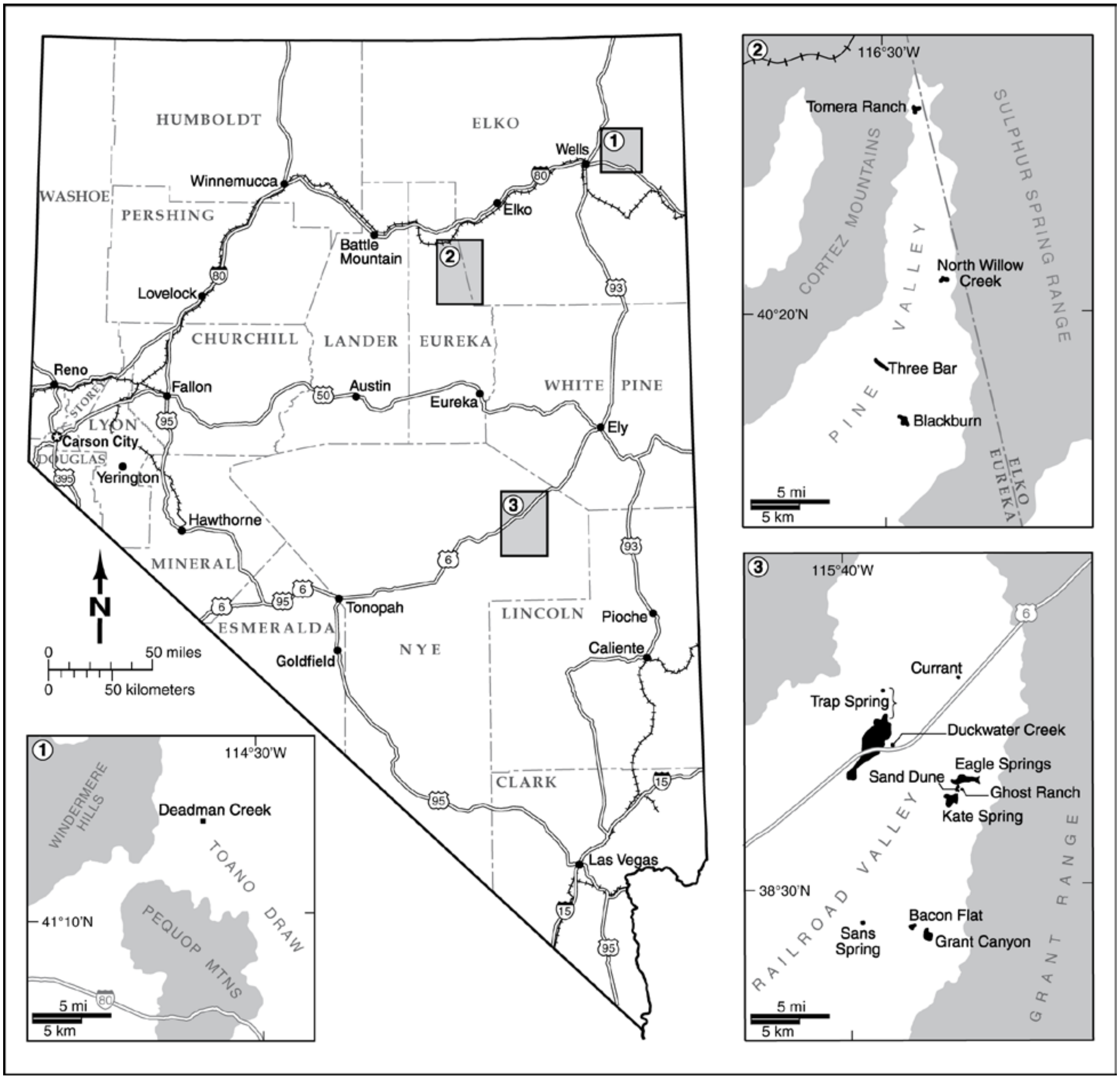

Figure 29. Location and relative sizes of oil fields from which production has been recorded in Nevada.

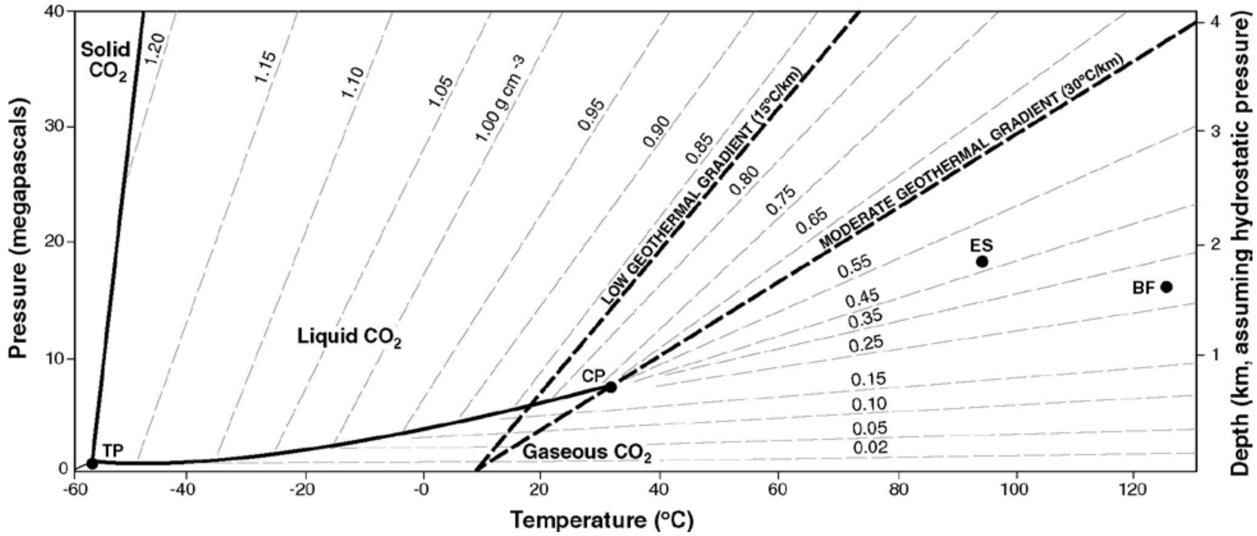

Figure 30. Phase relations, with lines of equal density, for CO$_2$ (modified from Roedder, 1984). TP = triple point (-56.6°C, 0.5 megapascals), at which solid, liquid, and gaseous CO$_2$ coexist. CP = critical point (31.0°C, 7.38 megapascals), above which the distinction between gas and liquid cannot be made with increasing pressure or temperature. ES = bottom-hole temperature (93°C at 1,830 m) in the Eagle Springs oil field (Shevenell and Garside, 2005, and http://www.nbmg.unr.edu/geothermal/gthome.htm). BF = reservoir temperature (120-130°C at about 1,625 m) in the Bacon Flat-Grant Canyon oil fields (Hulen et al. 1994).

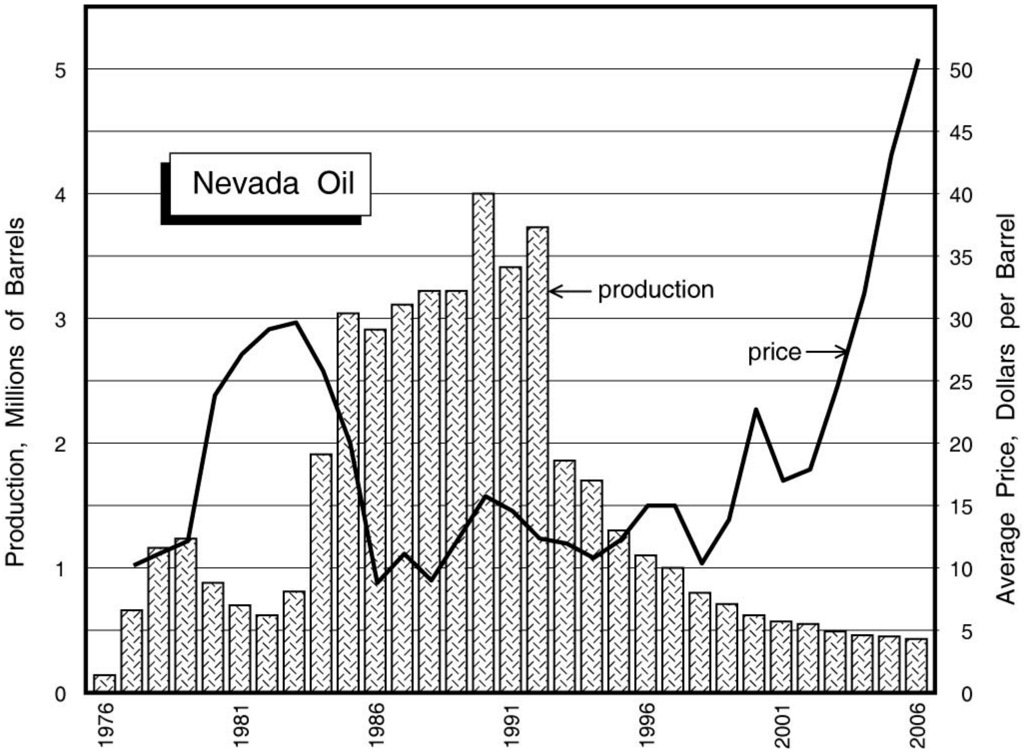

Figure 31. Production and price history for Nevada oil, 1976-2006 (from Price and Meeuwig, 2007).

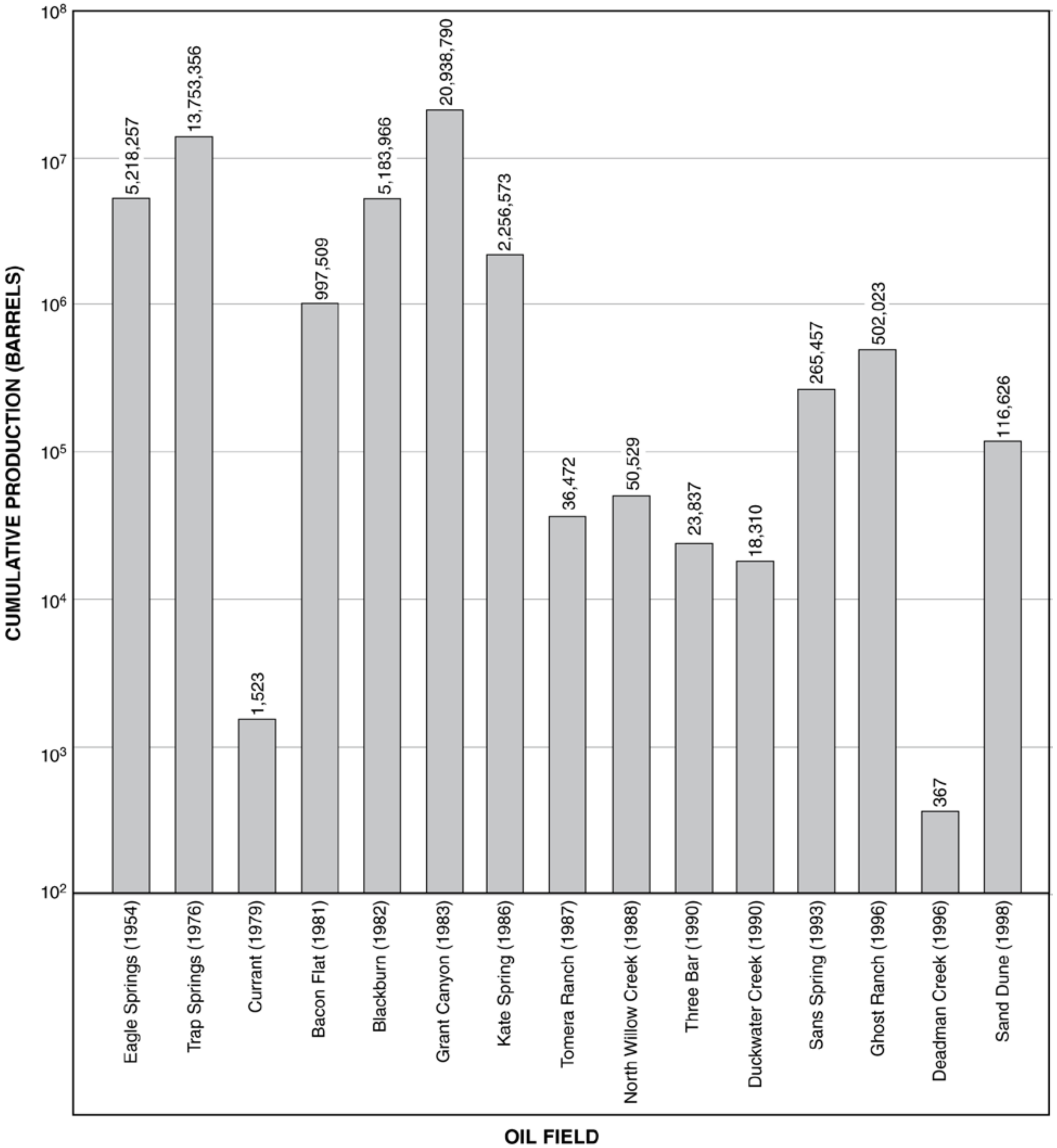

Figure 32. Cumulative Nevada oil production, through 2006, by field, with year of discovery in parentheses.

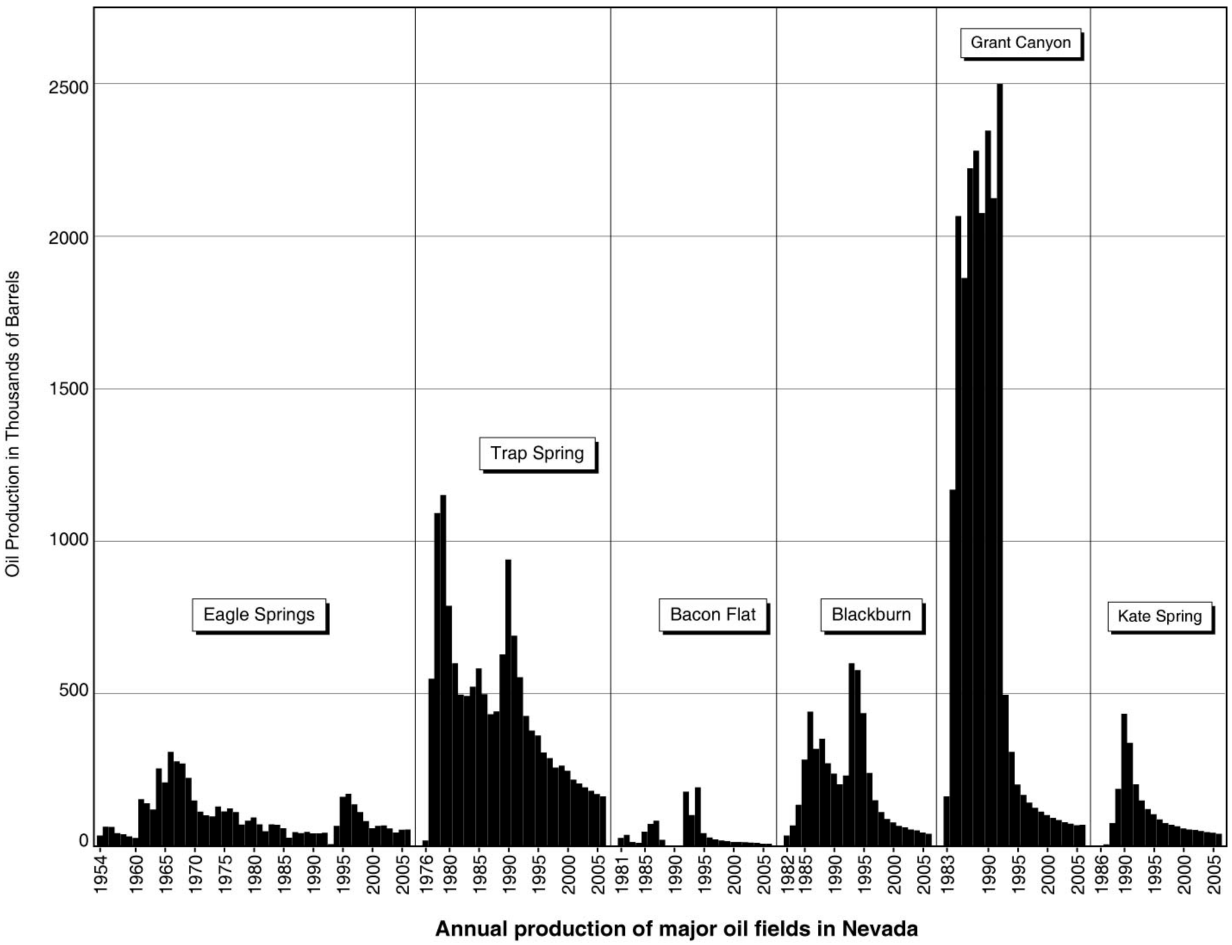

Figure 33. Production histories of Nevada's largest oil fields (from Davis, 2007).

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STORAGE ESTIMATES – WASHINGTON AND OREGON ONSHORE AND OFFSHORE SEDIMENTARY BASINS

Stephen D. Thomas

Golder Associates Inc.

DOE Contract No.: DE-FC26-05NT42593

Contract Period: October 1, 2005 - May 11, 2011

Golder Associates Inc.
18300 NE Union Hill Road, Suite 200
Redmond, Washington 98052
Telephone: (425) 883 0777
Fax: (425) 882 5498

TECHNICAL MEMORANDUM

TO:	Larry Myer, Ph.D. – CIEE	**DATE:**	February 10, 2009
CC:	Paul La Pointe, Ph.D., L.H.G.		
FR:	Stephen D. Thomas, L.HG.	**OUR REF:**	063-1282.100

RE: **STORAGE ESTIMATES – WASHINGTON AND OREGON ONSHORE AND OFFSHORE SEDIMENTARY BASINS**

1.0 INTRODUCTION

This technical memorandum presents the approach, results and conclusions for the estimated storage CO_2 capacity for the onshore and offshore sedimentary basins in the states of Washington and Oregon. This memorandum follows an earlier report prepared by Golder for the WESTCARB team that identified all onshore sedimentary basins in these two states, and provided background information of their physical and hydraulic properties, and provides the first storage estimates. This memorandum follows the guidelines presented in the US Dept. of Energy's *Methodology for Development of Geologic Storage Estimates for Carbon Dioxide* (March 2008) for making the estimates.

2.0 ONSHORE SEDIMENTARY BASINS

Tables 1 and 2 list the sedimentary basin identified in the Phase 1 study (Golder, 2006) in the states of Washington and Oregon respectively. These tables also include basin area estimates, and indicators of whether representative well logs exist, whether the basin is deeper than 800 meters and if a resource estimate can be made. Storage estimates could only be made for basins for which the target formation had reservoir volume below 800 m and for which logs were available to determine porosity and lithology. Figures 1 and 2 show the locations of these basins as currently defined.

2.1 Geologic Data

Since the Phase 1 report was prepared, Golder obtained new geologic data for four basins in the two states; the Willapa Hills and Puget Basins in Washington, and the Astoria-Nehalem and Tyee-Umpqua basins in Oregon. The new data consist of published borehole logs for hydrocarbon exploration wells. The data for the Washington basins were obtained from log databases provided by M.J. Systems (a private company located in Denver, Colorado) (M.J. Systems, 2008). The data for the Oregon basins was obtained from Oregon's Department of Geology and Mineral Industries log database (ODOGMI, 2008).

The borehole log data was used to revise the initial resource estimates presented in the Phase 1 study. The new data enabled basin-specific estimates of sandstone porosity to be made. For the purpose of estimating the resource volumes, a porosity of zero was assumed for other geologic units such as siltstone, shale, claystone and coal. The analyses used lithologic and neutron-density logs. First, the lithologic logs were used to determine the percent of sandstone in each borehole. Basin-wide sandstone percentages were calculated by averaging the values from the available logs in each basin. Between 5 and 18 lithologic logs were used in each basin (Table 3).

TABLE 1

Onshore Consolidated Sedimentary Basins – Washington State

Basin Name	Geomorphic Province	Approx. Basin Area (sq. km.)	Well Logs?	Depth >800m?	Estimate Storage?
Tofino-Fuca Basin	Western Tertiary	1,044 3.0	Y	Y	Y
West Olympic Hills Basin	Western Tertiary	1,360 4.0	Y	Y	Y
Willapa Hills Basin	Western Tertiary	6,731 5.0	Y	Y	Y
Whatcom Basin	Western Tertiary	955 6.0	Y	Y	Y
Puget Trough	Western Tertiary	25,206 7.0	Y	Y	Y
Methow Basin	Cascades-CRBG	2,838 8.0	N	Y	N
Chiwaukum-Swauk Basins	Cascades-CRBG	2,905 9.0	N	Y	N

TABLE 2

Onshore Consolidated Sedimentary Basins – Oregon State

Basin Name	Geomorphic Province	Approx. Basin Area (sq. km.)	Well Logs?	Depth >800m?	Assess for Storage?
Astoria-Nehalem	West Coast Tertiary	4,716	Y	Y	Y
Willamette Trough	West Coast Tertiary	6,718 10.0	Y	Y	Y
Tyee-Umpqua Basin	West Coast Tertiary	16,213 11.0	Y	Y	Y
Ochoco Basin	Eastern Oregon	22,967	Y	Y	Y
Coos Basin	Western Tertiary	2,420	Y	Y	N
Hornbrook Basin	Eastern Oregon	636	N	Y	N

The neutron-density logs were used to calculate the sandstone porosity in each borehole. Only boreholes with both lithologic and neutron-density logs were used for the analysis; the lithologic logs were used to identify the sandstone and the neutron-density logs were used for the calculation. For each basin between 1 and 7 boreholes had both lithologic and neutron-density logs (Table 3). Neutron porosity and density porosity values for each sandstone unit were obtained from the logs and the total porosity was calculated using the root mean square formula (Asquith et. al, 1982), where:

$$Total\ Porosity = \sqrt{\frac{(Neutron\ Density)^2 + (Density\ Porosity)^2}{2}}$$

A weighted average porosity was determined for each borehole. The gross porosity for a basin was calculated by multiplying the average sandstone porosity by the percent of sandstone calculated from the lithologic logs. The porosity values are shown in Table 3.

TABLE 3

Revised Porosity Estimates

Basin	Number of Well Logs Used to Determine Sandstone Thickness	Average Sandstone Thickness (ft)	Number of Well Logs Used to Determine Porosity	Revised Gross Porosity Estimate
Puget Trough	11	1,727	1	16.2%
Willapa Hills	8	762	2	6.3%
Astoria-Nehalem	18	891	7	6.8%
Tyee-Umpqua	5	2,932	2	8.7%

2.2 Resource Estimation Assumptions

The analysis approach that was used followed the guidelines in the US DOE manual. The results are summarized in Table 4. The following key assumptions were made:

1. Basin areas (Tables 1 and 2):
    a. For Puget Trough, the basin extent was based on the 800-meter isopachs that were included in the sediment thickness data set developed previously.
    b. For all other basins, the basin outlines were determined by evaluating published geologic maps that show outcropping units, and previous estimates of basin extents.
2. Net basin sediment thickness
    a. For Puget Trough basin, the isopachs were used. Within the basin extent under consideration, these range from 800 to 10,000 meters. The average sediment thickness was 4,500 meters.
    b. For all other basins, the basin thicknesses were based on information contained in available borehole logs.

The uppermost 800 meters of all basins was excluded for the purpose of estimating total basin volume.

3. Porosity. The determination of a representative porosity for each basin to estimate resource was made in one of two ways for each basin. Firstly, porosity values were estimated for the four basins in which borehole logs included lithologic neutron-density logs (Table 3). These four basins are the Puget Trough, Willapa Hills, Tyee-Umpqua and Astoria-Nehalem, and the values ranged from 6.3 to 16.2 percent. For the remaining ten basins, a single value of 7.5 percent was used for the resource assessment, which is approximately the average for the Willapa Hills, Astoria-Nehalem and Tyee-Umpqua basins. This value is expected to change if future drilling and logging provide better estimates of net porosity.

4. Carbon Dioxide Density. The density of CO_2 in the subsurface is known to vary depending on pressure and temperature conditions. In general, the density increases with increasing depth below atmospheric (land surface) conditions. For the purpose of this assessment, the uppermost 800 meters of geologic material were excluded from consideration. Therefore, the CO_2 density conservatively determined for a depth of 800 meters, and was applied for all basins regardless of the total depth of each. This density was 469 kg/m^3.

2.3 Results

Tables 4 and 5 summarize the resource estimates (mass of CO_2) for the five Washington and four Oregon onshore basins, respectively. Resource estimates are included assuming both low and high Efficiency Factors (E) of 0.01 and 0.04, respectively, and a range of minimum, average and maximum basin effective sediment thicknesses (no minimum thickness was determined for the Whatcom, Ochoco and Willamette Trough Basins). All six resource estimates for each basin are included in the GIS database.

In Washington state, the Puget Trough has by far the largest potential, with average mass estimates ranging from 86.4 x10^6 to 345.4 x10^6 Mt (Figure 2). The remaining four Washington basins have a combined average resource potential of between 3.9 x10^6 and 15.5 x10^6 Mt. In Oregon state, the four onshore basins have a combined average resource potential of between 16.7 x10^6 and 66.9 x10^6 Mt (Figure 3). The Tyee-Umpqua Basin has the largest potential in the state, constituting 63 percent of the Oregon total.

TABLE 4

Resource Estimates for Washington Basins

Basin Name	**Basin Area (sq. km.)**	**Effective Sediment Thickness (meters)**			**Storage Estimate (Mt x 10^3)**						**Basin Class**
		Min.	*Ave.*	*Max.*	*Min.*		*Ave.*		*Max.*		
					E=0.01	E=0.04	E=0.01	E=0.04	E=0.01	E=0.04	
Tofino-Fuca	1,044	732	2,545	1,655	NA	NA	608	2,431	935	3,740	4
West Olympic	1,360	224	2,054	1,075	107	429	514	2,056	982	3,930	4
Willapa Hills	6,731	369	2,845	1,173	737	2,948	2,340	9,360	5,676	22,704	4
Whatcom	995	325	1,758	1,258	-	-	423	1,691	591	2,363	4
Puget Trough	25,206	4,500	4,500	4,500	86,360	345,441	86,360	345,441	86,360	345,441	4

Notes:

Mt – thousands of metric tons. E – Efficiency factor (as defined by USDOE Guidance document). Basin Class – assigned level of confidence (see US Dept of Energy, 2008).

TABLE 5

Resource Estimates for Oregon Basins

Basin Name	**Basin Area (sq. km.)**	**Effective Sediment Thickness (meters)**			**Storage Estimate (Mt x 10^3)**						**Basin Class**
		Min.	*Ave.*	*Max.*	*Min.*		*Ave.*		*Max.*		
					E=0.01	E=0.04	E=0.01	E=0.04	E=0.01	E=0.04	
Astoria-Nehalem	4,716	361	2,891	1,440	545	2,181	2,175	8,700	4,368	17,470	4
Willamette Trough	6,718	NA	2,259	792	-	-	1,873	7,490	5,338	21,353	4
Tyee-Umpqua	16,213	417	3,397	1,597	2,767	11,067	10,586	42,346	22,522	90,087	4
Ochoco	22,967	NA	1,515	259	-	-	2,093	8,374	12,235	48,941	4

Notes:

Mt – thousands of metric tons. E – Efficiency factor (as defined by USDOE Guidance document). Basin Class – assigned level of confidence (see US Dept of Energy, 2008).

3.0 OFFSHORE BASINS

3.1 Resource Estimation Assumptions

The continental margin along the western boundary of Washington and Oregon rests on a subduction zone. In this area the oceanic crust of the Juan de Fuca plate is being thrust underneath the North America plate. This process resulted in development of the Cascade Range, the Olympic Mountains and an offshore trench, now filled with sediment, located along the base of the continental slope. The subduction also produced a series of north-south basins that were gradually uplifted as much as 1 to 2 km (Kulm and Fowler, 1974) and these are now located within the continental shelf (see Map 1; McLean and Wiley, 1987). Large-scale extensional growth faults are a dominant feature offshore Washington and shale diapirs are present offshore Washington and Oregon.

The basin fill (Eocene and younger) is primarily sedimentary but may contain localized deposits of volcanic rock (Snavely and Wanger, 1980). The sediment thickness is typically greater than 10,000 feet and in some areas as much as 20,000 feet. Basement rock was produced by Miocene underthrusting which produced a melange. Tables 6 and 7 summarizes the lithostratigraphic sequence as interpreted from a well near Ocean City, Washington (Palmer and Lingley, 1989). Figure 7 shows the locations of the six identified off-shore basins and the sediment isopachs.

A total of 96 million barrels (MM bbl) of oil and 650 billion cubic feet (Bcf) of gas are estimated to be economically recoverable from the Washington-Oregon assessment area. No accumulations of resources have been discovered in the Washington-Oregon assessment area.

TABLE 6

Interpreted Offshore Geologic Sequence

Geologic Age	Unit	Description
Quaternary/Pliocene	Quaternary deposits and Quinault Formation	Shallow marine siltstone, sandstones, conglomerate and siltstone.
Middle to Upper Miocene	1.Montesano Formation Siltstone member 2.Montesano Formation Sandstone member 3.Montesano Formation Claystone member	Claystones and siltstones with minor sandstone interbeds. Thick sandstones minor shale interbeds. Claystones with interbedded sandstones.
Middle Miocene to Upper Oligocene	Hoh Rock Assemblage	Sandstone with abundant siltstones and claystones.
Upper to Middle Eocene	Ozette Melange	Interbedded sandstones, siltstones and claystones.

TABLE 7

Geologic Properties for Offshore Sequence

Geologic Age	Thickness	Porosity	Permeability
Quaternary/Pliocene	300 to 500 ft	High porosity. No apparent confining layer.	High permeability
Pliocene	800 to 1,200 ft	25%	100 to 10,000 md
M. Miocene- U. Miocene			
- Siltstone	600 to 1,000 ft	20%	0.1 md
- Sandstone	200 to 800 ft	20%	1000 md
- Claystone	4,000 to 8,000 ft	10 to 20%	0.1 to 5 md
M. Miocene – U. Oligocene	5,000 ft	10-20%	0.1-0.4 md
Eocene (basalts)	unknown	unknown	Unknown

The Washington-Oregon assessment area is approximately 400 miles in length and 30 to 50 miles wide. Water depth in the area ranges from approximately 100 feet to 600 at the shelf-slope boundary. Within this region six (6) basins have been identified base on a limited number of offshore borings and seismic reflection transects (Figure 1).

The quality of the data varied greatly within and among the various surveys. Furthermore, none of the seismic data were acquired in a conventional grid. Consequently, these data are more useful for regional tectonic studies and less useful for prospect delineation or for mapping the extent of clastic sedimentary deposits such as the Montesano sandstones.

3.2 Results

Table 6 summarizes the resource estimates (mass of CO_2) for the six offshore basins. Resource estimates are included assuming both low and high Efficiency Factors (E) of 0.01 and 0.04, respectively, for an average basin effective sediment thicknesses. Both resource estimates for each basin are included in the GIS database.

The resource estimates range from 0.8 $x10^6$ Mt to 3.1 $x10^6$ Mt for the smallest basin (Newport; 4 percent of the offshore total) to 7.48 $x10^6$ Mt to 29.9 $x10^6$ Mt for the largest basin (Heceta; 35 percent of the offshore total) (Figure 4).

TABLE 8

Resource Estimates for Offshore Washington and Oregon Basins

Basin Name	Basin Area (sq. km.)	Effective Sediment Thickness (meters)			Storage Estimate (Mt x 10^3)						Basin Class
		Min.	*Ave.*	*Max.*	*Min.*		*Ave.*		*Max.*		
					E=0.01	E=0.04	E=0.01	E=0.04	E=0.01	E=0.04	
Olympic	4,930	-	3,810	-	-	-	6,610	26,440	-	-	3
Willapa	4,190	-	2,290	-	-	-	3,372	13,488	-	-	3
Heceta	5,581	-	3,810	-	-	-	7,483	29,932	-	-	3
Astoria	1,611	-	2,290	-	-	-	1,296	5,186	-	-	3
Newport	975	-	2,290	-	-	-	785	3,139	-	-	3
Coos	2,420	-	2,290	-	-	-	1,947	7,790	-	-	3

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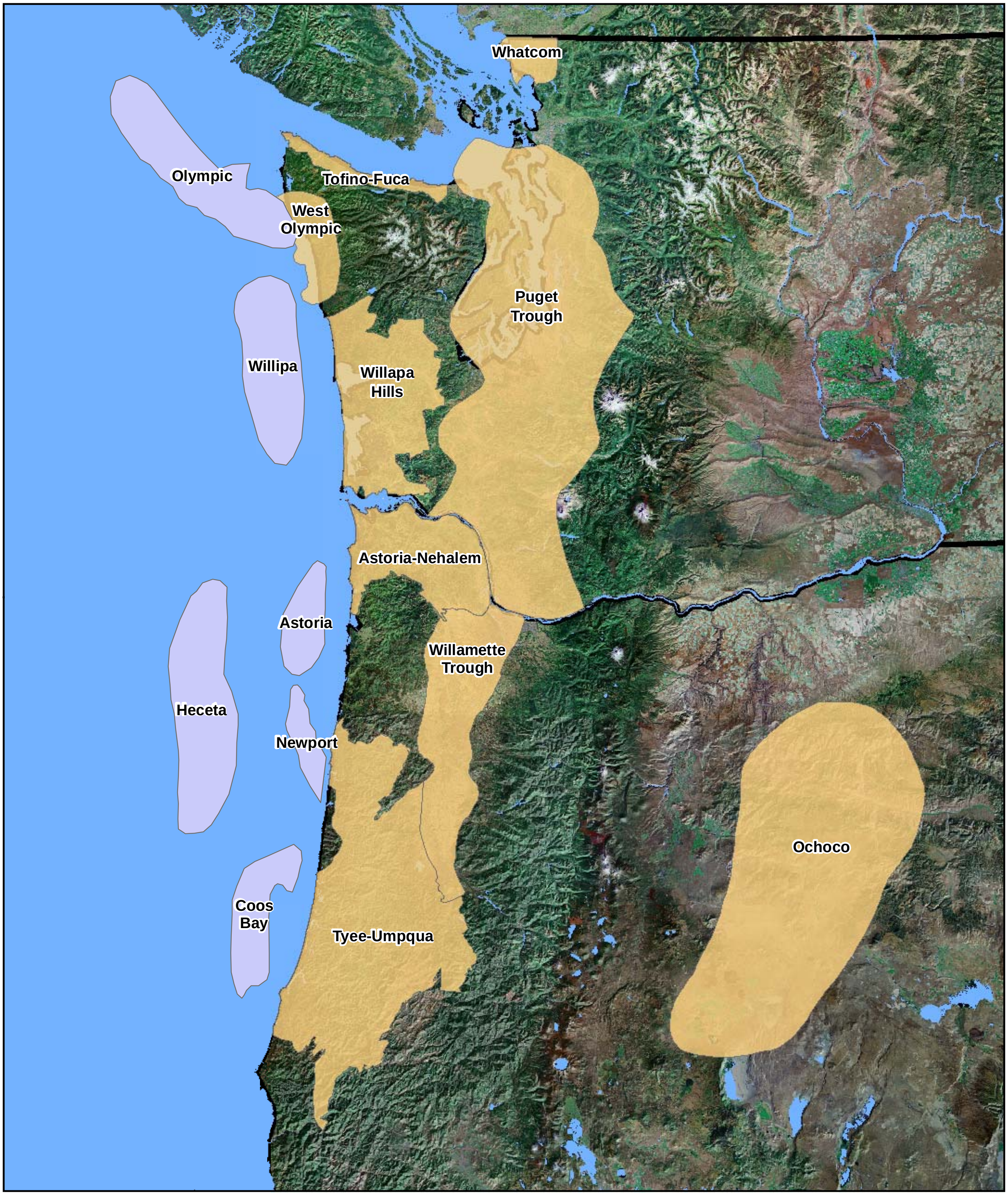
FIGURES



LEGEND

🟪 Offshore Basin

🟧 Onshore Basin

Scale in Feet

Map Projection:
Washington State Plane
North Zone NAD 1983

Source:
EarthSat, ESRI

N

This figure was originally produced in color. Reproduction in black and white may result in a loss of information.

FIGURE 1

LOCATION OF ONSHORE AND OFFSHORE SEDIMENTARY BASINS, WASHINGTON AND OREGON

CIEE/WESTCARB PROJECT PHASE II/USA

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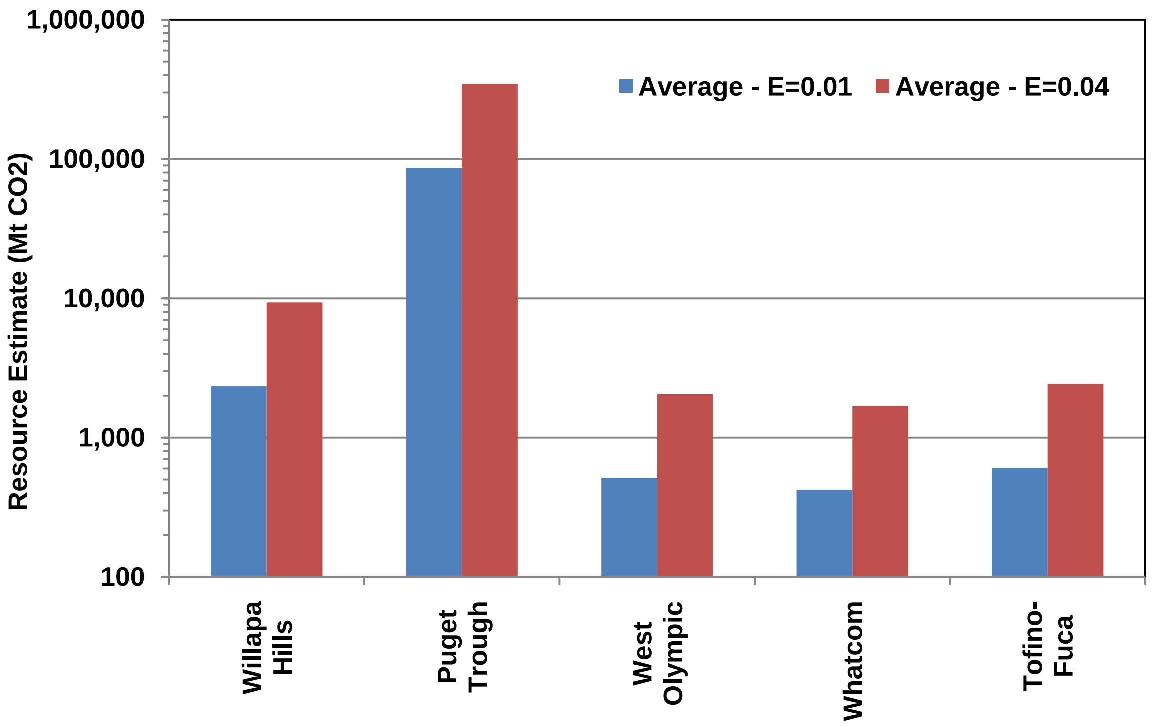
Golder Associates



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TITLE	Resource Estimates for Washington Basins

WESTCARB – Resource Estimates for Washington and Oregon Basins

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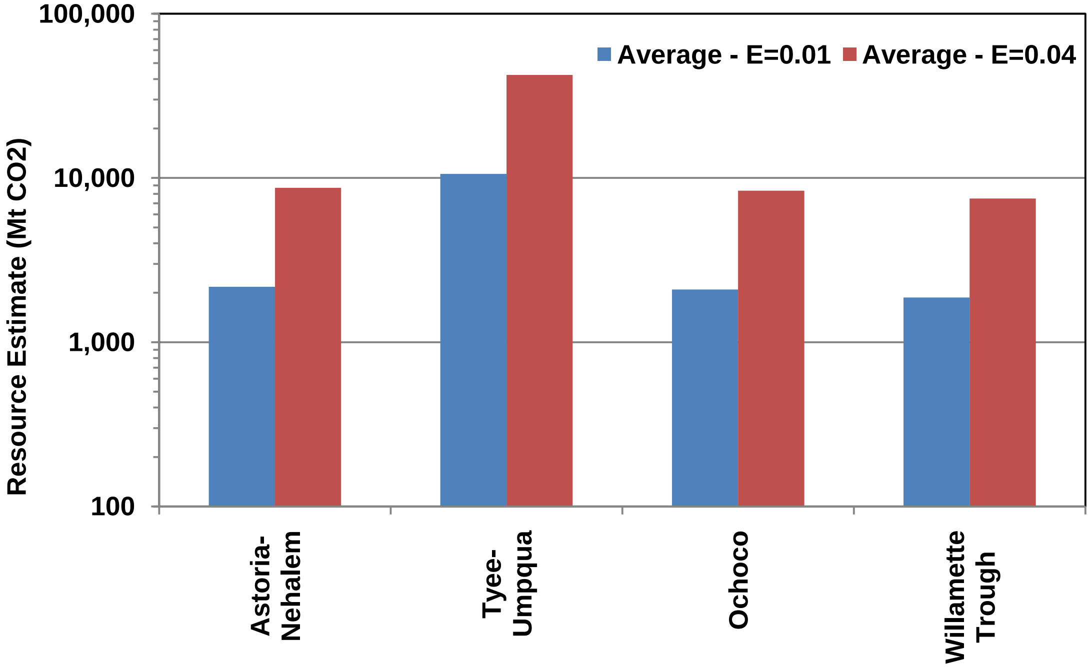

Golder Associates

TITLE	Resource Estimates for Oregon Basins

WESTCARB – Resource Estimates for Washington and Oregon Basins

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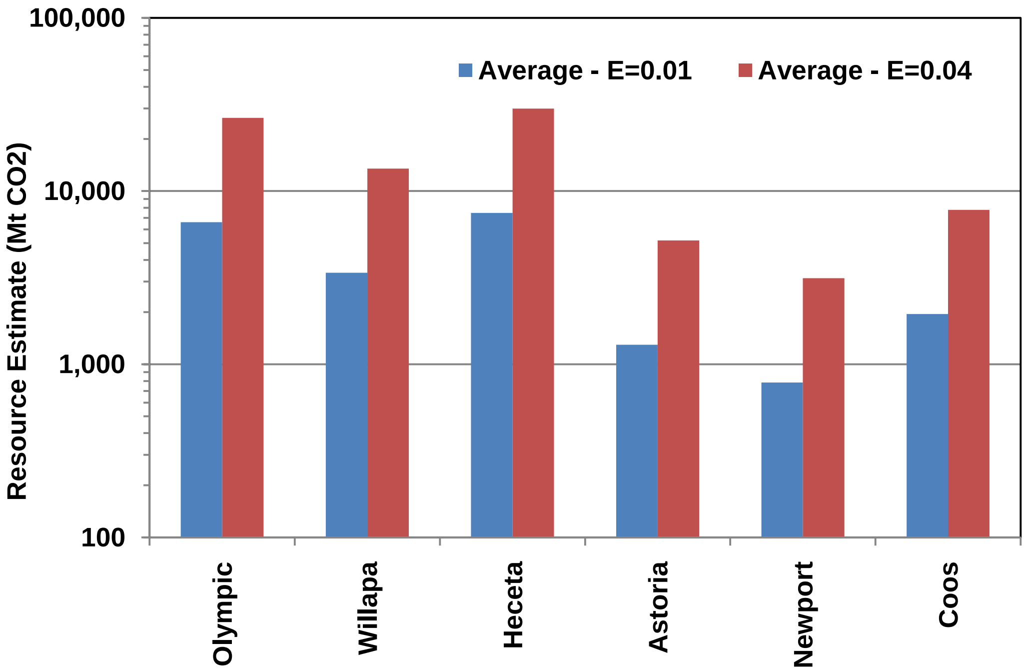

Golder Associates

TITLE

Resource Estimates for Offshore Washington and Oregon Basins

WESTCARB – Resource Estimates for Washington and Oregon Basins

DRAWN	SDT	DATE	1/16/09	PROJECT No.	063-1282.100
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OPPORTUNITY ASSESSMENT FOR ESTABLISHING HYBRID POPLARS IN CALIFORNIA, OREGON AND WASHINGTON

Netzer, M., Goslee, K., Pearson, T.R.H. and Brown, S.

Winrock International

DOE Contract No.: DE-FC26-05NT42593

Contract Period: October 1, 2005 - May 11, 2011

Arnold Schwarzenegger
Governor

Opportunity Assessment for Establishing Hybrid Poplars in California, Oregon and Washington

PIER PROJECT REPORT

Prepared For:

California Energy Commission
Public Interest Energy Research Program

Prepared By:

Winrock International

January 2010

CEC-XXX-XXX-XXX

PUBLIC INTEREST ENERGY RESEARCH
"Research Powers the Future"

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Commission Contract No. 500-02-004
Commission Work Authorization No. MR-045

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Acknowledgements

Greenwood Resources provided assistance and background information integral to this report.

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Please cite this report as follows:

Netzer, M., Goslee, K., Pearson, T.R.H. and Brown, S. 2010. *Opportunity Assessment for Establishing Hybrid Poplars in California, Oregon and Washington.* California Energy Commission, PIER. XXXX.

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission) conducts public interest research, development, and demonstration (RD&D) projects to benefit the electricity and natural gas ratepayers in California. The Energy Commission awards up to $62 million annually in electricity-related RD&D, and up to $12 million annually for natural gas RD&D.

The PIER program strives to conduct the most promising public interest energy research by partnering with RD&D organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration

Opportunity Assessment for Establishing Hybrid Poplars in California, Oregon and Washington is a final report for the West Coast Regional Carbon Sequestration Partnership – Phase II (contract number 500-02-004, work authorization number MR-06-03L. The information from this project contributes to PIER's Energy-Related Environmental Research program.

For more information on the PIER Program, please visit the Energy Commission's Web site at www.energy.ca.gov/pier or contact the Energy Commission at (916) 654-5164.

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Abstract

Hybrid poplar (*Populus* spp.), a short rotation woody crop, is of growing interest in the West Coast States of California, Oregon and Washington. This increased interest has been driven in recent years by hybrid poplar's potential as a bioenergy crop or multiple wood products crop in combination with the potential revenue from carbon credits. This report aims to identify eligible lands within the West Coast States for the planting of hybrid poplar crops using a geographic information System (GIS) framework. . The eligible lands will be evaluated for their suitability based on a spatial analysis of environmental variables (datasets) that best predict the growth and productivity of hybrid poplar. The resulting suitability map is then analyzed against current research on the growth and productivity of hybrid poplar under different site conditions, which can then be related to carbon sequestration. The results showed that California has the most eligible land with around 14 million acres, but the majority of these acres would need irrigation. Washington State has the second largest amount of eligible land with 8 million acres, with around 27% of it suitable for planting with limited to no irrigation. Oregon has 5 million acres with nearly one third suitable for limited to no irrigation hybrid poplar plantations.   Of these eligible lands the most suitable could produce an average of 3-4 t C/ac.yr, moderate suitability of 2-3 t C/ac.yr, and lands with poor suitability would average 1-2 t C/ac.yr.   Revenue from a dedicated bioenergy plantation on a 6 year rotation is estimated to be $737-$976/acre with $86-$325/acre of that being earned from carbon credits. Revenue from a wood products plantation on a 20 year rotation is estimated to be $9,396-$10,989/acre with $425-$1,592/acre of that being earned from carbon credits. This study identifies counties or localities that may have considerable opportunities for hybrid poplar plantations, and can aid project developers in assessing those opportunities.

Executive Summary

Introduction

Hybrid poplar (*Populus* spp.), a short rotation woody crop, is of growing interest in the West Coast States of California, Oregon and Washington. This increased interest has been driven in recent years by hybrid poplar's potential as a bioenergy crop or multiple wood products crop in combination with the potential revenue from carbon credits. This report aims to identify eligible lands within the West Coast States for the planting of hybrid poplar crops using a geographic information System (GIS) framework.

There is interest in hybrid poplars because they are one of the fastest growing tree species in North America. This species is typically established on marginal agricultural lands or conservation reserve lands and as wind breaks, to reduce soil erosion, as riparian buffers, and as crops on marginal lands for generating income from secondary forest products. Over the past 10-15 years there has been increased interest in using these fast growing woody crops for large scale bioenergy crops and multiple wood product crops in combination with carbon credits (Kaster, 2009; Perry *et al.* 2001).

Purpose

The purpose of the report is to identify areas throughout California, Oregon and Washington State (hereafter referred to as the West Coast Region) that are suitable for hybrid poplar plantations, to estimate the potential carbon sequestration, and provide information for project developers interested in the potential for developing large scale hybrid poplar projects for bioenergy or multiple market wood products and carbon sequestration.

As part of the Westcarb project's terrestrial carbon sequestration component, Winrock International undertook a regional characterization study of areas suitable for hybrid poplar (*Populus Spp.)* afforestation projects in the West Coast Region). The regional characterization study first identified areas eligible for hybrid poplar plantations. "Eligible" is merely an indication that the land could support hybrid polar plantations ecologically and topographically; it does not address current land use, so does not necessarily mean that the area is available. Second, environmental datasets were analyzed to identify suitability classes for the growth and production of hybrid poplar. Suitability classes ranged from "high suitability" to "not suitable," based on factors of climate, soil and slope. Using the suitability map and growth and yield curves for hybrid poplar, the potential yield and carbon sequestration of hybrid poplar on different sites was modeled. This report will be helpful for project developers interested in large scale hybrid poplar plantation. This report is primarily focused on the potential for large scale hybrid poplar afforestation and reforestation projects that would provide carbon credits in combination with revenue from biomass for bioenergy plants, or from multiple market wood products crops that produces things like lumber or veneer.

Project Results

The final suitability map defined 18 different suitability classes ranging from "highly suitable" to "not suitable" using environmental variables of climate, soil and slope (Figure 1). The suitability classes were stratified by areas where irrigation would be needed, limited-no irrigation would be needed and where no irrigation would be needed based on precipitation and evapotranspiration rates.

Results show that most of the prime lands ideal for hybrid poplar, and where no irrigation or limited irrigation would be needed, are located primarily on the western side of the Cascade Mountains in Oregon and Washington State. Washington State has approximately 8 million acres of eligible lands, with 82% needing irrigation, 8% needing limited irrigation and 9% needing no irrigation. Oregon has 5 million acres in total, with 59% needing irrigation, 27% needing limited irrigation, and 13% needing no irrigation. California had the most total land eligible, with 14 million acres. However, 96% of the land would need irrigation, with only 3% needing limited irrigation and less than 1% needing no irrigation. If irrigation is supplied to areas where moisture availability is limited, the amount of highly suitable land throughout the West Coast Region more than doubles.

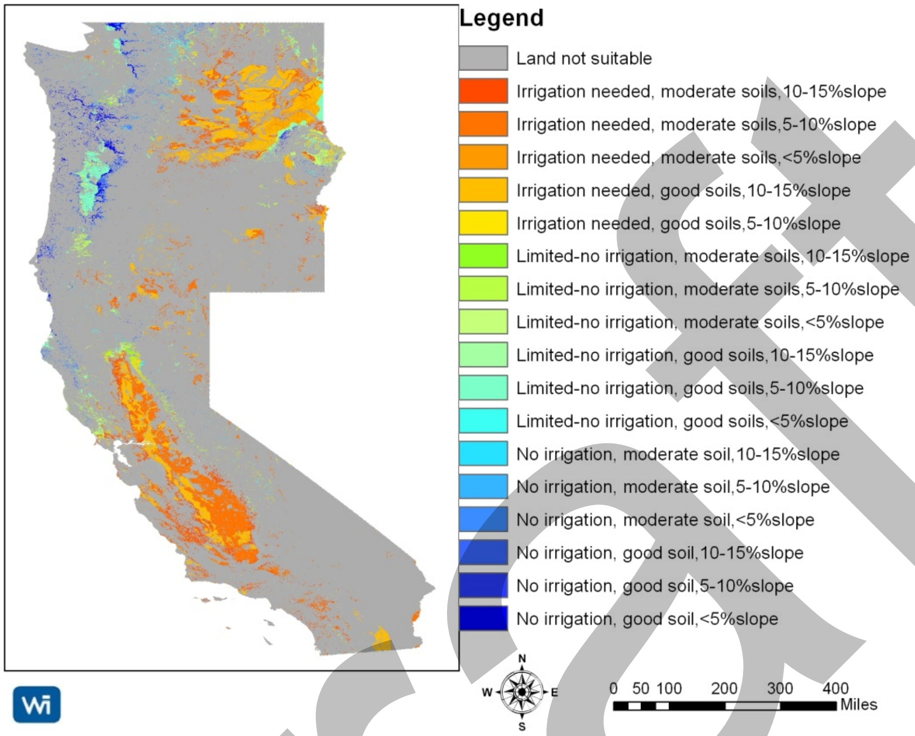

Figure 1. Final suitability map for the entire West Coast Region

Using the suitability map and published literature for hybrid poplar, growth and yield was estimated, and subsequently carbon sequestration. Growth and yield of hybrid poplar averages from 8-11 green tons/ac.yr of above ground biomass on highly suitable sites with ample water, 6-8 green tons/ac.yr on moderate sites, and 4-6 green tons/ac.yr on poor to moderate sites. This growth and yield relates to approximately 3-4 t C/ac.yr on highly suitable sites, 2-3 t C/ac.yr on moderate sites, and 1-2 t C/ac.yr on poor to moderate sites (Figure 2). Carbon sequestration per year was modeled with irrigation (Figure 2 A), and without irrigation (Figure 2 B). These results indicated that over 6 year rotation approximately 20 t C/ac could be achieved, and Over a 20 year rotation 81 t C/ac.

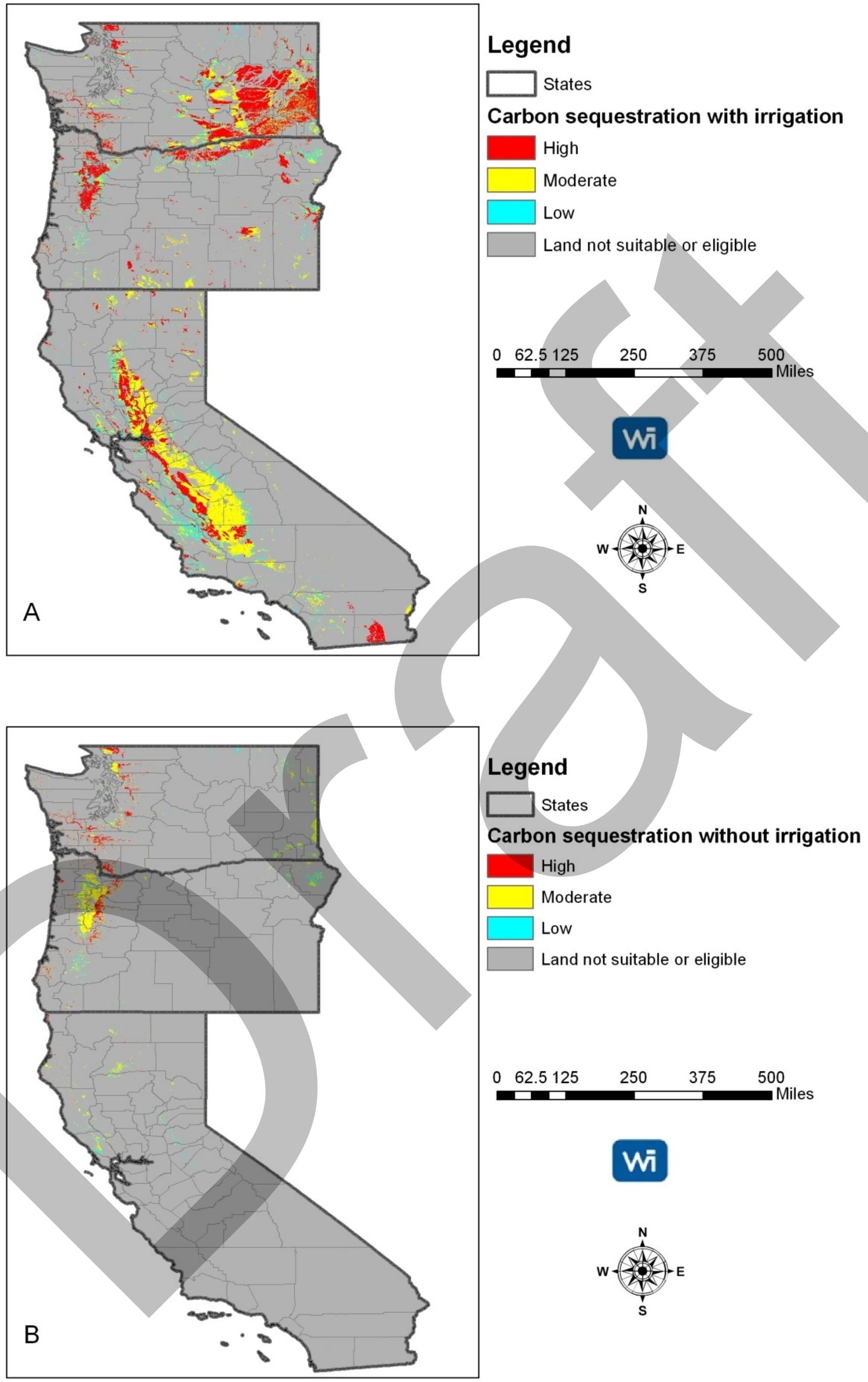

Figure 2. Potential carbon sequestration across the West Coast Region with irrigation (A) and without irrigation (B) based on the suitability map.

The financial analysis of large scale hybrid poplar plantations showed that a dedicated biomass energy crop could earn estimated revenue of $737-$976/ac with $86-$325/ac of that being earned from carbon credits. For a multiple market wood product crop the revenue over a 20 year rotation is estimated to be $9,396-$10,989/ac with $425 - $1,592/ac of that being earned from carbon credits.

The results from this study will be useful to project developers interested in identifying counties or locales that would be productive for investing in and establishing hybrid poplar crops. Project developers identifying areas for investment will be able to use this study to gauge the level of investment and resources need to establish a hybrid poplar plantation. This study should be used to identify counties or local regions where more detailed spatial analysis can be done.

1.0 Introduction

1.1. Background and overview

Fast growing woody crops have traditionally been used as shelter belts for protecting agricultural crops, to reduce wind and water erosion, and on marginal agricultural land for generating secondary forest products (Perry *et al.* 2001). Poplars (*Populus* spp.) have long been known as one of the fastest growing North American trees species, and as such have been selectively bred and hybridized to increase their potential as a short rotation woody crop. The popularity of hybrid poplar has been a result of their fast growth and adaptability to different environments. However, growing hybrid poplars as a short rotation woody crop involves intensive management more similar to agriculture than forestry with significant investment (Agri-Food Canada, 2009).

In the last 10-15 years there has been increased interest in hybrid poplar crops for both financial revenue as a bioenergy crop or multiple wood products crop, and for their environmental benefits to reduce erosion, improve local water quality in riparian areas, and more recently to mitigate global greenhouse gas emissions (Boswell *et al.* 2008; Kaster, 2009; Perry *et al.*, 2001; Pinno, 2008). Because of this, the establishment of afforestation hybrid poplar crops on marginal agricultural lands is of considerable interest in the West Coast states of California, Oregon and Washington (Boswell *et al.*, 2008; Shock *et al.* 2002; Washington State Univ. 2000). However, given the variability of climates in these states, and the fact that much of the area has limited water resources, special care needs to be taken when deciding where hybrid poplar can be grown in large scale afforestation projects.

To support the regional interest in hybrid poplar afforestation, knowledge is required about suitable locations that are capable of, but are not presently involved in growing trees. This type of analysis is best undertaken using a GIS framework, where environmental data sets are analyzed and decisions made concerning the relative productivity of an area.

1.2. Project objectives

The purpose of this study is to develop a regional characterization map that shows areas eligible for establishing hybrid poplar plantations across the three West Coast states of CA, OR, and WA and evaluates the suitability of these areas based on environmental factors that affect growth and productivity. Using the regional characterization maps this study aims to project potential carbon sequestration of hybrid poplar plantation under different suitability conditions, and to inform project developers on large scale hybrid poplar plantations for bioenergy, and multiple wood product crops. This will be accomplished in three main steps:

a. Create a suitability map for all eligible lands in the West Coast Region that could support hybrid poplar plantations.
b. Compare the suitability map to current published literature on the growth and yield of hybrid poplar under different site conditions. Relate this information to potential carbon sequestration.
c. Assess the economic feasibility of multiple market wood products, bioenergy and carbon sequestration projects.

2.0 Methods

Spatial datasets were used to identify areas that are eligible for hybrid poplar plantations, and to analyze environmental variables that are important to the growth and productivity of hybrid poplar (Figure 3, Table 1). Using expert knowledge and primary literature, the environmental datasets were grouped into suitability classes, ranging from “not suitable,” to “highly suitable” (Table 2). By overlaying these spatial datasets and implementing a Boolean Logic analysis the final suitability map was created (Tegelmark, 1998; Malczewski, 2002; Joss *et al.* 2008).

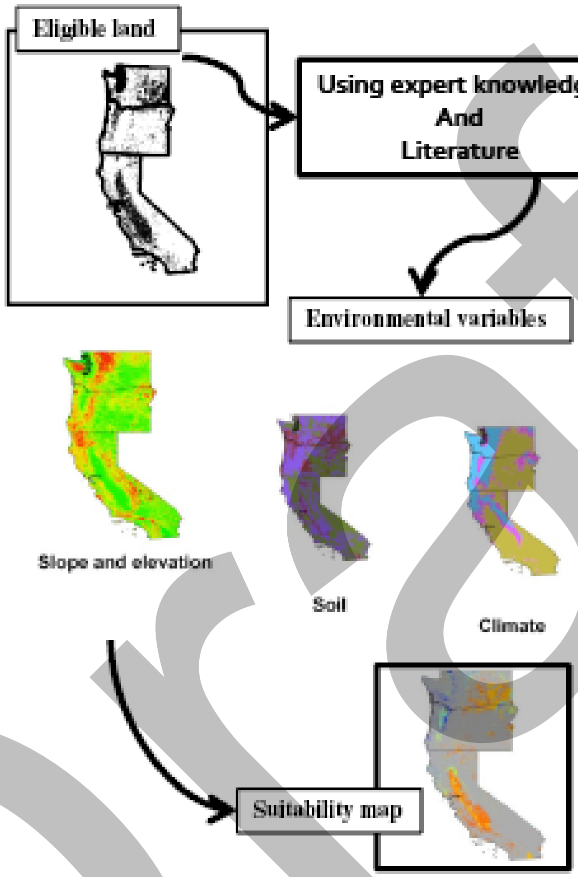

Figure 3. Diagram of the process and datasets used to create the suitability map.

Table 1. GIS data sources used for the regional characterization study

Description	Source
Land eligibility	National Land Cover Database (NLCD) 2001, developed by USGS
Federal lands	Federal lands dataset, developed by USGS
Climate data	PRISM Climate Group, developed by Oregon State University
Soil data	Natural Resource and Conservation Service (NRCS), STATSGO soil data mart maps
Slope and elevation	National Elevation Dataset 30m DEM, developed by USGS

2.1. Land Eligibility

All eligible land in the West Coast Region was identified based on the National Land Cover Dataset from 2001 (NLCD). Based on the NLCD dataset, areas defined as crop land, rangeland and grassland were considered eligible for hybrid poplar plantations. Areas excluded are all forestlands, shrub lands, wetlands, and urban/developed and all areas located on Department of Defense, National Park, Wildlife Refuge or Wilderness land.

2.2. Environmental variables

Environmental variables which were most important for the growth and productivity of hybrid poplar were identified using primary literature and expert knowledge. Climate type was defined by available moisture index (MI) that is estimated as millimeters of rain fall minus evapotranspiration (driven by air temperature) during the growing months of March-August (Table 2). Soils were characterized by available soil water (ASW) that is related to percent silt and clay and is measured as centimeters of water that can be held within 1 meter of soil. A higher percent of silt and clay in the soil indicates a higher ASW. Less than 10cm/m of ASW was considered too poor a soil for hybrid poplar plantings. Slope was characterized into four classes based on percent slope—greater than 15% slope was considered unsuitable for hybrid poplar plantations.

Table 2. Environmental variables and the definition of suitability classes.

Climate (available moisture mm)		
	low suitability	<240mm
	moderate suitability	240-375mm
	high suitability	>375mm
Soil (available soil water cm/m)		
	not suitable	<10cm/m
	low suitability	10-20cm/m
	high suitability	>20cm/m
Slope		
	not suitable	>15%
	low suitability	10-15%
	moderate suitability	5-10%
	high suitability	<5%

2.2.1. Climate type

It is well recognized that at large regional scales climate is a dominant factor defining the growth and productivity of hybrid poplar (Ung *et al*., 2001; Hogg *et al*., 2005). Specifically, available moisture is the most important factor determining the growth and productivity of hybrid poplars (Shock *et al*. 2002; Joss *et al*. 2007; Agri-Food Canada 2003). In contrast, cold temperatures relating to northing and elevation have not been found to substantially affect the growth of hybrid poplars (Pinno, 2008). Available moisture is a function of precipitation and potential evapotranspiration (related to high temperatures), which is measured as moisture index (MI). For this study the MI was determined using the method from Loey Knapp *et al*. (1996), which is calculated monthly by subtracting potential evapotranspiration (PET) from precipitation (P).

$$MI=P-PET$$

Where P is monthly precipitation and monthly PET is calculated using the Hamon model (Hamon, 1961) as:

$$PET=13.97*D^2*W$$

Where D is the monthly mean hours of daylight in units of twelve hours, and W is the saturated water vapor density calculated as:

$$W=4.95e^{(0.062*TC)}/100$$

Where TC is the monthly temperature in degrees Celsius.

Using the national climate data from the PRISM Group, which provides mean monthly temperature (C) and precipitation (mm) (averaged from 1971-2000), average MI was calculated for each month.

In a study from Joss *et al*. (2007) in South Central Canada, growing season precipitation below 240 mm was considered not suitable, levels approximating 307.5 mm (the mid-point between 240 and 375mm) were considered marginally suitable, and levels above 375 mm were rated highly suitable for hybrid poplar. Using conclusions from a recent study by GreenWood (appendix C), precipitation levels below 300mm per year would require irrigation, while moderate growing conditions range from 300-350mm a year, with at least 50% falling during the growing season (March-August).

Following this process, suitability classes were defined as the total MI for the months of March-August. MI totals of 240-375mm are marginally suitable and greater than 375mm are highly suitable. Anything below 240mm requires irrigated unless there is a ground water table (see the section 2.2.3 Available Ground Water).

2.2.2. Soil

While climate is important for defining growth conditions across large areas, it is soil conditions that are most important at local sites where management decisions are being made (Pinno, 2008). In a study by Pinno (2008) the most important predictor of hybrid poplar productivity was soil texture, represented by percent silt and clay. For trembling aspen (*Populus tremuloidies)*, Pare *et al.* (2001) in Quebec and Martin and Gower (2006) in Manitoba found that aspen trees were taller on finer textured clay soils as opposed to coarser textured soils, presumably because of the greater water holding capacity of the clay soils.

Using the GIS soil dataset STATSGO from the NRCS soil data mart it was decided that the soil classification "Available Soil Water" (ASW) would be the best for predicting site suitability at this regional scale. This is because ASW incorporates soil depth and soil texture (percent clay and sand), as texture is related to amount of water that can be stored.

Based on data from Perry *et al.* (2001) available soil moisture of 10-20cm/m were considered marginally suitable, and greater than 20cm/m good suitability. Less than 10cm/m ASW was considered unsuitable for hybrid poplar plantations.

2.2.3. Slope

Slopes are an important factor in the planting of hybrid poplar. Much of the literature suggests that slopes less than 10% are the best sites for hybrid poplar plantations. Slope is a factor in erosion and runoff that affect soil available water, and therefore will affect the growth and productivity of hybrid polar (Andrew Bourque, GreenWood 2009, pers. comm.)

Following the Greenwood Report, slope was grouped into four suitability classes: <5% good, 5-10% moderate, 10-15% low, and >15% unsuitable.

3.0 Results

3.1. Suitable land analysis

3.1.1. The West Coast Region

The regional characterization resulted in the final suitability map for the West Coast states identifying 18 different suitability classes ranging from "high suitability"=no irrigation needed, good soil, <5% slope to "low suitability"=irrigation needed, moderate soils and 10-15% slope (Figure 4). Areas classified as low suitability due to the need for irrigation could actually be highly suitable if optimal irrigation was supplied. Therefore, if moisture was not a limiting factor sites with good soil and low slope would equal "high suitability."

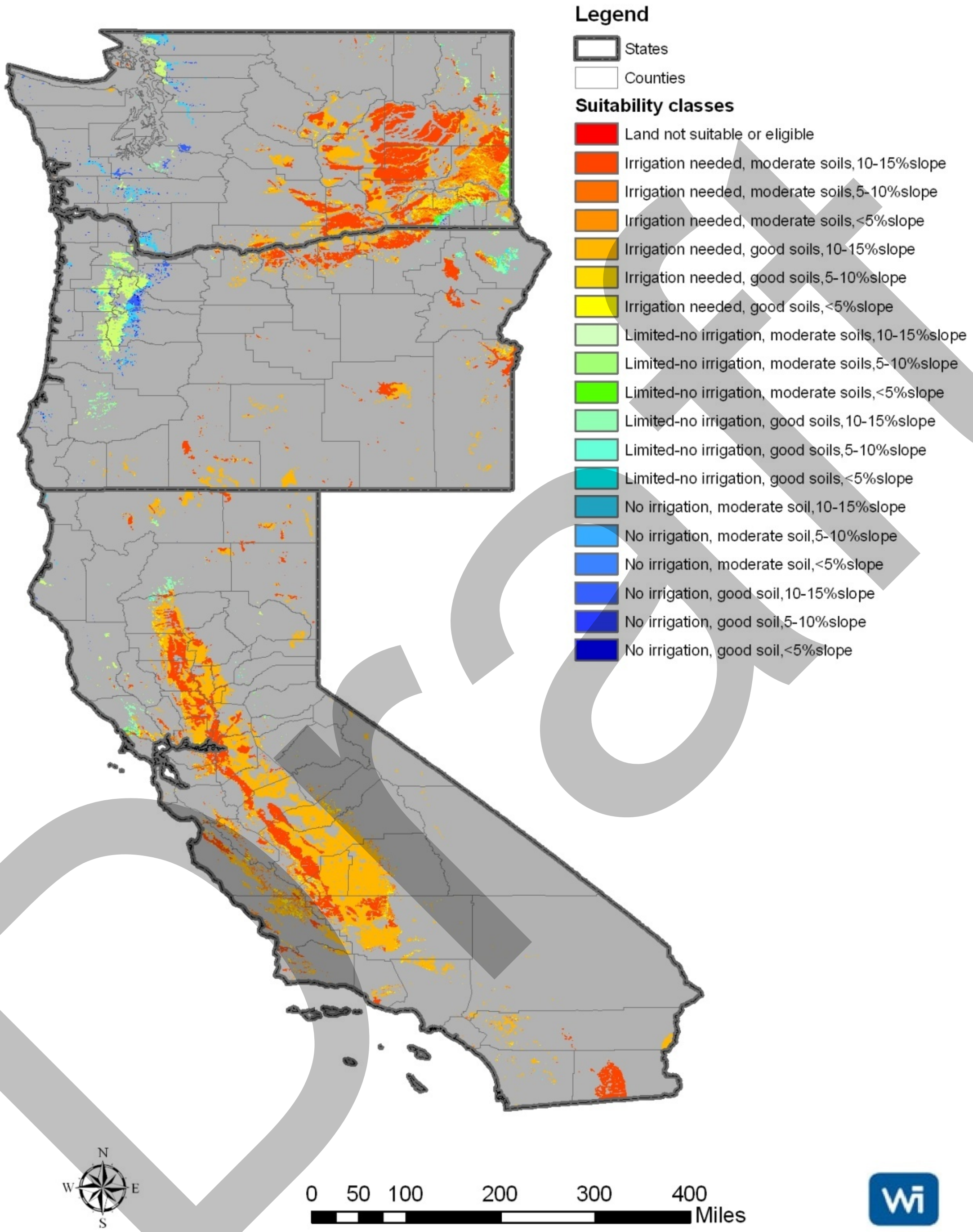

Figure 4. The final suitability map for the West Coast Region. Red to yellow indicates dryer climates where irrigation would be needed, while green to blue indicate wetter climates where limited to no irrigation would be needed. See Appendix A for a map with county names.

3.1.2. California

In the State of California there are approximately 14,205,000 acres of eligible land, with the majority in the Central Valley. Ninety-six percent of the land would need irrigation, with 3% needing limited irrigation and less 1% needing no irrigation (Figure 5).

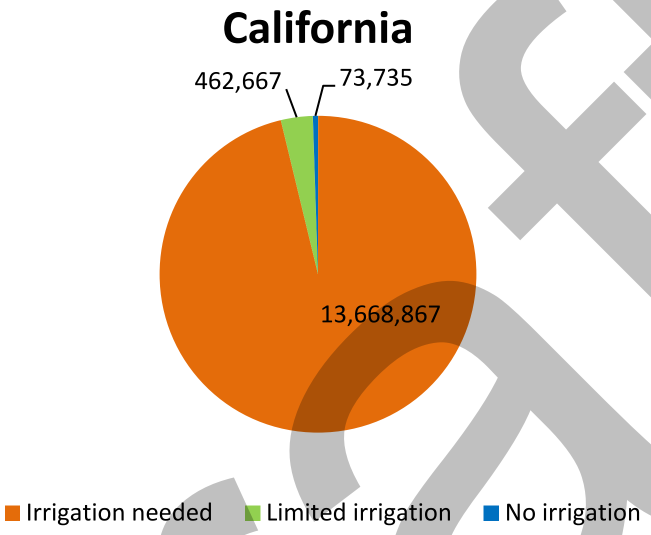

Figure 5. The amount of land (ac) in California that is eligible for hybrid poplar with irrigation, limited irrigation and without irrigation. For a county level analysis see Appendix B.

Out of the 57 counties in California, Kern County had the most total area eligible for hybrid poplar with 1.6 million acres, all of which would need irrigation (See Appendix B). Fresno, Tulare and Kings Counties had the next largest amount of land eligible for hybrid poplar, with 1,504,556, 959,867, 735,052 acres respectfully. All of these lands would need irrigation for the plantation of hybrid poplar (Appendix B).

Counties in California that have some land that may not need irrigation were Sonoma, Shasta, Mendocino, Humboldt and Trinity counties, with 106,415, 94,561, 78,526, 73,045, 12,555 acres of total eligible land, respectfully.

3.1.3. Oregon

Oregon has the least total area among the West Coast states for hybrid poplar plantations, with approximately 4,971,000 acres in total, 59% which would need irrigation, 28% needing limited irrigation and 13% needing no irrigation (Figure 6). Almost half of that area is located in the Willamette Valley where considerable rain and cool summers may provide good conditions for limited to no irrigation hybrid poplar planting.

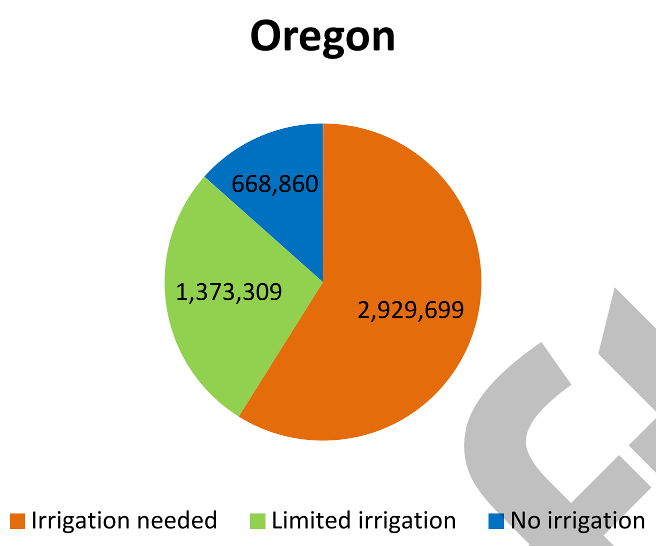

Figure 6. The amount of land (ac) in Oregon that is eligible for hybrid poplar with irrigation, limited irrigation and without irrigation. For a county level analysis see Appendix B.

In Oregon State, Umatilla County had the most total area eligible for hybrid poplar plantation, with 543,859 acres, however 96% would need irrigation (Appendix B). In contrast, along the eastern edge of the Willamette Valley Linn, Clackamas, Marion, and Lane counties all had near or above 100,000 acres of land that would not need any irrigation and would be highly suitable for hybrid poplar plantations (Appendix B).

3.1.4. Washington

Washington State has around 8,424,716 acres of suitable land for hybrid poplar, with 82% needing irrigation, 8% needing limited irrigation and 9% not needing any irrigation (Figure 7). Most of that land is in the dry valleys east of the Cascade Mountains, however in the Pacific Northwest and near the Canadian border almost 1.5 million acres could provide opportunities for limited to no irrigation hybrid poplar plantations.

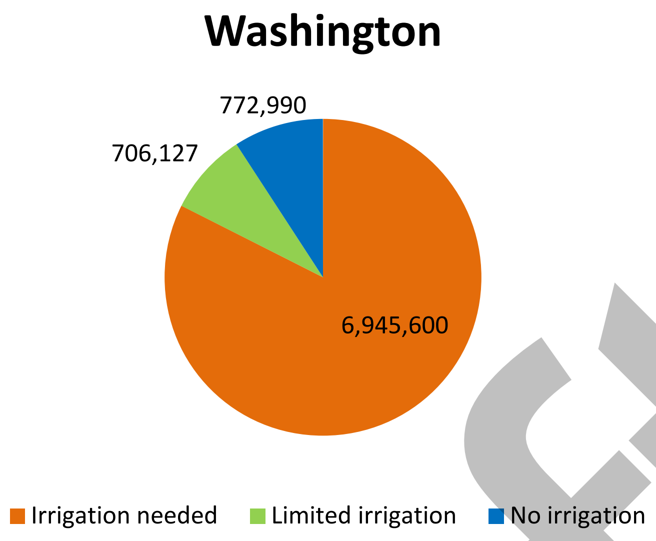

Figure 7. The amount of land (ac) in Washington that is eligible for hybrid poplar with irrigation, limited irrigation and without irrigation. For a county level analysis see Appendix B.

The three counties with the highest percent of suitable land in Washington State are Whitman, Adams, and Grant, with 888,561, 881,726, 778,518 acres respectfully (Appendix B). All are located in the dry southeast portion of the State. In the western part of the State all the counties are dominated by wet growing seasons that provide good land that would need limited to no irrigation. These western counties with the most eligible land for hybrid poplar plantations are Lewis, Whatcom, Skagit and Clark, with 154,861, 126,728, 109,349, 107,715 acres respectfully that would likely need limited to no irrigation (Appendix B).

3.2. Hybrid poplar growth and yield

The estimated growth and yield of most tree species is usually derived using regression equations from field measurements that predict individual tree biomass or stand biomass on a per area basis. Individual tree equations and stand biomass have been published for poplar by several authors including Tuskan and Rensema (1992), Clendenen (1996), Lodhiyal and Lodhiyal (1997), Scarascia-Mugnozza *et al.*(1997), Kort and Turnock (1999), Netzer and Tolsted (1999), and Zambek Prescott (2006) (from Zambeck and Prescott, 2006). These studies have shown that plantation grown hybrid poplar productivity is variable depending on site suitability (primarily available moisture and soil), density of planting, management regimes and genotype (Zabek and Prescott, 2006). The purpose of this section of the report, and section 3.3, is to relate potential productivity and carbon sequestration of hybrid poplar plantations to the suitability map. Due the lack of information on hybrid poplar's growth and yield under different site conditions over an extended growth period (≈20 years) assumptions had to be made to relate growth and yield to the suitability map.

3.2.1. Growth and yield

The current literature on the growth and yield of hybrid poplar (primarily *P. trichocarpa × P. deltoids*) as summarized by Zabek *et al.* (2006) reports that in the US above ground green woody biomass of commercial hybrid poplar ranges from 5-16 t /ac.yr planted in densities ranging from 295-4040 stems/ac. However, many of the high growth results were achieved by small plot sizes associated with experimental studies. More realistic estimates for commercial plantations ranged between 4-11 green tons/ac.yr. At the high end, plantations in the Pacific Northwest achieved an average of 11 green tons/ac.yr at densities of 465-630 stems/ac (Stanturf *et al.* 2001). At the lower end, hybrid poplar in the Central US achieved between 5-6 green tons/ac.yr with stem densities of 683-747 acre (Hansen, 1992). In Sweden plantations achieved between 6-8 green tons/ac.yr with 404 stems/ac (Karacic *et al.* 2003), and in Lake County Oregon estimated growth ranged between 4-9 green tons/ac.yr at planting densities of 440-1,450 stems/acre (Boswell *et al.* 2008).

Based on the literature it is assumed that the growth and yield of hybrid poplar across the West Coast Region ranges between a mean annual increment (MAI) of 4 to 11 green tons/ac.yr, depending on environmental conditions. These differences in growth have been shown to be correlated with moisture availability/climate (Hogg 2005; i.e. moisture deficit; Shock et al. 2002; Joss et al. 2007; Agri-Food Canada 2003) and soil (Pare *et al.* 2001; Perry *et al.* 2001; Pinno 2008). Slope is also an important variable, however there was no literature we found that related growth and yield to slope. For moisture availability, Pinno (2008) showed a linear trend of growth and yield for hybrid poplar, ranging from 1-4cm diameter growth difference, at increasing levels of summer moisture during the first two years planted. These same levels of moisture were considered when defining the suitability map. For soil, Pinno (2008) showed that the growth and yield of hybrid poplar during the first few years of growth increased linearly from 1-2.5cm diameter growth deference, based on the percent silt and clay in the soil. The percent of silt and clay is directly related to the ASW that we used to define the soil maps in the suitability analysis.

Using this information it was estimated that highly suitable sites with plenty of available moisture, good soils and level slopes could achieve 11 green tons/ac.yr, while sites with poor suitability, where water is limited, the soil is poor and slope is steep, productivity would be closer to 4 green tons/ac.yr. Using this assumption, a growth curve from Boswell *et al.*(2008) that shows hybrid poplar grown on poor sites (MAI of 4 green tons/ac.yr) to good sites (MAI of 9 tons/ac.yr) was adapted to include very good sites at 11 green tons/ac.yr. These growth curves projected the growth and yield of hybrid poplar (P. trichocarpa × P. deltoids) over 20 years (Figure 8). These growth curves were then related to the suitability map assuming a linear increase in productivity with increasing site conditions to identify the potential growth and yield of hybrid poplar across the West Coast Region.

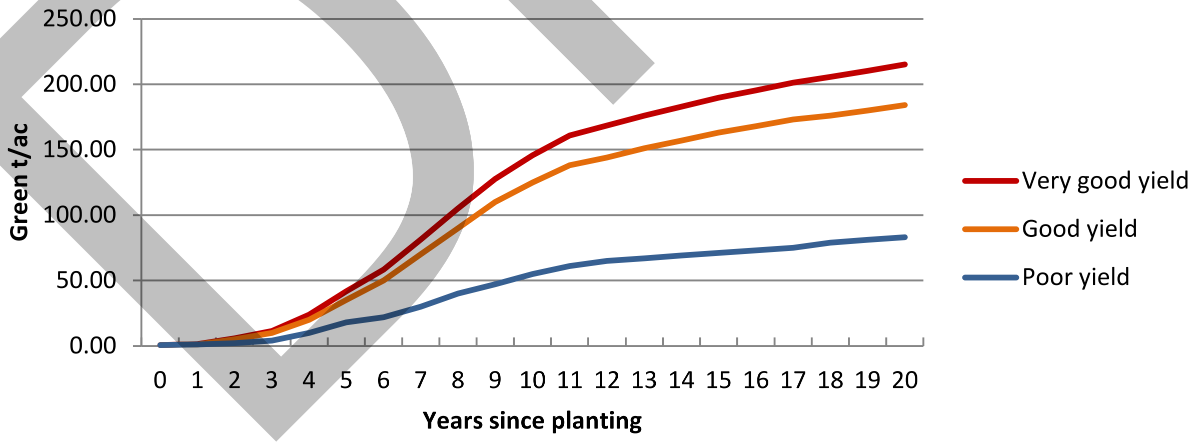

Figure 8. Growth curves for hybrid poplar (P. trichocarpa × P. deltoids) over 20 years.

3.3. Hybrid poplar carbon sequestration

3.3.1. Carbon sequestration

The growth and yield curves for hybrid poplar (above ground green tons/ac) can be converted to carbon by calculating the total dry biomass. For this study the total carbon for a hybrid poplar tree farm per acre was calculating by first adding above ground and below ground biomass together to get total biomass. The below ground biomass for hybrid poplar is assumed to be 40% of above ground (Boswell *et al.* 2008). Green tons were then converted to bone dry tons assuming hybrid poplar biomass is 45% dry matter (Boswell *et al.* 2008). Bone dry tons were then converted to carbon which is approximately 50% of the dry biomass.

The resulting carbon sequestration curves show that over a 20 year rotation hybrid poplar would range from 81 t C/ac on highly suitable sites, to 69 t C/ac on good sites, and 31 t C/ac on poor sites (Figure 9). These results were then related to the suitability map.

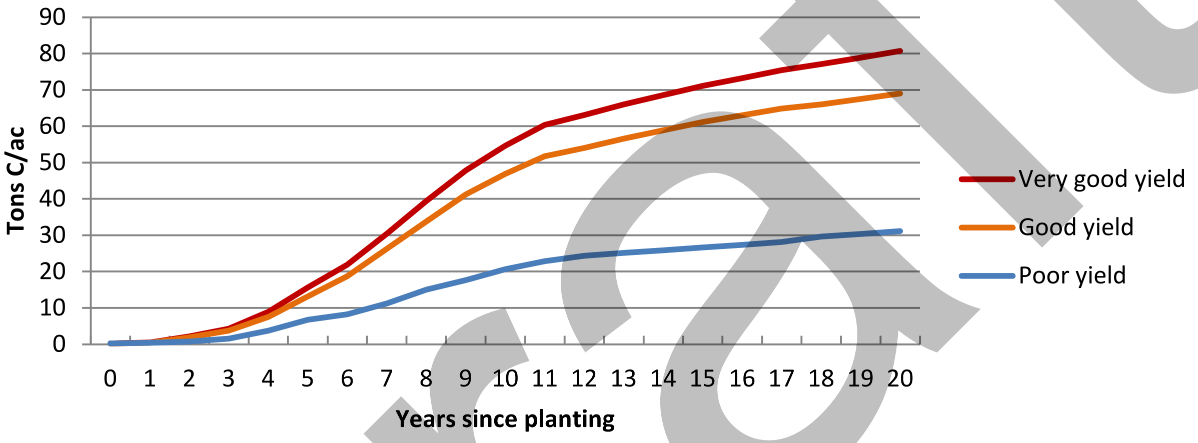

Figure 9. Cumulative quantities of sequestered carbon (tons per acre) for a hybrid poplar plantation over 20 years for three different site conditions.

To project potential carbon sequestration based on the suitability map two scenarios were developed: 1) irrigation is available and used on all eligible land, and 2) irrigation is not used on any eligible land.

From the growth and yield numbers the amount of carbon sequestered each year ranged from 1.5-4.1 t C/ac.yr with increasing site conditions. Again, growth was assumed to increase linearly from poor site conditions to very good site conditions.

Using the scenario where irrigation is provided, it is assumed that hybrid poplar can be grown on all suitable sites. Under these conditions climate and moisture is not considered a factor, therefore, the amount of carbon per acre per year ranges from 1.5-4.1 t C/ac.yr depending on the suitability of the soil and slope (Table 3).

When no irrigation is provided all sites with less that 240mm of available moisture during the summer months are considered not suitable for hybrid poplar. On sites with 240-375 mm of available moisture during the growing season, carbon sequestration ranges between 1.5-3.1 t C/ac.yr depending on soil and slope. In areas where available moisture is >375 mm during the growing season, carbon sequestration is between 2.5-4.1 t C/ac.yr depending on soil and slope (Table 3).

Table 3. The carbon sequestration potential (t C/ac.yr) with and without irrigation that was related to the suitability map.

Suitability classes	Without Irrigation	With Irrigation
Irrigation needed, Moderate soil, 10-15% slope	na	1.5
Irrigation needed, Moderate soil, 5-10% slope	na	2.0
Irrigation needed, Moderate soil, 0-5% slope	na	2.5
Irrigation needed, Good soil, 10-15% slope	na	3.1
Irrigation needed, Good soil, 5-10% slope	na	3.6
Irrigation needed, Good soil, 0-5% slope	na	4.1
Limited irrigation, Moderate soil, 10-15% slope	1.5	1.5
Limited irrigation, Moderate soil, 5-10% slope	2.0	2.0
Limited irrigation, Moderate soil, 0-5% slope	2.5	2.5
Limited irrigation, Good soil, 10-15% slope	2.0	3.1
Limited irrigation, Good soil, 5-10% slope	2.5	3.6
Limited irrigation, Good soil, 0-5% slope	3.1	4.1
No irrigation, Moderate soil, 10-15% slope	2.5	1.5
No irrigation, Moderate soil, 5-10% slope	3.1	2.0
No irrigation, Moderate soil, 0-5% slope	3.6	2.5
No irrigation, Good soil, 10-15% slope	3.1	3.1
No irrigation, Good soil, 5-10% slope	3.6	3.6
No irrigation, Good soil, 0-5% slope	4.1	4.1

3.3.2. California

In the state of California, assuming that all 14 million acres of eligible lands are irrigated and are planted with hybrid poplar, the total carbon sequestration amounts to just over 40.6 million t C/yr, with 39 million t C/yr on land that needs irrigation, 1.2 million t C/yr needing limited irrigation, and 180,000 t C/yr that *d*oes not need irrigation (**Error! Reference source not found.**). The counties with the most potential for carbon sequestration from hybrid poplar plantations with irrigation are Kern, Fresno, Tulare and Kings, with about 4.7, 4.5, 2.4 and 2 million t C/yr respectfully (Appendix B). All of these counties would need almost 100% of their area irrigated**.**

If irrigation is not provided the amount of total area eligible for hybrid poplar plantations drops to 536,000 acres, with the potential for 1.3 million t C/yr (Figure 11). This is distributed between 1.1 million t C/yr that could be achieved with limited irrigation, and 235,000 t C/ac.yr in areas where no irrigation would be needed.

If irrigation is not provided, the counties with the most potential for carbon sequestration are Sonoma, Shasta, Humboldt and Mendocino, with 234,000, 231,000, 215,000 and 194,000 t C/yr respectfully (Appendix B). This relates to 106,000 acres in Sonoma, 95,000 acres in Shasta, 73,000 acres in Humboldt and 79,000 acres in Mendocino (Appendix B). Twenty six counties in California have no suitable land for hybrid poplar without irrigation and another 20 counties have less than 10,000 t C/yr potential (Appendix B).

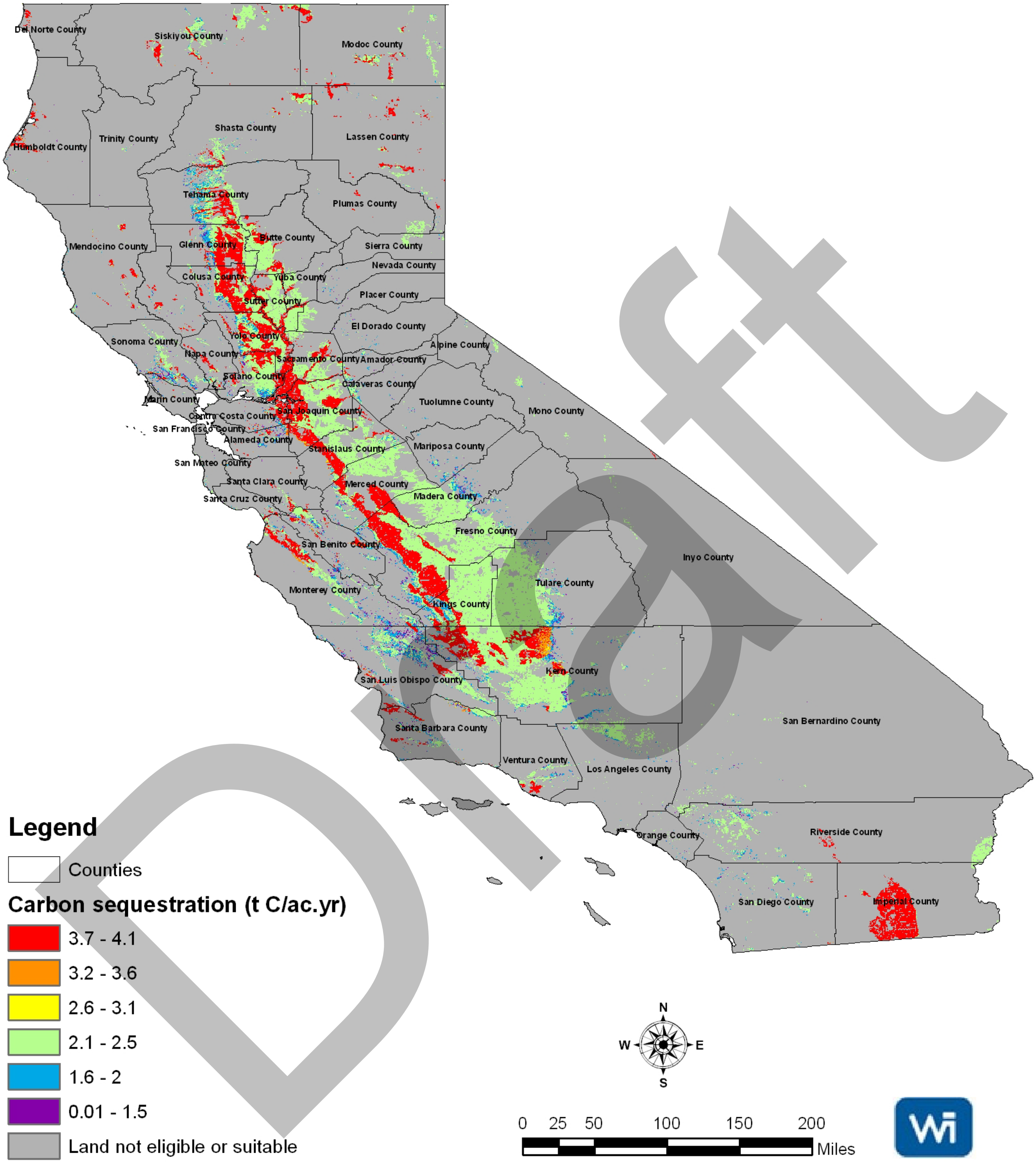

Figure 10. Potential annual rate of carbon sequestration (tons of carbon per acre per year) for hybrid poplar plantations in California with irrigation based on the suitability map

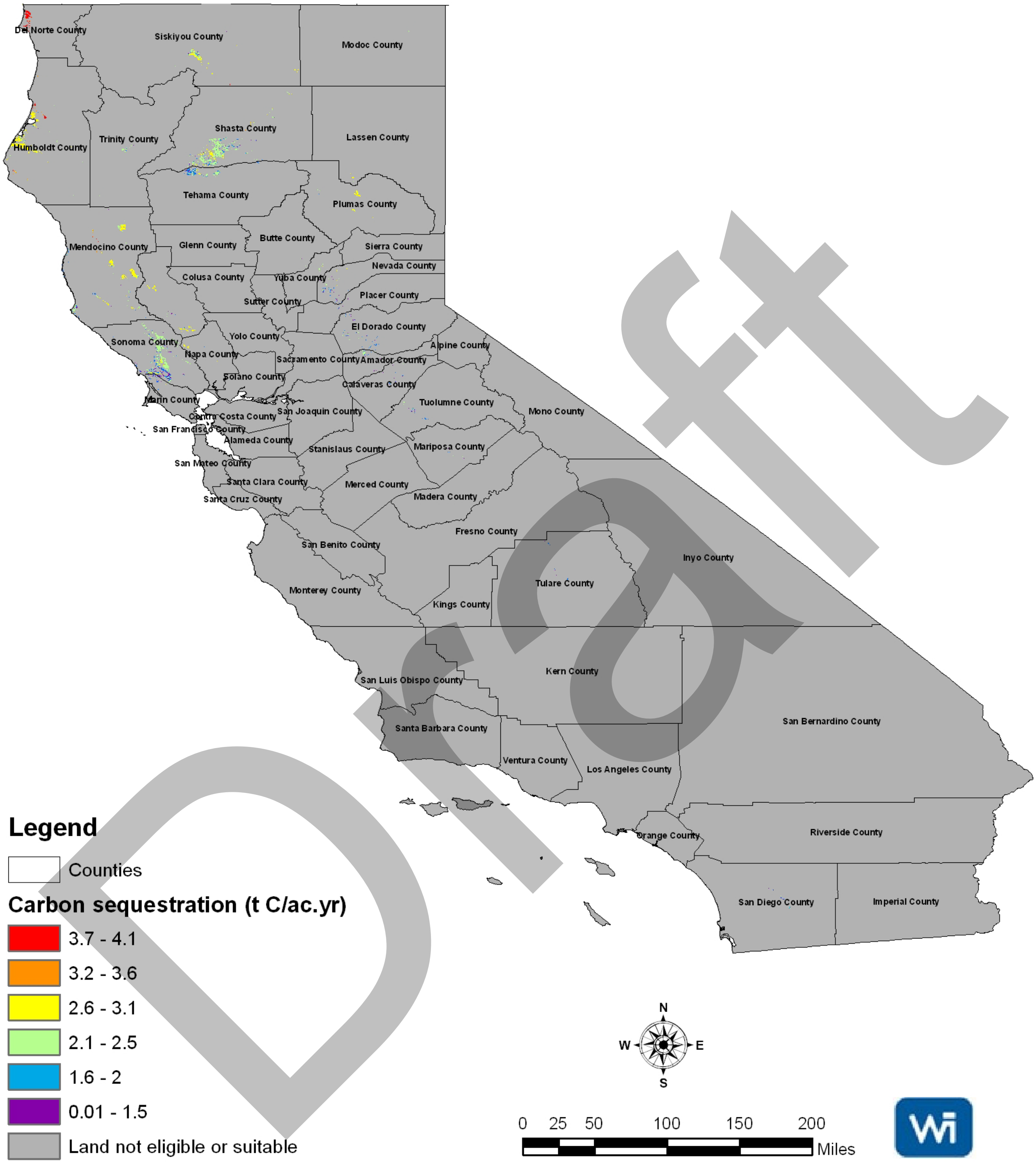

Figure 11. Potential tons of carbon per acre per year for hybrid poplar plantations in California without irrigation based on the suitability map.

3.3.3. Oregon

Oregon State has around 5 million acres of land eligible for hybrid poplar plantations if irrigation is provided. If all eligible lands were planted with hybrid poplar plantations it would amount to 16 million t C/yr, with 9.4 million t C/yr on lands that would need irrigation, 4.7 million t C/yr where limited irrigation would be needed, and almost 2 million t C/yr on lands that would likely not need any irrigation (Figure 12 A). The counties with the most potential for carbon sequestration from hybrid poplar plantation if irrigation is provided are Umatilla, Malheur, Linn and Morrow, with 1.9, 1.3, 1.3 and 1.1 million t C/yr (Appendix B, Oregon). While Malheur and Morrow would need almost 100% irrigation, Linn County could achieve about 1.3 million t C/yr on 147,000 acres of land that would need limited to no irrigation, and to a lesser extent Umatilla could achieve 73,000 t C/yr on 21,000 acres of land that needs limited to no irrigation (Appendix B, Oregon)

If irrigation is not provided the amount of total area available for hybrid poplar plantations goes down to 2 million acres, equating to roughly 6 million t C/yr, with 3.7 million t C/yr on land that would need limited irrigation, and 2.3 million t C/yr on land that would not need any irrigation (Appendix B, Oregon).

Without irrigation the counties with the most potential for carbon sequestration are Linn, Marion, Lane and Clackamas, with 1.1 million, 845,000, 567,000 and 531,000 t C/yr respectfully. This equates to 350,000 acres in Linn, 269,000 acres in Marion, 180,000 acres in Lane and 165,000 acres in Clackamas that would need limited or no irrigation for hybrid poplar plantations (Appendix B, Oregon).

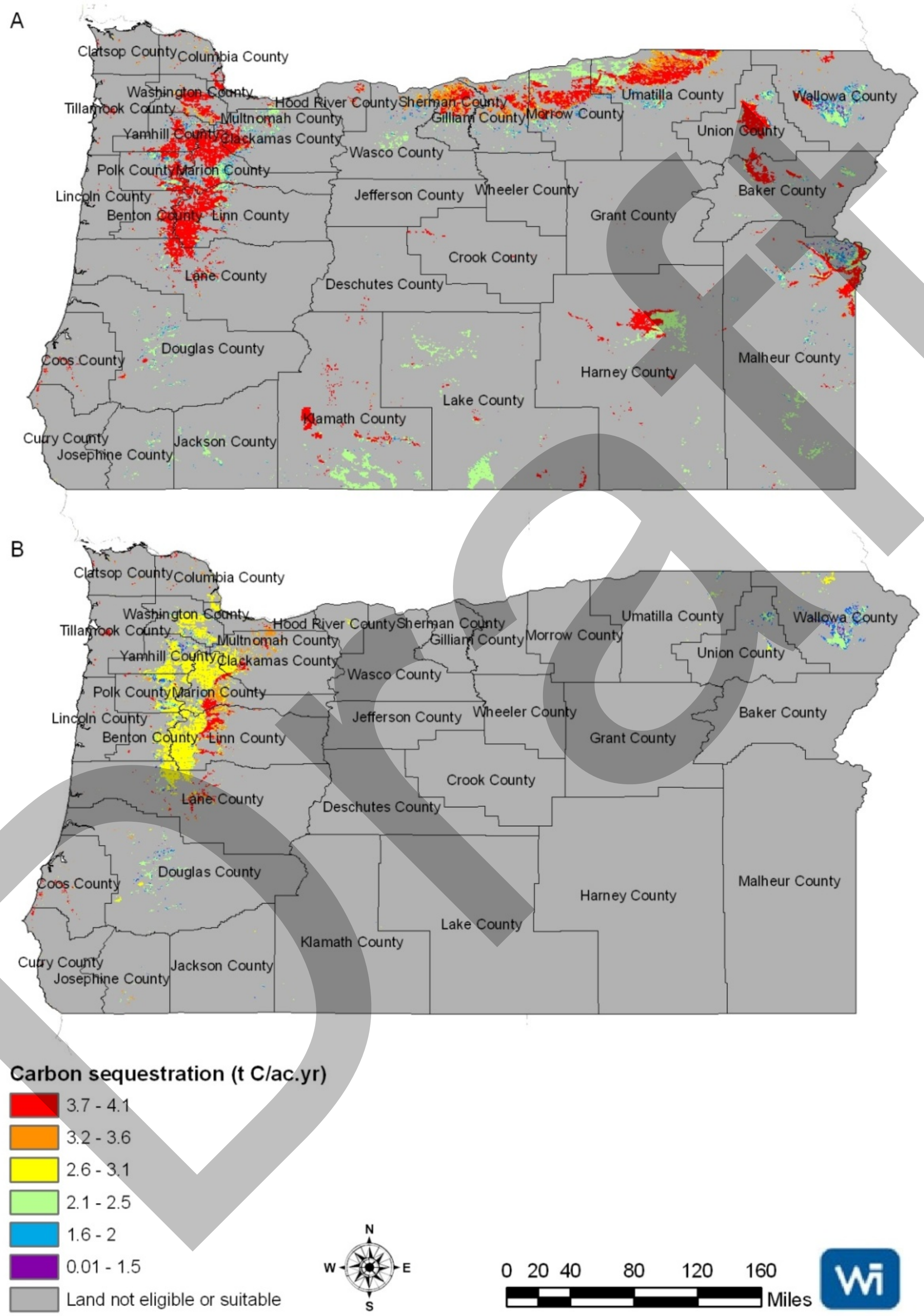

Figure 12. Potential tons of carbon per acre per year for hybrid poplar plantations in Oregon with irrigation (A), and without irrigation (B), based on the suitability map.

3.3.4. Washington

Washington State has about 8.4 million acres of land that is eligible for hybrid poplar if irrigation is provided. Assuming all that land is planted in hybrid poplar the total amount of carbon sequestration would be 28.5 million t C/yr, with 23 million t C/yr on the east side of the Cascades where irrigation would be necessary, and 5 million t C/yr west of the Cascades where wet cool summers provide potential for limited or no irrigation (Figure 13 A).

With irrigation the counties in Washington that have the highest potential for carbon sequestration are Whitman, Adams, Lincoln and Grant, with 3.7, 3.2, 2.9 and 2.6 million t C/yr respectfully (Appendix B, Washington)All of these counties are in the dryer area east of the Cascade Mountains.

If irrigation is not provided the total area of land eligible for hybrid poplar decreases to around 2 million acres with 1.8 million t C/yr on limited irrigation land and 2.8 million t C/yr on land that would not need any irrigation (Figure 13 B). Without irrigation the counties with the most potential for hybrid poplar plantation are Lewis, Whatcom, Whitman and Clark, achieving about 561,000, 466,000, 433,000 and 402,000 t C/yr respectfully. This equates to 155,000 acres in Lewis, 127,000 acres in Whatcom, 165,000 acres in Whitman and 108,000 acres in Clark (Appendix B, Washington)

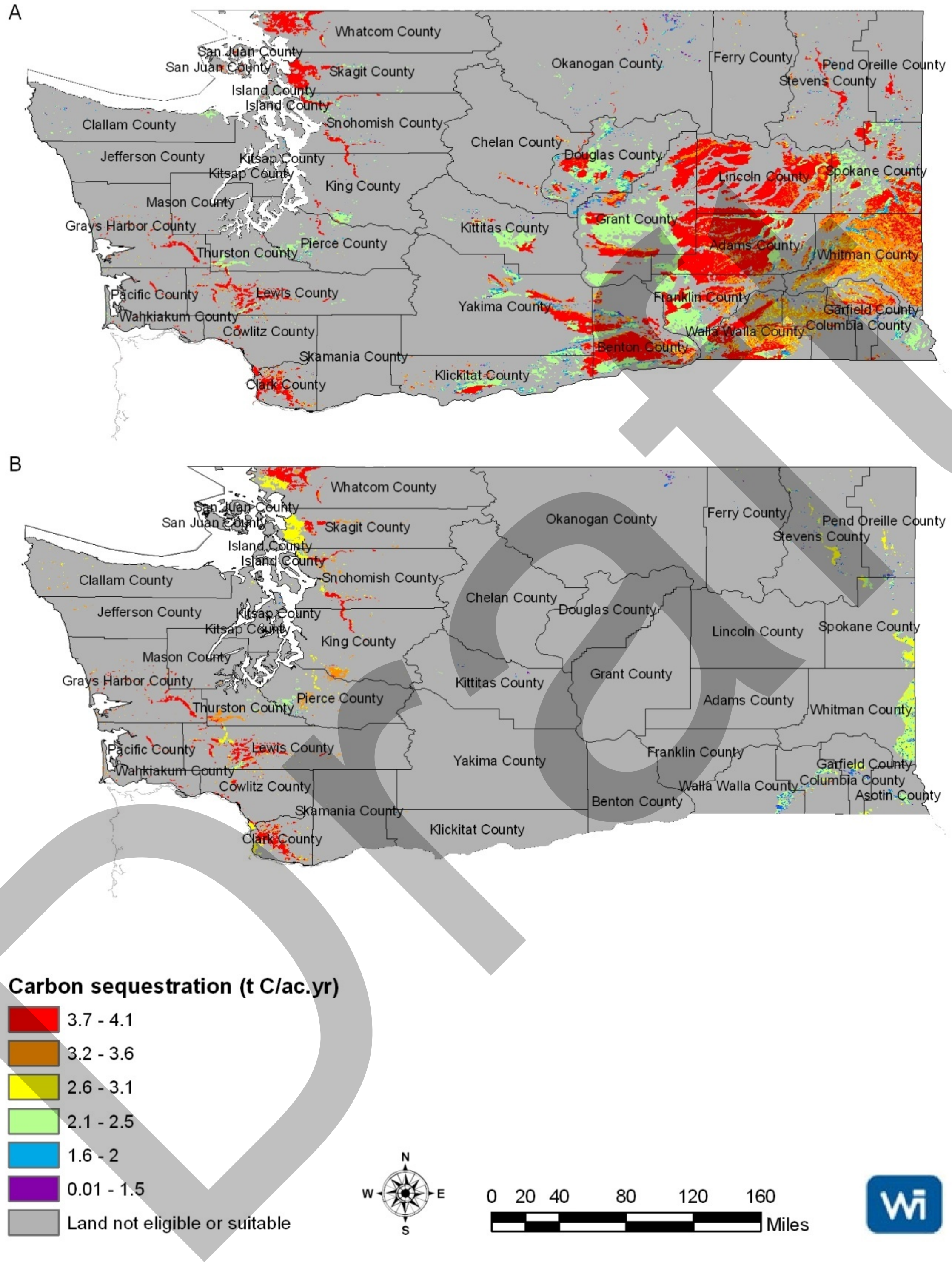

Figure 13. Potential tons of carbon per acre per year for hybrid poplar plantations in Washington with irrigation (A), and without irrigation (B), based on the suitability map.

3.3.5. West Coast Region analysis by county

To identify which counties in the West Coast Region have the highest potential for carbon sequestration from hybrid poplar plantation, the carbon per unit area (total carbon/total county area—t C/ac) was calculated. The carbon per unit areas for each county was then analyzed with and without irrigation (Figure 14 and Figure 15).

This analysis shows that with irrigation, counties in the Central Valley of California, the Central Willamette Valley of Oregon and the Eastern Cascades of Washington have the highest potential for hybrid poplar plantation (Figure 14). In particular Adams, Walla Walla, Whitman and Garfield in Eastern Oregon, and Kings County in Central California. These counties ranged from 6.6-5.4 T C/ per unit of land.

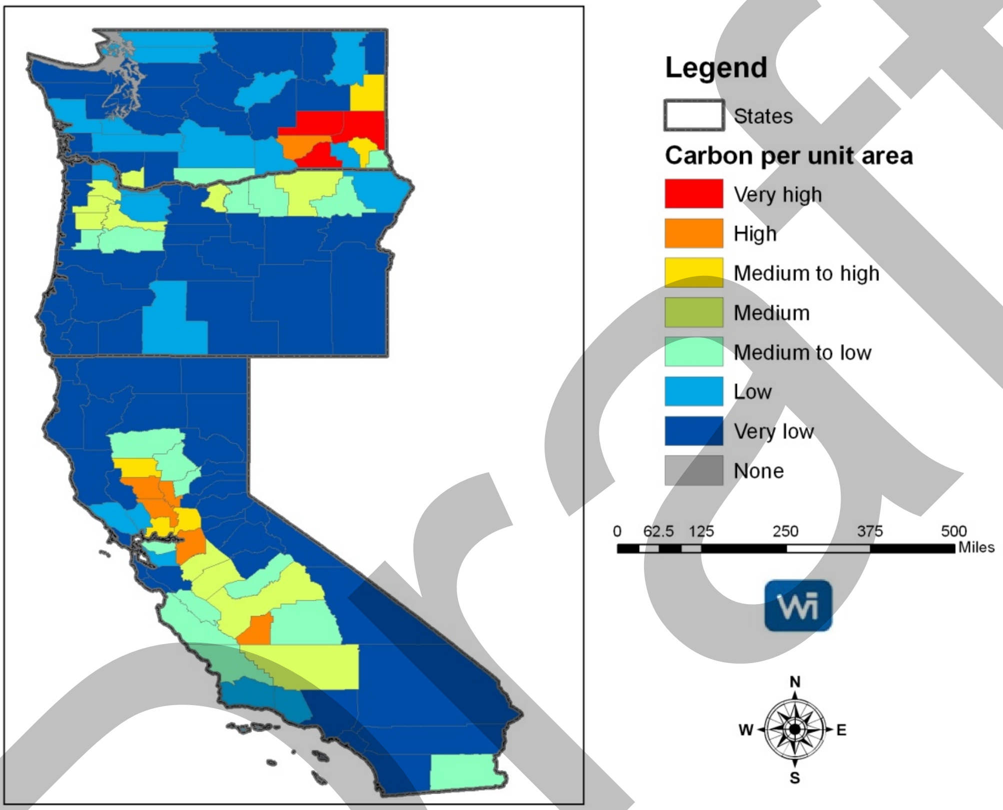

Figure 14. Potential carbon sequestered each year (t C/ac) for each county in the West Coast Region with irrigation. Tons of carbon sequestered each year assumes all eligible lands are planted with hybrid poplar. For a map of county names see Appendix A.

When irrigation is excluded, the majority of the counties that have high potential carbon sequestration per unit of land shift to the Willamette Valley in Oregon and the Pacific Northwest of Washington (Figure 15). The counties with the highest carbon per unit of land are Clark County in Washington, with 2.3 t C/ per unit of land, and Marion, Polk and Yamhill in Oregon with 2.4, 2.2 and 2.1 t C/per unit of land respectfully.

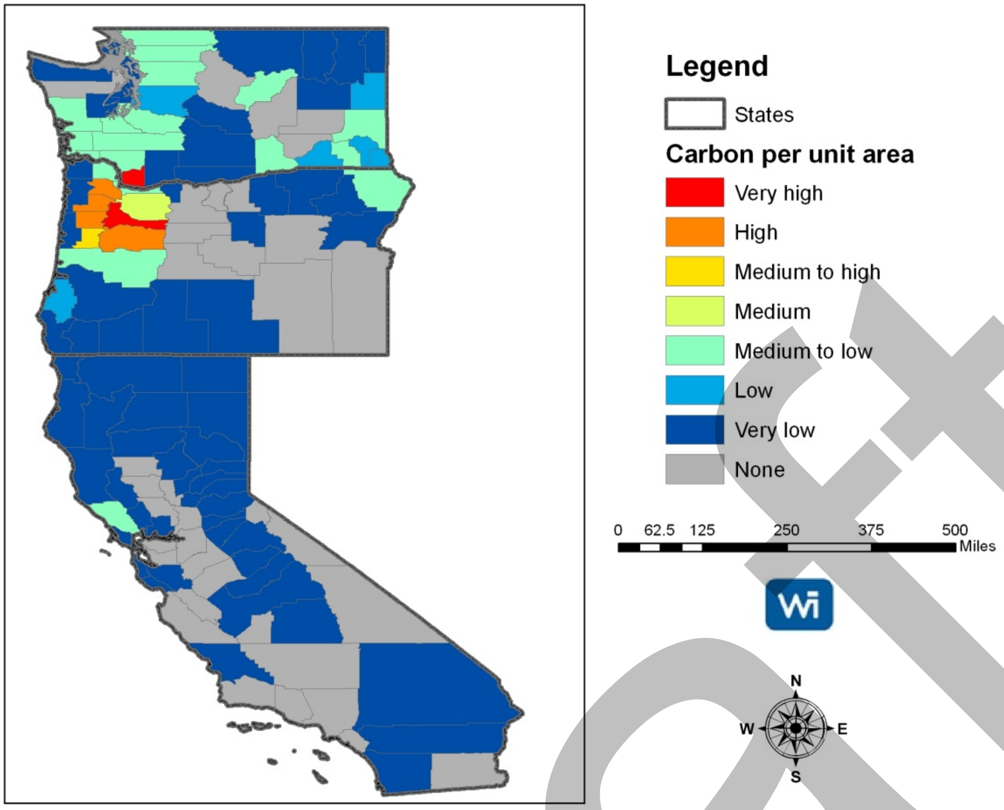

Figure 15. Potential carbon sequestered each year (t C/ac) for each county in the West Coast Region without irrigation. Tons of carbon sequestered each year assumes all eligible lands are planted with hybrid poplar. For a map of county names see Appendix A.

3.4. Financial analysis

The focus of this financial analysis is on large scale hybrid poplar plantations as afforestation and reforestation projects with carbon credits as a primary component. Two management scenarios were reviewed: 1) long rotation (≈20years) multiple market wood products (which includes lumber, veneer, and other wood products), and 2) as a short rotation (≈6years) bioenergy crops used as feed stock for local power plants

The development of large-scale hybrid poplar plantations requires initial research into areas where there is enough suitable land available within reasonable distance from markets. These markets would be, for example, the presence of a bioenergy plant for biomass crops, or a local mill for the processing of wood products. A purely carbon based projects would not have the limitation of local market demand.

Once a location and market has been found, a cost benefit analysis should be conducted analyzing the cost of production for hybrid poplar, and the estimated revenue. Below is a brief break down of the costs and processes associated with the production of hybrid poplar and an estimation of the potential revenue. Information was gathered from literature and from Greenwood's report for Lake County Oregon by Boswell *et al.* (2008) (see Appendix C of this report).

3.4.1. Cost of production

The cost of production varies depending on the management scenario. For a dedicated biomass plantation trees are harvested every 6-7 years using a system of coppicing, where stumps are allowed to resprout after being cut. This technique is generally acceptable for about 5 harvests before new plant material is needed. Biomass crops are usually planted at densities of 1000-2000 stems/acre, and require little maintenance. In contrast, multiple market wood products crops are generally harvested on 15-20 year rotations, are planted at densities of 100-500 stems/ac, and require pruning and other types of tree maintenance necessary for producing good sawlogs. The harvesting of sawlogs for wood products also requires properly felling trees and preparing logs for the mill. Table 4 shows a comparison between a dedicated biomass and multiple wood products management scenario adapted from Boswell *et al.* (2008).

Table 4. Comparison of dedicated biomass and multiple market management systems.

	Biomass	**Wood products**
Density (trees per acre)	1450	440
Regeneration	Coppice	Replanting
Rotation	6	20
Harvesting	Whole tree chipping	Log merchandizing
Stand improvement	None needed	Pruning
Site suitability	poor to good	marginal to good
Integrated pest management	similar	similar
Plant material	similar	similar

The costs of these two management scenarios can be broken down into two groups: 1) establishment, and 2) running cost.

Establishment costs would be relatively similar for both market scenarios. General site establishment should start in June, but late August can suffice. Typically sites will be mowed and after some regrowth, herbicide applied (Downing 1996). Within 1-2 weeks, disking (plowing) should occur to bring grass rhizomes to the surface where they can be killed by drying. The field should be smoothed and groomed, and if erosion is a concern a cover crop should be planted. In the spring weeds need to be removed again and stems planted at designated densities (Boswell *et al.* 2008, Downing 1996). Based on the report by Greenwood, the capitol costs for site preparation are around $539/acre for bioenergy crops, and $632/acre for multiple market wood products (Table 5). The difference in costs between biomass crops and wood product crops is associated with the more intensive site preparation necessary to establish trees that are good for sawlogs.

Table 5. Costs for the establishment of a hybrid poplar plantation.

Activities	Biomass	Wood products
Establishment and preparation	$159.92	$277.87
Site preparation	$39.42	$52.01
Planting and replanting	$326.59	$228.00
Infrastructure development	$13.51	$74.30
Cost per acre	$539.44	$632.18

Running costs include management fees, harvesting, transportation and land rental and irrigation (Table 6 and Table 6). Management costs are crop care, such as pruning and pest management, salaries for managers and any other costs concerning the maintenance of the trees. Transportation includes maintenance activities and the delivery of products to the mill or biomass plant. Fell and skid are the harvesting costs, and Processing is the costs associated with preparation of logs for the mill or power plant.

Table 6. Harvesting, processing and transportation costs.

Activities	Biomass	Wood products
Management fees	$81.08	$2,307.31
Transportation	$324.33	$1,337.35
Fell and skid	$432.45	$2,139.76
Process logs	$432.00	$2,134.34
Total cost per acre	$1,269.86	$7,918.76

While these costs are estimates, and can vary depending on location, it is assumed for this study that they will be relatively consistent across the West Coast Region. In contrast, the costs for land rental and irrigation can vary greatly across the West Coast region.

The cost of irrigation varies depending on different combinations of sources, suppliers, distribution systems and other factors such as proximity to water, topography, aquifer conditions, and energy source (Gillehon & Quinby, 2004). Costs for irrigation in California in 2003 ranged from $36/ac to $79/ac, while costs in parts of Washington State range from $10/ac to $41/ac (Gillehon & Quinby, 2004). The cost of agricultural land rental also varies substantially across the West Coast Region, from two thousand dollars per acre along California's coast to as low as $25/ac in the Northeast of Washington and Oregon.

For this study, to estimate the cost of land rental and irrigation per county, data from the USDA/NASSA National Agriculture Statistics Service was used (USDA, 2009). This data shows the land rental rates with irrigation for select counties in each state, and for the remaining counties an average for the region is applied. These data were mapped across the West Coast Region (Figure 16).

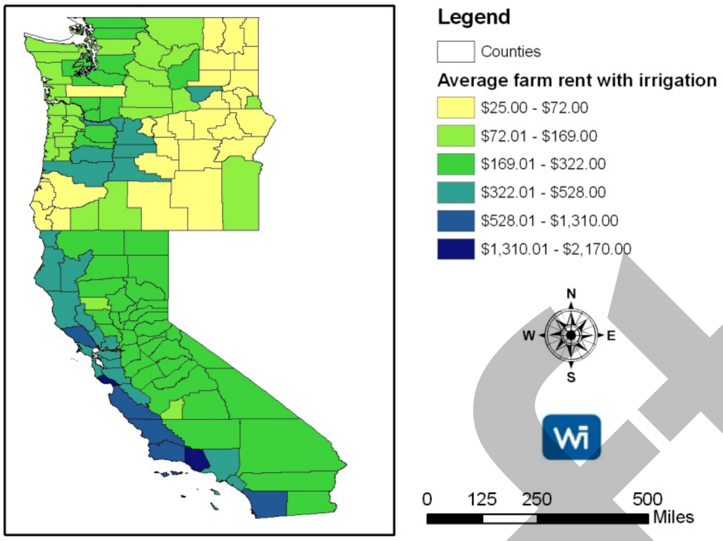

Figure 16. Average farm rental costs per acre across the West Coast Region. For a map of county names see Appendix A.

The results show that rental costs including irrigation can vary widely from $25/ac in areas like Eastern Washington to over $2,000 in the Central and Southern Coast of California. Therefore, the rental and irrigation costs would likely play an important role in deciding the feasibility for the establishment of a hybrid poplar plantation. However, in reality the establishment of hybrid poplar is most suited to marginal farm and pasture land that is of limited value. Based on expert opinions and the average cost of sub prime farm land rental values calculated from the USDA/NASSA data set, it was determined that land rental with irrigation of around $56/ac was the best estimate for the rental and irrigation costs associated with land that would be suitable for hybrid poplar plantations. Any land much more expensive than this would probably be financially unfeasible. While Figure 16 shows that most counties would be excluded from considering hybrid poplar plantations based on land rental costs, it must be understood that even within counties land rental and irrigation is highly variable. Therefore counties that show a higher than $56/ac average rental cost should not necessarily be excluded. Based on the assumption that yearly rental and irrigation costs are $56/ac rental and irrigation costs were calculated. This resulted in total land rental costs of $336 over 6 years for bioenergy crop, and $1,120 over 20 years for multiple wood products crops.

3.4.2. Revenue

Revenue depends on the market the wood is designated for and the potential carbon credits that can be generated over the period of the crop rotation. For bioenergy the revenue is from wood chip and small logs. For multiple market wood products the revenue is from sawlogs and residuals wood products from the excess cuttings. For either management scenario initial capital would be needed because no trees are harvested during the development period. Therefore, there would be several years of negative cash flow followed by a relatively large positive net cash flow to perpetuity (Boswell *et al.* 2008).

3.4.2.1. *Multiple market wood products crop*

Planting hybrid poplar for carbon sequestration and multiple market wood products is estimated to be feasible at a 20 year harvest rotation. This was based on growth trajectories and the tree size necessary for merchantable sawlogs (Boswell *et al.* 2008). These growth trajectories and harvest rotation will vary depending different location across the West Coast Region, with higher potential in the Pacific Northwest, and possibly lower potential due to limited available moisture in drier Southern and Eastern regains. Development of a 20 year rotation carbon and multiple market tree farm is suggested to have approximately 440-680 stems per acre planted in stages so that a fully developed farm would have an even age class distribution and a sustained harvest volume. Carbon pools would grow steadily through the first twenty years as more acres were planted, peaking during the twentieth year (Boswell *et al.* 2008).

Based on the report by Green Wood Resources (Appendix C) for Lake County, to make a multiple market tree farm feasible it is estimated that approximately 17,900 acres would need to be planted. This would most likely be achieved by aggregating many different land owners in a particular area. The justification for a development of this scope is based on attracting the infrastructure that would be needed for cost effective delivery of goods and services, including nursery, production, farming and harvesting. A production volume of this magnitude would be necessary to attract the value added processing necessary to drive sawlog prices into the range of \$400-\$500 per thousand board feet (Boswell *et al.* 2008).

The revenue for a multiple market wood product crop over a 20 year rotation with a yield of 9 green tons/ac.yr is expected to be around \$17,947/ac excluding carbon. This revenue is based on projected prices from the Greenwood report of \$90/green tons for sawlogs, and \$33/green tons for residual wood and small logs. The revenue from carbon credits after 20 years at \$4/ton of $C0_2$ would be \$425/ac, at \$7/ton of $C0_2$ it would be \$743/ac, and at \$15/ton of $C0_2$ it would gross \$1,592/ac.

For the multiple market wood product crop the net revenue with carbon is estimated to be \$9,821/ac at a carbon price of \$4/ton of $C0_2$, \$10,139/ac at a carbon price of \$7/ton of $C0_2$, and \$10,989/ac at a carbon price of \$15/ton of $C0_2$ (Table 7).

Table 7. Estimated revenue from a multiple market hybrid poplar crop over a 20 year rotation.

Products	Wood products
Sawlogs	\$14,443.41
Small logs	\$2,189.91
Residual	\$1,313.95
Carbon credits *	\$425 - \$1,592
Gross revenue	\$18,372 - \$19,539
Net revenue (Gross – Cost)	\$9,396 - \$10,989

The carbon credits generated from a multiple market wood crop are based on a MAI 9 green tons/ac.yrac.y(Boswell *et al.* 2008) (Figure 17). This assumes marginal to good site suitability with 440 stems per acre, and irrigation supplied where needed.

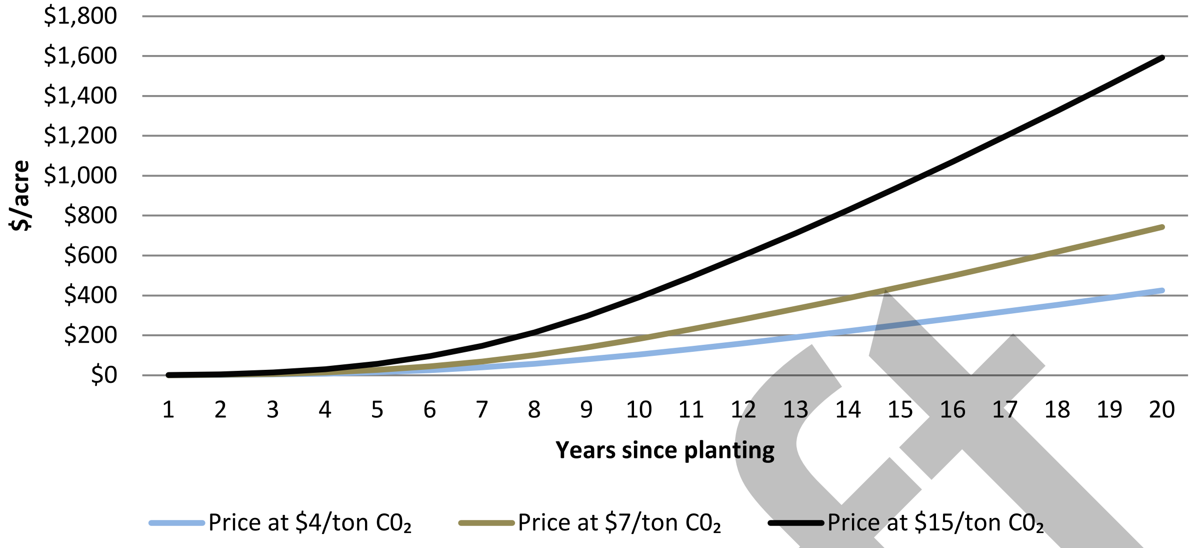

Figure 17. The revenue from hybrid poplar carbon credits per acre over twenty years of growth under a multiple market management scenario.

3.4.2.2. *Dedicated biomass energy crop*

A dedicated biomass energy tree farm where the only product is feedstock for a regional biomass plant is a very different management scenario than the multiple market wood product plantation. A dedicated hybrid poplar bioenergy plantation would require a short rotation of around 6 years, regenerated by coppicing. To achieve the financial requirements to meet market demands biomass crops generally requires relatively fewer acres with higher planting densities (stems/ acre) than multiple market plantations.

Using the numbers from the Greenwood report (Appendix C), the revenue from a dedicated bioenergy crop is estimated to be $650/ac, based on a 6 year rotation at a price paid per ton of $58/green ton. When carbon credits are included the net revenue at $4/ton of C0$_2$ is $737/ac, at $7/ton of C0$_2$ it is $802/ac, and at $15/ton of C0$_2$ it would be $976/ac (Table 8).

Table 8. Estimated revenue from a dedicated biomass hybrid poplar crop over a 6 year rotation.

Products	Biomass
Sawlogs	na
Small logs	$2,799.00
Residual	na
carbon credits	$86 -$325
Gross revenue	$2,885 - $3,124
Net revenue	$737 - $976

The carbon credits generated from a dedicated biomass crop are based on a MAI 8 green tons/ac.yr (Boswell *et al.* 2008) (Figure 18). This assumes marginal to good site suitability with 1,450 stems/acre, and irrigation is supplied where needed.

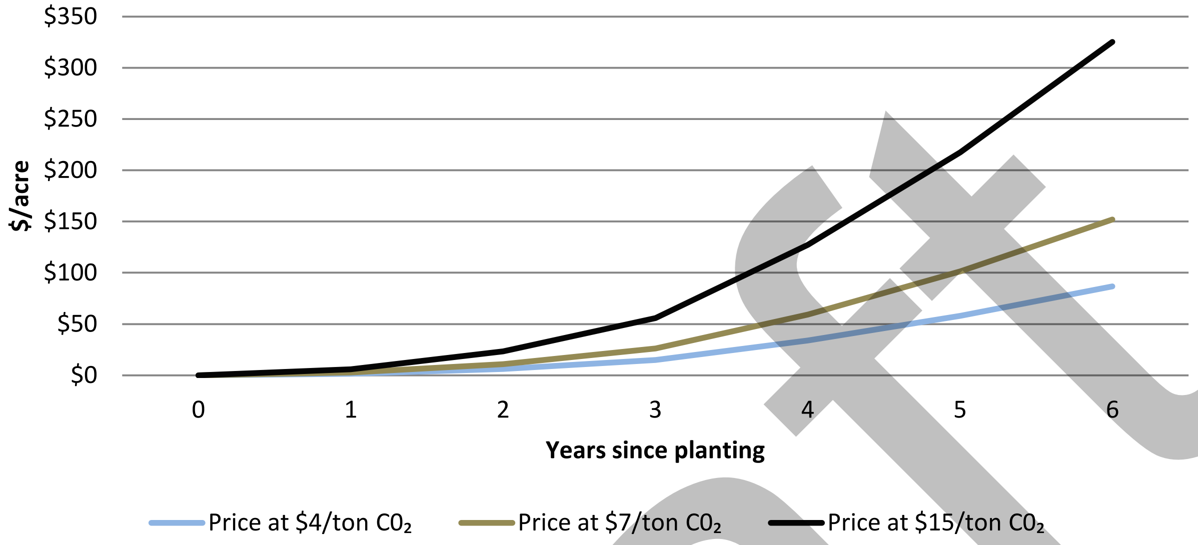

Figure 18. The revenue from hybrid poplar carbon credits per acre over six years of growth under a dedicated biomass management scenario.

4.0 Conclusions and Recommendations

4.1. Conclusions

This report describes the spatial distribution of potential afforestation sites where fast growing high-yielding forestry crops, most notably hybrid poplar, could be established. Results show that most of the prime lands ideal for hybrid poplar, and where no irrigation or limited irrigation would be needed, is located primarily in the counties west of the Cascade Mountains in Oregon and Washington State. If irrigation is supplied in areas where moisture availability is limited, the amount of highly suitable land throughout the West Coast Region more than doubles, and the counties identified with high potential for hybrid poplar plantations shift to the Central Valley of California, and the farm lands east of the Cascade Mountains in Washington State. The areas reported in this study as "eligible" for hybrid poplar may or may not be "available," and should only be interpreted as eligible for consideration. In reality many of the areas identified as eligible are prime farmlands which would not likely be considered for conversion to hybrid poplar because of the economic benefits of the current crops being grown on them. Similarly, areas such as native grassland would not be eligible for hybrid poplar due to the potential loss of important native biodiversity and ecosystem services. The reality is that areas within the eligible lands for hybrid poplar plantations would mostly be on marginal agricultural lands, degraded areas or as riparian buffers where both the economic and ecological benefits of planting poplars can be better realized.

The development of hybrid poplar growth and yield based on the suitability classes from the regional characterization map involved assumptions on the potential productivity of poplar under different site conditions. To improve the ability to project productivity and carbon sequestration more research needs to be conducted on growth and yield over longer periods of time and under different site conditions. It also needs to be mentioned that due to the extent of this analysis productivity of hybrid poplars is based on generalized site conditions, and a more detailed analysis (for example, on a county level) should be conducted for locations identified as valuable for hybrid poplar plantations.

The results from the financial analysis showed decent revenues from hybrid poplar as a bioenergy crop and as a multiple wood product crop. When carbon is included in the revenue, bioenergy crops receive a much higher return than multiple wood products, with carbon from bioenergy crops making up 10-50% of the revenue, while for wood products carbon only makes up 2-10% of the potential revenue. However, any large scale hybrid poplar afforestation project needs to be assessed on a site by site basis, and depending on local markets, the price of goods, and the price of carbon credits financial feasibility will vary considerably.

The planting of hybrid poplars on pasture, farmland, or degraded lands has multiple environmental benefits in addition to its potential for reducing global greenhouse gasses through carbon sequestration. In particular hybrid poplars have been cited as valuable along riparian areas to reduce erosion, and as ground water filters taking up excess nutrient and chemicals coming from farmlands and other developed areas (Johnson, 1999; O'Neill and Gordon 1994; Schultz *et al.* 1994). Hybrid poplars have also been planted in degraded areas specifically to absorb organic chemicals such as trichloroethylene, carbon tetrachloride and atrizine dumped or spilled on the soil (Johnson, 1999; Gordon *et al.* 1997).

While these environmental benefits are all important considerations when evaluating the potential for establishing a hybrid poplar plantation, it is also important to consider the water demands that hybrid poplar needs for good production and the effects that those demands will have on the local and regional environment. Within the West Coast Region almost 75% of the eligible land is considered arid and prone to drought. Because of this the risks and environmental consequences of planting water demanding crops, such as hybrid polar need to be considered. In addition, climate change models predict that average temperatures in the Western US will increase, and the frequency and severity of some extreme weather events such as drought will also increase making some ecosystems, particularly vulnerable (IPCC, 2008).

Many poplar species are native to areas where there is high soil moisture; however, hybrid poplars are being used in many areas where soil moisture may be limiting and evaporative demands high (Nash 2009). Throughout these moisture-limited areas, which accounts for the majority of eligible hybrid poplar land in the West Coast Region, the availability of water for irrigation is going to be a major factor in poplar establishment, growth and survival.

Water requirements for hybrid poplar in the arid region of Eastern Oregon was found to be around 21 ac-in/ac of irrigation during the first year, 35 ac-in/ac during the second year, and 44 ac-in/ac for all the remaining years(1 acre-inch ≈ 27,100 gallons). By the end of the third year, trees receiving optimum irrigation averaged 26 ft tall and produced 256 ft^3 of wood/ac (Shock et al 2002). These irrigation requirements after the third year of growth are about 10-20ac-in./ac more than traditional crops such as sweet corn, which needs 20-35 ac-in/ac, and wheat, which uses about 25 ac-in/ac. In the more arid and water restricted areas of the West Coast Region these water requirements are considerable, and therefore may not be feasible.

While concerns about the amount of water available for hybrid poplar production is important, the amount of water that escapes as runoff is equally important to consider when looking at whole catchments. This is because forests are known to have a significant effect on water yield; as amounts of land change from open arable land to closed forest, water downstream may become limited (Perry *et al.* 2001). Studies that looked at other short rotation woody crops in the Southern US showed no difference in runoff when compared to corn or cotton during the first two growing seasons, but once the canopy closed, runoff volumes were lower (Thornton *et al*., 1998). In the Netherlands changes in soil water balance during a conversion from arable land to hybrid poplar showed a 23% reduction in percolation (Rijtema and de Vries, 1994). Measurements in Wisconsin show that the timing of water yield also changes as forests replace cultivated fields and other non-forested types of land use (Potter, 1991). Therefore, large areas planted in hybrid poplar may generate cumulative watershed effects on the cycles of flooding and on total water yield (Perry et al. 2001). These potential changes in the hydrology of watersheds due to increased plantations of woody crops like hybrid poplar could have varying effects on downstream water availability.

In summary hybrid poplar crops may provide considerable ecological and financial benefits if planted responsibly in locations that can support the needed production. These requirements include the ability to provide ample water now and into the future, good soil, investment into the proper infrastructure to properly establishment and maintain a healthy hybrid poplar crop, and a robust market demand that is predicted to remain strong over time.

4.1 Recommendations

Based on the conclusions from this Regional Characterization study, future research should be undertaken by conducting more detailed characterization studies on a county or local level, in areas identified to have high potential for hybrid poplar plantations. A more detailed local characterization study would follow a similar methodology, but would use a higher resolution soils analysis and, if available, a land ownership, current and past land use dataset. This next step would be essential for any project developer that wanted to begin identifying individual properties and sites for the establishment of hybrid poplar or other fast growing forestry crops. Development of local regional characterization studies could be accomplished in 2-4 month of time, and would likely cost from $25,000 to $35,000.

In addition, areas where large scale conversion of arable land to fast growing woody crops is planned, research should be conducted on water resources on a catchment level. The study would need to address the predicted change in the frequency of flooding events, and water availability downstream. A catchment level study like this would likely take 7-9 months and cost from $35,000 to $50,000.

More research into the growth and yield of hybrid poplar on different site conditions would greatly improve the estimated carbon sequestration numbers developed using the results from the suitability analysis. With better growth and yield numbers that are representative of different site conditions across the West Coast Region a more robust analysis could be conducted for the potential for hybrid poplar as a carbon sequestration crop.

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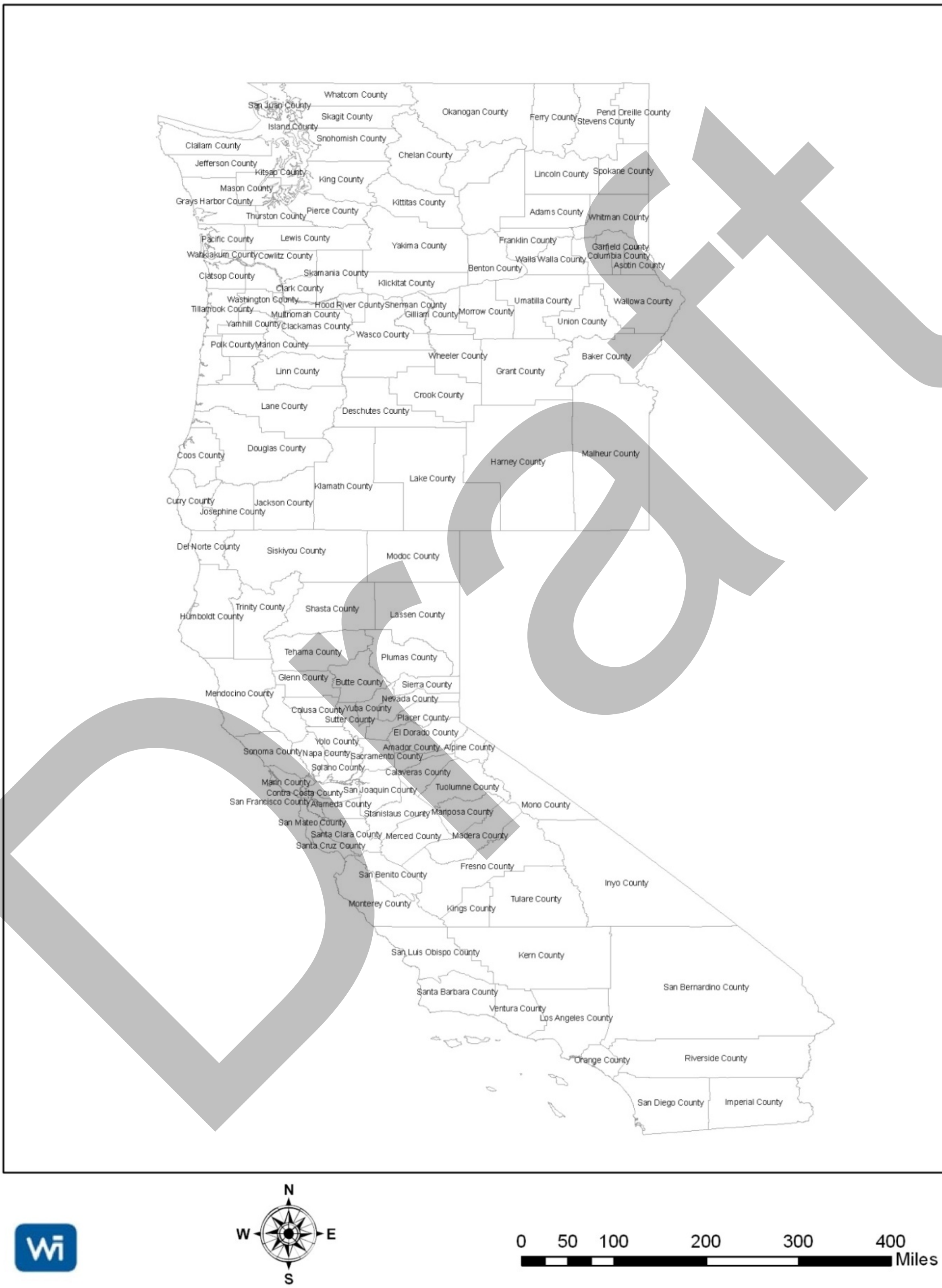
6.0 Appendices

Appendix A: County maps for the West Coast Region



Appendix B: Suitability tables

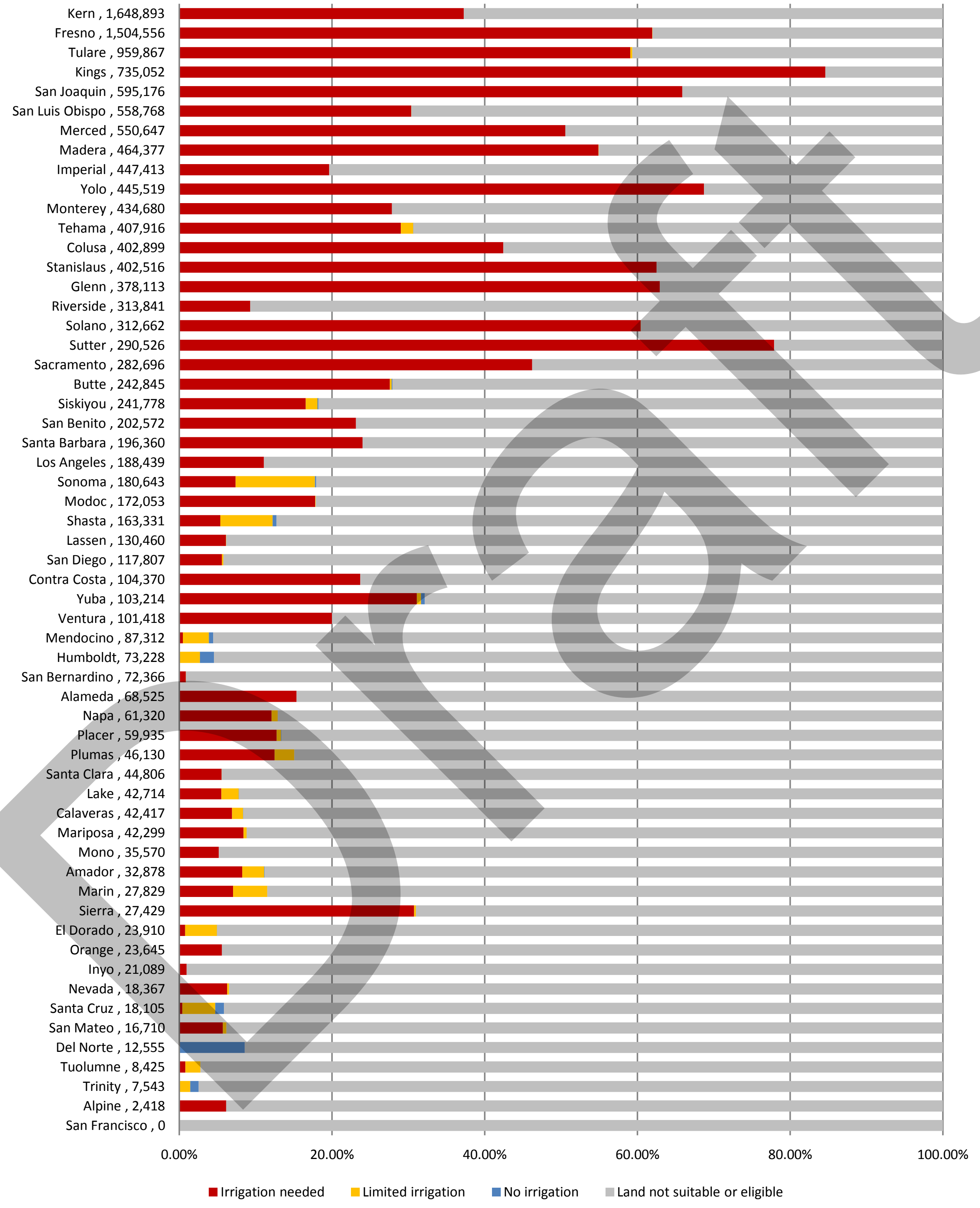
California

For each county in California: the total county area in acres and total area in acres for different suitability classes defined by irrigation need and soil quality. Counties are listed from the top starting with the county that has the most total suitable area and ending with the least.

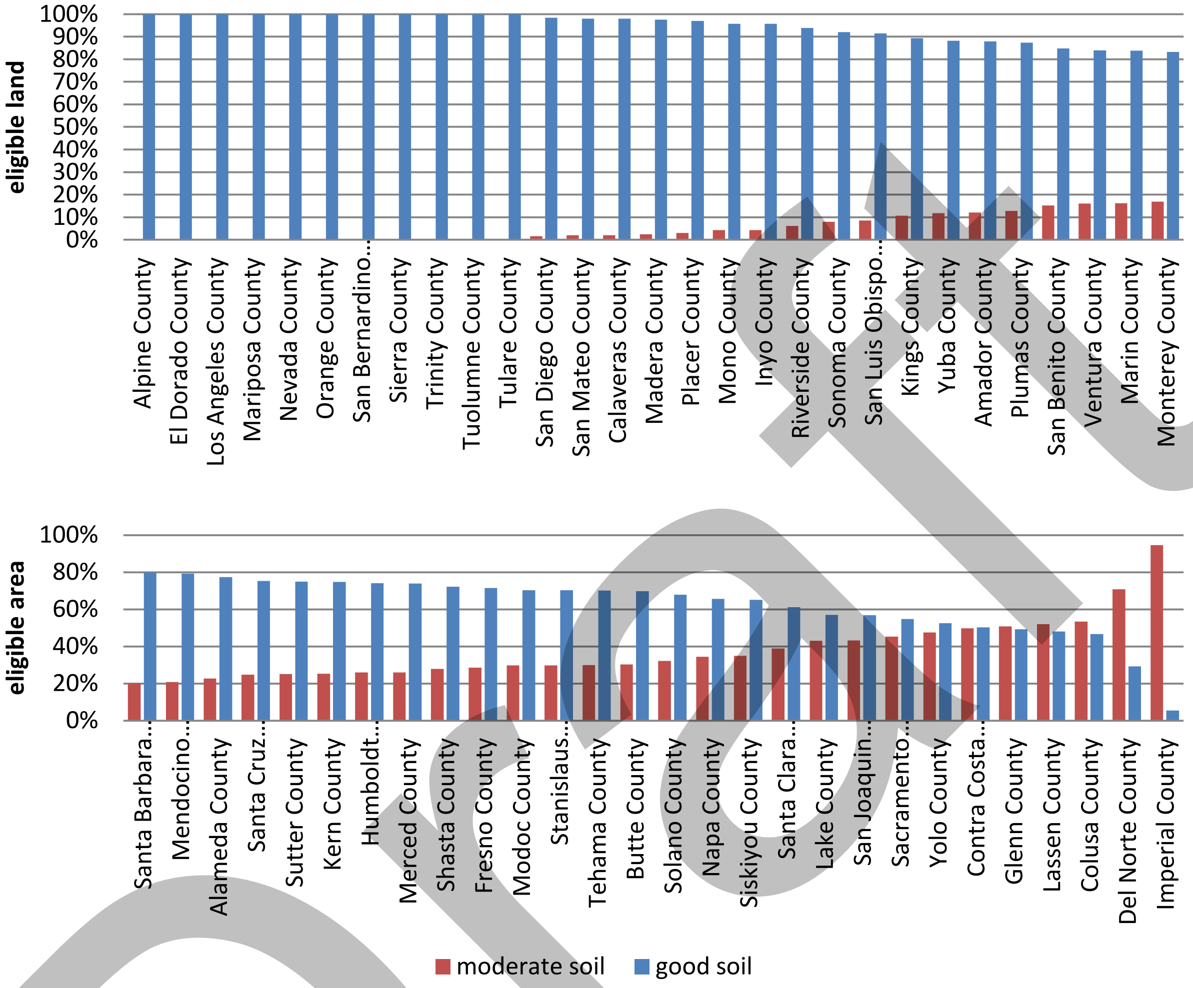
County	Total county area (ac)	Irrigation needed		limited irrigation		No irrigation	
		mod. soil	good soil	mod. soil	good soil	mod. soil	good soil
Kern	5,230,029	462,990	1,188,221				
Fresno	3,860,068	471,686	1,032,853		944		
Tulare	3,113,430	447	954,692		4,352		
Kings	886,075	82,604	652,746				
San Joaquin	909,370	259,866	335,751				
San Luis Obispo	2,110,712	56,680	501,500		37		
Merced	1,259,982	155,857	394,630				
Madera	1,376,835	12,637	451,025		294		
Imperial	2,906,856	432,838	14,483				
Yolo	649,929	219,693	226,251				
Monterey	2,119,460	102,625	332,108				
Tehama	1,893,861	123,068	262,848	1,559	20,382		37
Colusa	751,071	228,896	174,032				
Stanislaus	965,787	118,079	284,567				
Glenn	838,444	193,880	184,389				
Riverside	4,712,358	20,826	293,058		15		
Solano	530,486	105,148	207,988		7		
Sutter	388,378	72,589	217,902				
Sacramento	629,839	126,555	155,768				
Butte	1,070,372	71,926	167,298	163	2,024		904
Siskiyou	4,057,082	48,387	171,610	12,944	7,796	1,473	12
San Benito	893,088	47,959	155,054				
Santa Barbara	1,737,796	58,125	139,316				
Los Angeles	2,601,458		189,106				
Sonoma	1,017,997	11,970	62,116	6,459	98,016		1,678
Modoc	2,675,270	66,095	105,301		598		
Shasta	2,459,335	30,404	37,993	13,554	74,518	217	6,259
Lassen	3,034,187	77,340	52,276	815	467		
San Diego	2,737,798	3,035	110,816		4,035		
Contra Costa	461,288	65,175	38,786				
Yuba	412,063	12,459	87,240		1,740		1,601
Ventura	1,188,873	24,595	76,841				
Mendocino	2,252,637	4,789	4,001	28,811	38,277	1,965	9,462
Humboldt	2,280,571	121	62	40,954	2,155	5,147	24,765
San Bernardino	12,998,243		71,944		79		
Alameda	477,160	19,284	49,654				
Napa	502,674	24,758	32,811	2,664	1,035		
Placer	957,087	2,222	54,821		2,614		376
Plumas	1,670,256	54	37,865	6,057	1,858		
Santa Clara	825,451	19,675	24,711		84		
Lake	852,554	13,954	16,208	9,163	3,217		198
Calaveras	663,135	1,147	33,738		7,361		111
Mariposa	937,874		40,215		2,053		
Mono	2,000,916	2,026	33,513				

Amador	387,693	5,298	18,963		8,520		121
Marin	327,542	4,801	12,383	1,643	9,422		
Sierra	609,235		27,516		225		
El Dorado	1,143,277		3,660		20,181		25
Orange	507,643		23,683				
Inyo	6,562,967	959	20,186				
Nevada	627,701		1,231		13,396		3,464
Santa Cruz	284,960	5,726	11,627		625		
San Mateo	284,903	413	14,970		1,263		
Del Norte	647,515					11,683	877
Tuolumne	1,457,027		2,350		6,034		
Trinity	2,048,500		5		4,253		3,272
Alpine	472,833		2,424				
San Francisco	28,185						

The percent of land in each county in California State suitable for hybrid poplar plantations with irrigation, with limited irrigation, without irrigation and land not suitable or eligible for hybrid poplar. Counties are listed with their total acres of suitable land, and are listed from the top by county with the most suitable land to the least.



California counties and percent of eligible hybrid poplar plantation land that has 10-20cm/m of available soil moisture and >20cm/m.

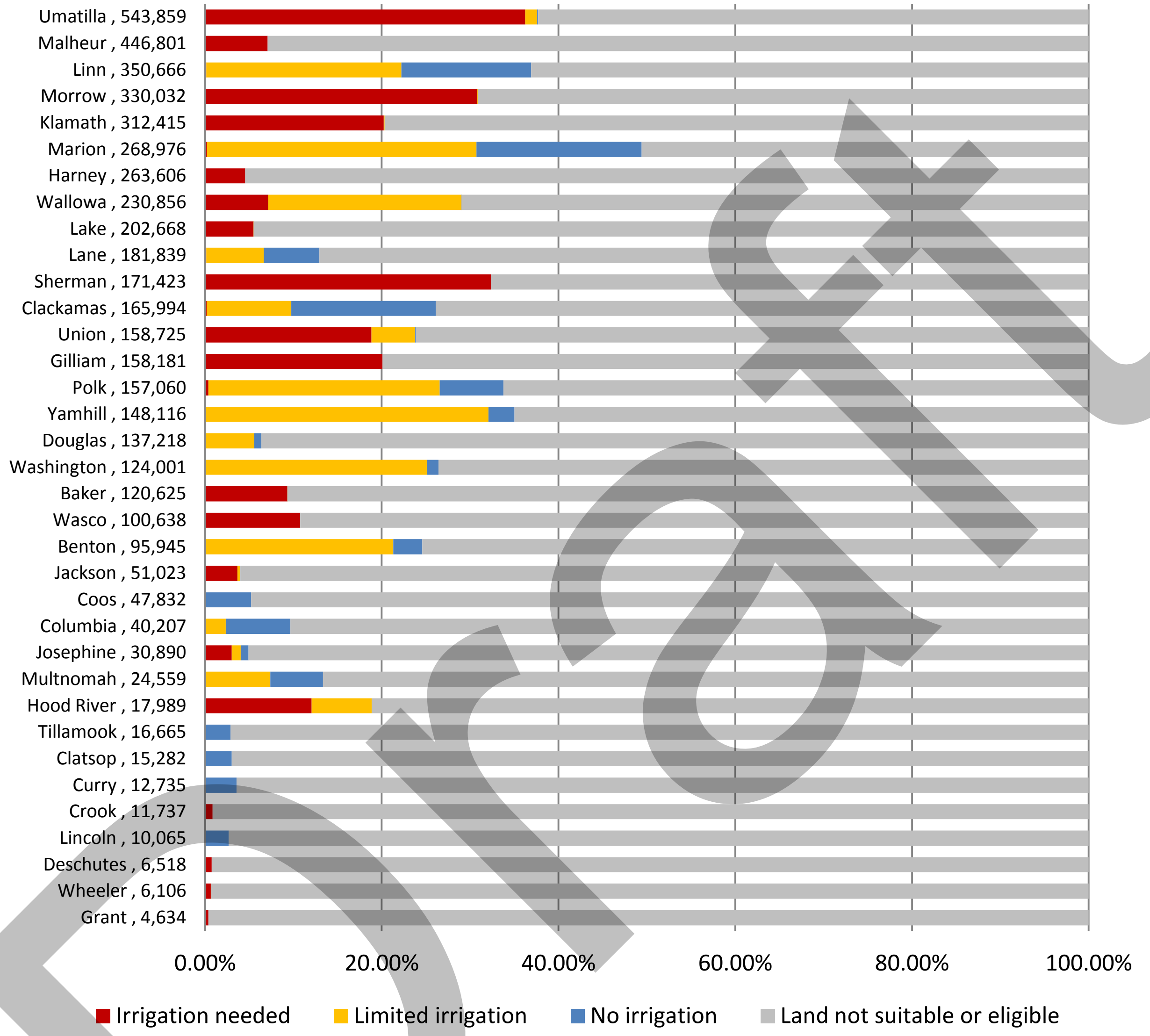


Oregon

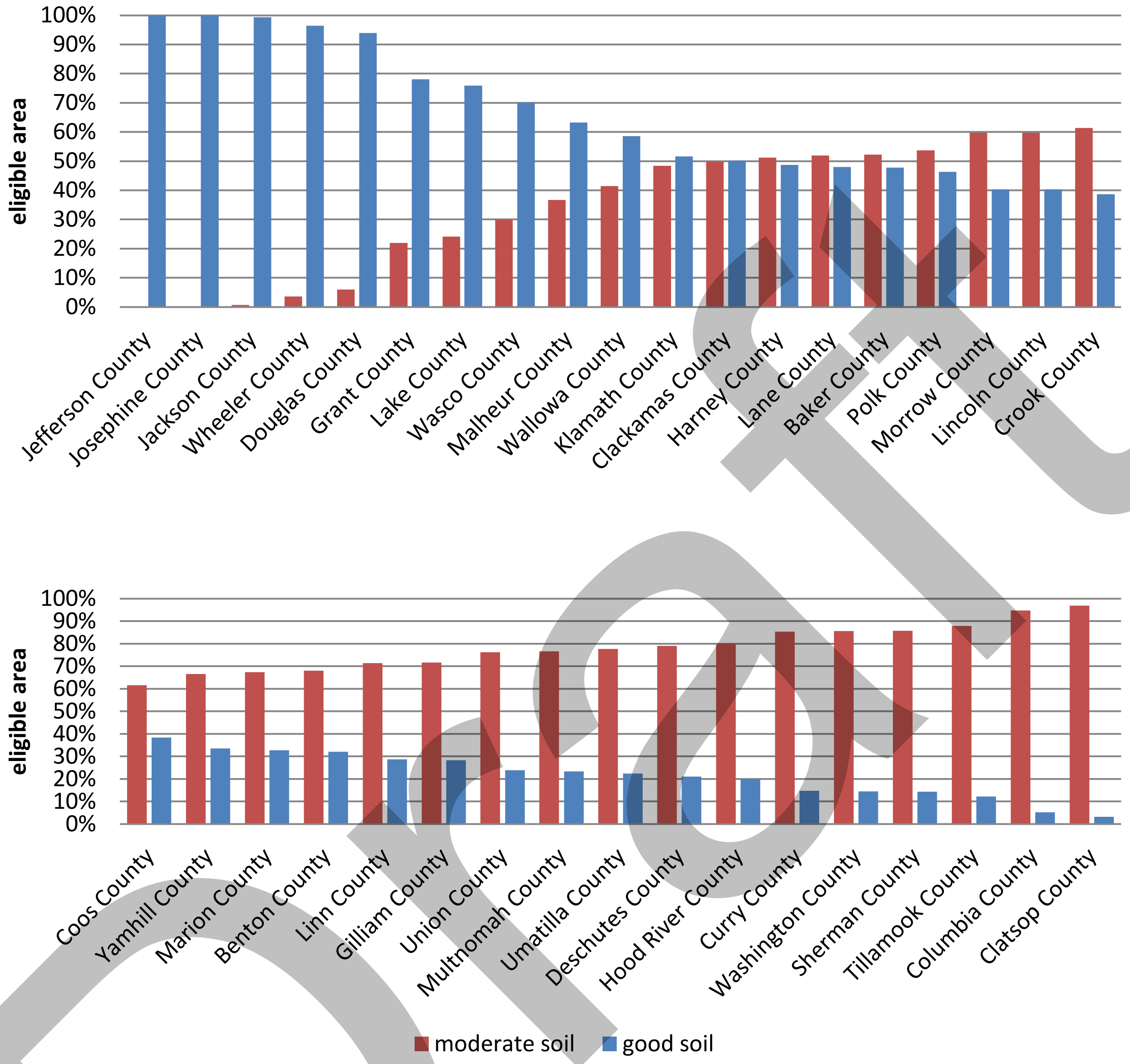
For each county in Oregon: the total county area in acres and total area in acres for different suitability classes defined by irrigation need and soil quality. Counties are listed from the top starting with the county that has the most total suitable area and ending with the least.

County	Total county area (ac)	Irrigation needed		limited irrigation		No irrigation	
		mod. soil	good soil	mod. soil	good soil	mod. soil	good soil
Umatilla	2,065,694	401,396	122,423	17,621	1,871	1,493	20
Malheur	6,359,939	181,517	265,386				
Linn	1,474,555	1,223	282	203,532	6,595	71,684	68,274
Morrow	1,306,137	206,960	123,118	403	5		
Klamath	3,917,677	120,236	190,376	497	1,011		
Marion	766,982	1,077		157,286	8,945	31,472	70,006
Harney	6,560,583	127,645	136,054				
Wallowa	2,023,678	18,877	38,052	32,055	142,108	27	
Lake	5,319,826	28,979	173,276	353			
Lane	2,952,154	1,307	880	72,680	18,815	44,072	44,626
Sherman	532,181	146,301	25,210				
Clackamas	1,205,138	1,129	86	56,971	3,709	30,345	73,745
Union	1,311,638	118,425	6,672	8,923	23,987	554	
Gilliam	789,084	114,229	43,988				
Polk	470,796	650	1,068	81,981	40,042	8,095	25,583
Yamhill	461,807	156	175	104,275	30,521	3,111	9,284
Douglas	3,233,476		1,300	8,530	109,739	1,611	16,109
Washington	469,981	69	74	108,832	8,627	2,261	3,988
Baker	1,983,789	74,521	46,222	17	126		
Wasco	1,529,122	28,761	71,973				
Benton	440,108	128	250	68,551	14,105	6,057	6,865
Jackson	1,788,473		46,862	647	3,195		341
Coos	1,019,176					37,662	10,094
Columbia	419,907	15		9,479	217	28,141	2,264
Josephine	1,044,672		19,047		6,331		5,535
Multnomah	270,509	17	32	13,134	447	6,133	4,653
Hood River	344,017	10,784	724	6,116	373		
Tillamook	694,396					16,159	516
Clatsop	512,313					14,965	321
Curry	1,037,627					12,467	284
Crook	1,913,239	11,174	568				
Lincoln	622,959					8,239	1,804
Deschutes	1,969,029	4,646	1,831				
Wheeler	1,094,675	158	5,874	72			
Grant	2,902,349	2,629	2,007				
Jefferson	1,143,034		2,385				

The percent of land in each county in Oregon State suitable for hybrid poplar plantations with irrigation, with limited irrigation, without irrigation and land not suitable or eligible for hybrid poplar. Counties are listed with their total acres of suitable land, and are listed from the top by county with the most suitable land to the least.



Oregon counties and percent of eligible hybrid poplar plantation land that has 10-20cm/m of available soil moisture and >20cm/m.

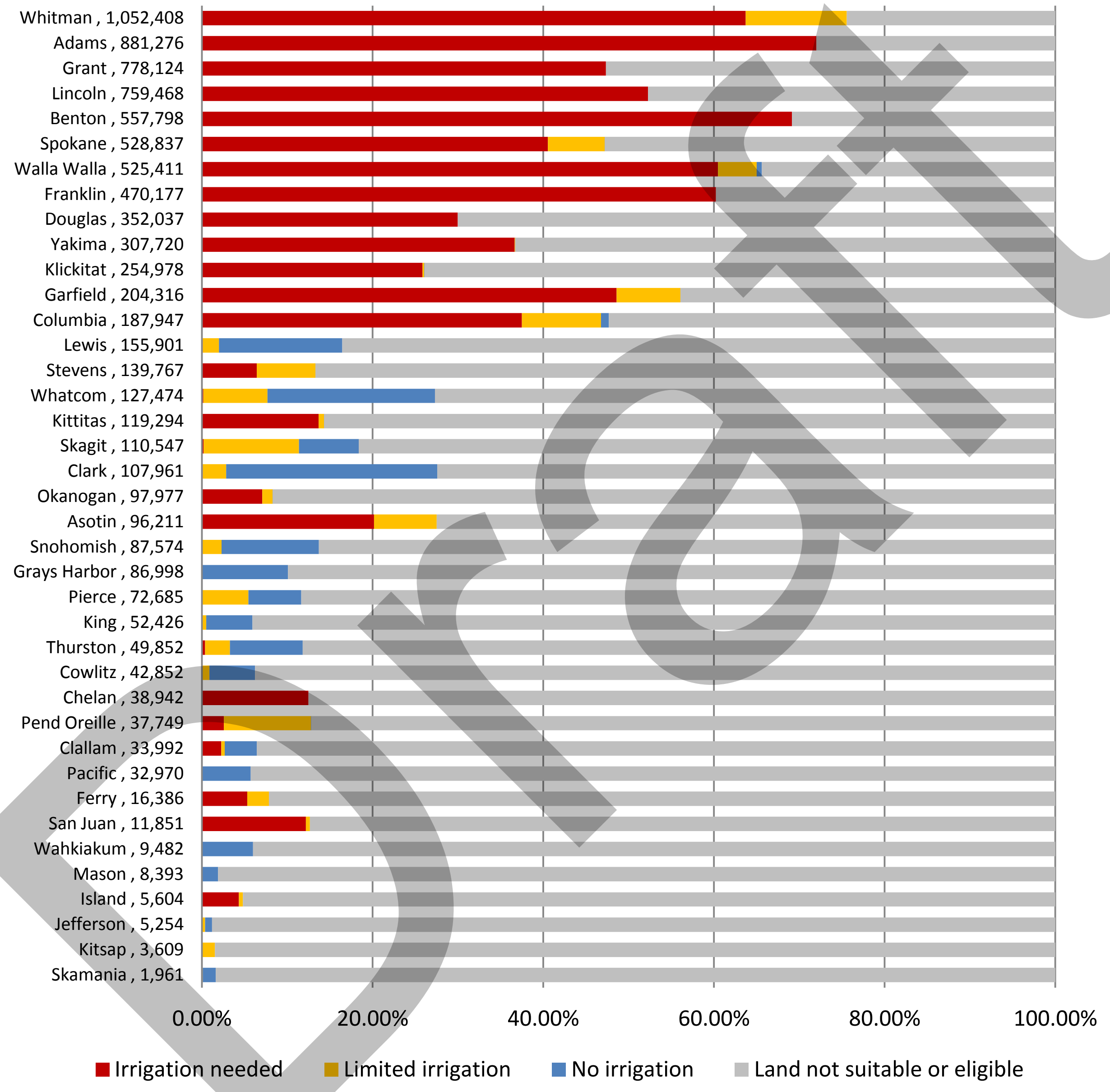


Washington

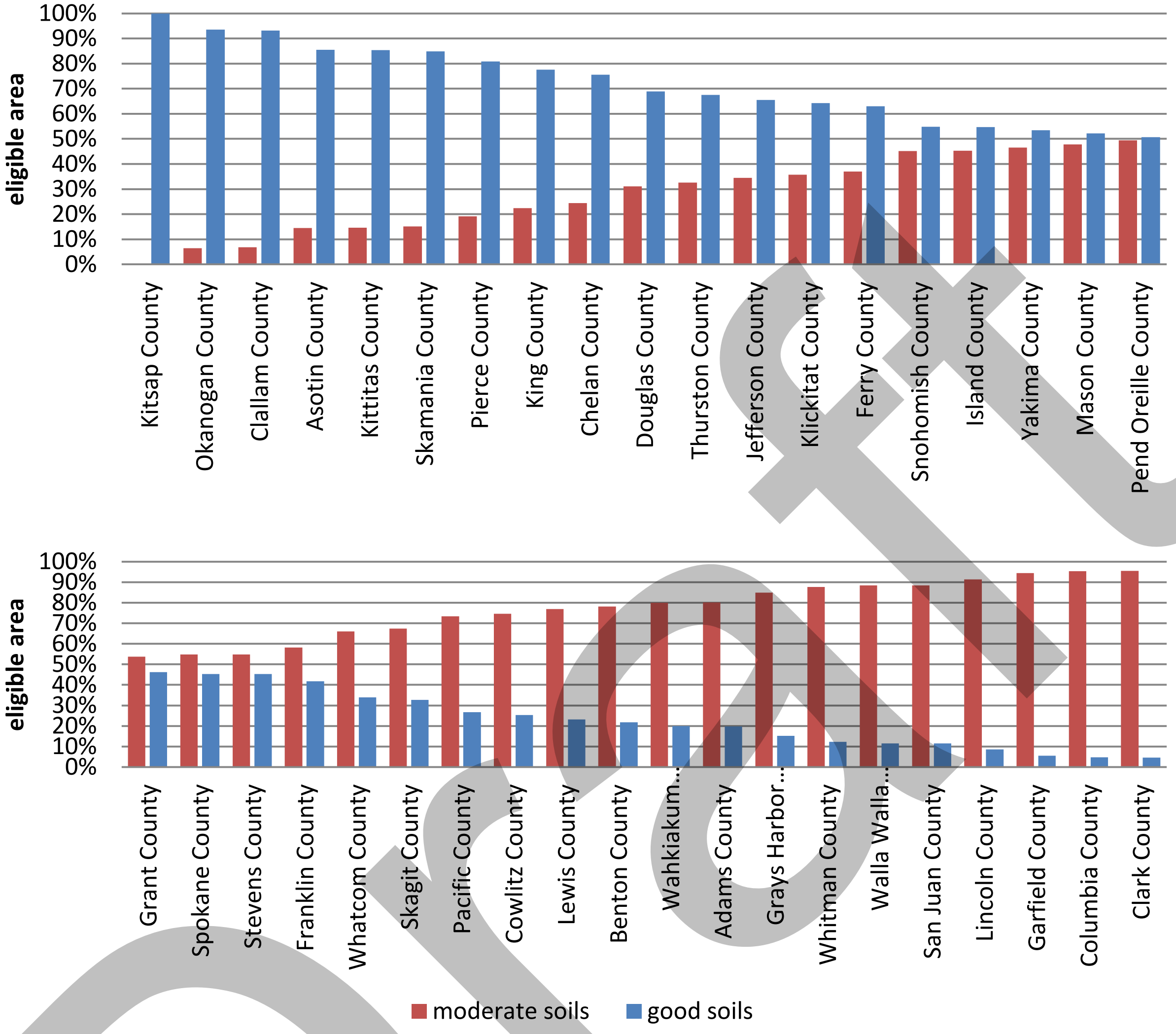
For each county in Washington: the total county area in acres and total area in acres for different suitability classes defined by irrigation need and soil quality. Counties are listed from the top starting with the county that has the most total suitable area and ending with the least.

County	Total county area (ac)	Irrigation needed		limited irrigation		No irrigation	
		mod. soil	good soil	mod. soil	good soil	mod. soil	good soil
Whitman	1,394,249	805,702	82,858	163,787	1,675		
Adams	1,240,927	710,019	171,707				
Grant	1,787,544	417,863	360,655				
Lincoln	1,491,771	707,674	50,729				
Benton	1,118,059	427,992	130,037				
Spokane	1,147,277	242,217	211,170	52,872	21,953		5
Walla Walla	824,831	424,251	59,482	29,989	6,442	4,806	
Franklin	815,241	275,033	196,850				
Douglas	1,177,818	113,614	238,313				
Yakima	2,770,153	171,027	135,906	40	445	5	5
Klickitat	1,197,490	78,492	174,929	682	1,100	262	121
Garfield	460,833	174,213	2,765	19,517	7,675		
Columbia	554,868	140,482	7,347	36,370	17	3,605	15
Lewis	1,559,867	934	190	12,516	5,288	120,899	16,159
Stevens	1,625,069	48,117	19,611	37,158	34,865		5
Whatcom	1,372,249	731	25	34,259	853	81,959	9,657
Kittitas	1,491,040	23,898	89,980		5,382		126
Skagit	1,128,240	1,137		66,156	1,035	23,295	18,862
Clark	406,676	361		10,220	618	93,590	3,287
Okanogan	3,384,970	16,509	67,113		14,283		37
Asotin	410,151	2,908	67,750	6,845	18,756		
Snohomish	1,342,363	343	156	11,360	2,891	33,632	39,347
Grays Harbor	1,222,223					78,789	8,187
Pierce	1,077,276		410	6,716	26,673	5,323	33,602
King	1,408,057	15	44	4,186	77	13,003	35,075
Thurston	471,088	756	741	1,493	10,922	8,389	27,568
Cowlitz	732,014	269		5,187	447	30,496	6,338
Chelan	1,912,921	27,254	11,614				
Pend Oreille	904,984	5,810	1,727	14,918	14,982		131
Clallam	1,132,794	82	12,064	1,275	880	1,171	18,640
Pacific	592,068					24,736	8,318
Ferry	1,450,098	8,342	2,768	3,902	1,384		
San Juan	111,844	11,029	368	269	203		
Wahkiakum	161,625					8,417	1,107
Mason	621,205					6,346	1,955
Island	137,257	2,177	2,886	524			
Jefferson	1,165,425	15		1,638	20	74	3,511
Kitsap	254,420				3,628		
Skamania	1,067,436		10		82	1,463	393

The percent of land in each county in Washington State suitable for hybrid poplar plantations with irrigation, with limited irrigation, without irrigation and land not suitable or eligible for hybrid poplar. Counties are listed with their total acres of suitable land, and are listed from the top by county with the most suitable land to the least.



Washington counties and percent of eligible hybrid poplar plantation land that has moderate (10-20cm/m ASW) and good (>20cm/m ASW) soil conditions



Appendix C – Greenwood Report

See attached: “Lake County Hybrid Poplar Feasibility Study and Carbon Sequestration Opportunities.”

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REGIONAL CHARACTERIZATION FOR THE STATE OF ARIZONA OF RIPARIAN AREAS ARIZONA: POTENTIAL FOR CARBON SEQUESTRATION

Petrova, S., T. Pearson, K. Goslee, and S. Brown

Winrock International

DOE Contract No.: DE-FC26-05NT42593

Contract Period: October 1, 2005 - May 11, 2011

Arnold Schwarzenegger
Governor

REGIONAL CHARACTERIZATION FOR THE STATE OF ARIZONA: POTENTIAL OF RIPARIAN AREAS FOR CARBON SEQUESTRATION

PIER PROJECT REPORT

Prepared For:

California Energy Commission
Public Interest Energy Research Program

Prepared By:

Winrock International

September 2009
CEC-500-2006-XXX

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Commission Work Authorization No. MR-045

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Please cite this report as follows:

Petrova, S., T. Pearson, K. Goslee, and S. Brown . 2009 . *Regional Characterization for the State of Arizona: Potential of Riparian Areas for Carbon Sequestration*. California Energy Commission, PIER. CEC-500-2006-XXX.

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission) conducts public interest research, development, and demonstration (RD&D) projects to benefit the electricity and natural gas ratepayers in California. The Energy Commission awards up to $62 million annually in electricity-related RD&D, and up to $12 million annually for natural gas RD&D.

The PIER program strives to conduct the most promising public interest energy research by partnering with RD&D organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration

Regional Characterization for the State of Arizona: Potential of Riparian Areas for Carbon Sequestration is a final report for the West Coast Regional Carbon Sequestration Partnership – Phase II (contract number 500-02-004, work authorization number MR-06-03L. The information from this project contributes to PIER’s Energy-Related Environmental Research program.

For more information on the PIER Program, please visit the Energy Commission’s Web site at www.energy.ca.gov/pier or contact the Energy Commission at (916) 654-5164.

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Abstract

In Arizona, riparian areas are important because of the limited amount of water and rapid population growth, that leads to the need for better management of riparian areas. We use PATHDISTANCE spatial model, incorporating rivers, water bodies, slope and elevation to model the extent of potential riparian areas in Arizona. We examined the geophysical potential of landform, rock formation and soil type factors for four native riparian woody vegetation types: cottonwood/willow, conifer/oak, mesquite and mixed broadleaf. To identify the suitable area for afforestation with these native riparian tree species, we analyzed the geophysical potential across the shrub/scrub land cover class (NLCD 2001) for three elevation strata. Total area identified for afforestation was estimated per native riparian tree species and potential carbon sequestration for 20, 40 and 80 year periods was estimated based on field carbon data collected along the Lower Colorado River. The analysis showed that area suitable for afforestation with conifer/oak could sequester more than 4 million t CO_2e after 80 years, while riparian areas suitable for growing cottonwood /willow, mesquite and mixed broadleaf species have greater sequestration capacity - 97 million, 98 million and 89 million CO_2e, respectively, after 80 years.

Keywords: Arizona, riparian areas, carbon, carbon sequestration

Executive Summary

Introduction

Riparian areas are a small portion of the Arizona landscape, but need proper management and restoration to provide their vital functions. Restoring the extent of the riparian forest could result not only in converting these areas into carbon sinks, but also improving the vital functions of riparian ecosystems. According to BIO-WEST (2006) approximately 400-450 thousand acres of riparian vegetation were historically estimated to exist in the Lower Colorado River between Fort Mohave and Fort Yuma, while currently riparian vegetation in this section of the river sums to approximately 89 thousand acres. In Arizona, riparian areas are important because of the limited amount of water and rapid population growth, which leads to the need for better management of riparian areas.

Purpose

The spatial analysis presented in this report aims to identify riparian areas that could reforested or afforested (termed in this report as forestation) and serve as potential carbon sequestration projects. For this purpose we model the potential riparian areas that could be used for forestation and estimate the potential carbon benefits from tree planting in identified riparian areas.

A spatial analysis of potential riparian area that could sequester carbon through forestation with native riparian woody species was conducted through the following steps:

- Modeling the extent of potential riparian areas.
- Defining geophysical potential for native woody riparian vegetation.
- Identifying opportunities for carbon sequestration through forestation with native woody vegetation within the potential riparian areas.

Project Outcomes

We used a modeling approach (PATHDISTANCE) incorporating river and water bodies as well as elevation and slope to model the extent of the riparian areas. This model resulted in predicting the potential riparian area in natural shapes rather than creating buffers around the rivers. The total modeled riparian area was estimated at 3 million acres (1.2 million ha), which is approximately 4% of the total area of Arizona. The results showed that Yuma, La Paz and Pinal County have the largest extent of potential riparian area as a percent of the total county area – 10%, 9% and 9%, respectively.

For this analysis, four riparian woody vegetation types were considered: cottonwood/willow, conifer/oak, mesquite and mixed broadleaf. We calculated the distribution of these four vegetation types across landform, rock formation and soil type classes. We created landform, geology and soil factor maps based on the percent distribution of each native woody vegetation type per landform, geology and soil class. Then we combined all factor maps using weighted averages to create a single geophysical potential map for each native woody vegetation type. We analyzed the geophysical potential scores for conifer/oak, cottonwood/willow, mesquite and mixed broadleaf on shrub/scrub land cover category across the tree elevation strata – (1) less than 3280 ft (1000 m), (2) between 3288 and 6560 ft (1000-2000 m) and (3) greater than 6560 ft (2000 m). We refined the area available for forestation on shrub/scrub riparian land by dividing the geophysical scores for each woody vegetation riparian type into four equal intervals to represent low, moderate, high and very high class of geophysical potential. The results showed that 88% of the total area was suitable for cottonwood/willow, 87% for mesquite, 33% for mixed broadleaf, and just 10% for conifer/oak located on very high geophysical potential class.

Data on carbon stocks in riparian areas in southwest of the US are very sparse, therefore applying standard forest growth rates will lead to overestimations of carbon stocks. Winrock International conducted measurements of mesquite, willow and cottonwood riparian areas along the Lower Colorado River in 2007 (Pearson et al., 2007). Due to the paucity of data at this time we are unable to provide separate carbon accumulation rates for the four proposed woody tree vegetation types: conifer/oak, cottonwood/willow, mesquite and mixed broadleaf.

The total amount of carbon that could be sequestered by forestation of riparian areas with high and very high geophysical potential after three time periods (20, 40, and 80 years) varies by native woody riparian vegetation type (Table ES-1). The analysis showed that areas defined as suitable for forestation with conifer/oak (69 thousand acres) on high and very high geophysical potential classes could sequester more than 4 million t CO_2e after 80 years. Riparian areas identified as suitable for growing cottonwood /willow, mesquite and mixed broadleaf species have a larger potential for carbon sequestration after 80 years, 97 million, 98 million and 89 million CO_2e, respectively.

Table ES-1. Potential riparian area for forestation, carbon accumulation rates, and total carbon sequestration for 20, 40 and 80 year projects.

Native woody riparian vegetation	Potential category	Potential area for forestation (acres)	Carbon sequestration rate (t CO_2e/acre) at age of:			Total carbon sequestration (t CO_2e) after project year (x 1 000)		
			20	40	80	20	40	80
Conifer/oak	High	62,130	46	57	60	2,858	3,541	3,728
	Very High	6,806				313	388	408
Cottonwood/ willow	High	191,864	46	57	60	8,826	10,936	11,512
	Very High	1,432,621				65,901	81,659	85,957
Mesquite	High	210,569	46	57	60	9,686	12,002	12,634
	Very High	1,430,920				65,822	81,562	85,855
Mixed broadleaf	High	1,004,446	46	57	60	46,205	57,253	60,267
	Very High	493,641				22,707	28,138	29,618

Conclusions

The approach used to map the extent of the riparian areas for the state of Arizona is robust because it allows calculating a surface of relative cost of moving from the stream or water source up into the stream valley, accounting for slope and elevation. This method resulted in mapping approximately 3 million acres (1.2 million ha) of riparian areas across the state of Arizona, which accounted for 4 % of the total state area. The result showed that Yuma, La Paz and Pinal County have the largest extent of potential riparian area as a percent of the total county area – 10%, 9% and 9%, respectively, while Greenlee and Gila County have the least extent of potential riparian area as a percent of the total county area - approximately 1%.

The analysis illustrated that approximately 59% of the mapped riparian area was occupied by shrub/scrub according to the NLCD 2001 across the whole range of the geophysical potential scores for the native woody riparian vegetation. Considering equal interval partition of the geophysical potential scores for each of the native woody vegetation, we selected riparian areas currently occupied by shrub/scrub in the high and very high geophysical potential class. The estimation of suitable riparian areas on very high geophysical potential accounted for approximately 1.4 million acres (566 thousand ha) for forestation with cottonwood/willow or mesquite, 500 thousand (202 thousand ha) for forestation with mixed broadleaf trees and only 7 thousand acres (3 thousand ha) for forestation with conifer oak.

Recommendations

The preliminary analysis presented in this report highlighted the needs of further research with an interest in restoration of riparian areas. Further research and analysis is needed particularly in the following areas:

1) Threshold selection of the relative cost surface

More in depth analysis and some empirical data collection are needed to select the correct threshold of the relative cost surface created through PATHDISTANCE. Aerial photographs or high resolution images can be used to develop a relationship between the value of the relative cost surface and the furthest and closest distance of riparian area edge per river class and/or elevation.

2) Collection of empirical data

Additional empirical data should be collected though field work and/or from aerial photographs or high resolution images to develop a relationship between the geophysical potential scores and location of existing native woody vegetation. This will allow for accurate determination of the interval of geophysical potential scores representative of each of the native woody vegetation.

3) Cross discipline analysis

The selection of sites that could be afforested within the identified riparian areas should consider additional functions of riparian forests such as water quality, stream integrity, wildlife habitat, and flood and storm water runoff. Information and data produced for the Arizona statewide freshwater assessment by the Nature Conservancy could be considered when selecting sites for forestation.

It is recommended that these further analysis and data collection are carried out at the county level. As indicated from this analysis, Pima, Navajo and Yavapai counties have the largest estimated areas suitable for forestation cottonwood/willow and mesquite, mixed broadleaf and conifer/oak, respectively and could be good candidates for further analysis.

1.0 Introduction

1.1 Background and Overview

Despite of their small percentage of the landscape, riparian areas provide resources for many ecological functions and multiple land uses. Riparian areas are often productive ecosystems providing resources for wildlife and people.

According to BIO-WEST (2006) approximately 400-450 thousand acres of riparian vegetation were historically estimated to exist in the Lower Colorado River between Fort Mohave and Fort Yuma, while current riparian vegetation in this section of the river sums to approximately 89 thousand acres. In Arizona, riparian areas are important because of the limited amount of water and rapid population growth, which leads to the need for better management of riparian areas.

Some riparian areas are covered by forests; others are covered by brush and grassland, while some are dominated by agriculture and development. In the last few decades many native riparian areas have been destroyed or degraded. Agriculture contributes to the degradation of riparian zones through the building of channels, levee construction and other means of diverting water from reaching the riparian zones.

Riparian areas are a small portion of the landscape, but need proper management and restoration to provide their vital functions. Restoring the extent of the riparian forest could result not only in converting these areas into carbon sinks, but also improving the vital functions of riparian ecosystems.

The high variability of riparian areas through the United States and the many different disciplines (geology, fisheries, hydrology, plant ecology, etc) involved in studying these areas make it difficult for there to be a single unified definition of riparian areas (Zaimes, 2007). Despite the different definitions of riparian areas by various state, national agencies and organizations, Zaines (2007) determined the following common points:

(1) adjacency to a water body and dependency on perennial and intermittent water flow
(2) transitional zone between terrestrial and aquatic ecosystems
(3) linear in nature
(4) lacking clearly defined boundaries

For this report, riparian zones, riparian areas, and riparian buffers are terms used synonymously. However these terms may be defined differently in the literature depending on the applications or agencies in question.

1.2 Project Objectives

The spatial analysis aims to identify riparian areas that could become potential carbon sequestration projects. For this purpose two objectives were identified:

- To identify the potential riparian areas that could be used for forestation

- To estimate the potential carbon benefits from tree planting in identified riparian areas

1.3 Report Organization

Methods or steps taken to date for identifying suitable riparian areas for forestation in Arizona are provided in section 2, and results of this research are summarized in section 3. Section 4 provides conclusions and recommendations for next steps.

2.0 Project Approach, or Methods

Analysis of potential riparian areas for forestation was conducted through the following steps:

- Modeling the extent of potential riparian areas.
- Defining geophysical potential for native woody riparian vegetation.
- Identifying opportunities for carbon sequestration through forestation with native woody vegetation within the potential riparian areas.

2.1 Modeling the extent of potential riparian areas

In this section we examine how to define the area around rivers, streams and lakes that could support riparian vegetation in Arizona.

The majority of literature identified as part of this study referred to establishing a minimum buffer width on either side of rivers and streams in order to facilitate different conservation practices:

- According to the National Resources Conservation Service (NRCS), a minimum width of 15 feet (4.5 m) is needed on either side of streams (Riparian Forest Buffer (Ac.) Code 391.2006). No guidance of maximum width of buffers is provided by this standard, but for increasing carbon storage in biomass and soils maximizing the width and length of the riparian forest buffer is recommended.
- Different regulations for establishing riparian buffers differ not only by state but also by the different riparian use properties and vegetation requirements. According to Wenger (1999), hydrological, soil, topographic and climate factors were considered in assessment of the width of the riparian buffer in Georgia. According to this source, a minimum of 100 feet (30 m) of buffer width is required for effectively catching the sediments and protection of water quality, 50 feet (15 m) buffers are sufficient to provide nitrogen control through plant uptake. Furthermore, riparian forest buffers between 35 and 100 feet (10 and 30 m) are required to protect an aquatic habitat and riparian forest buffers with a width of 300 feet (90 m) are necessary to provide habitat for diverse terrestrial riparian wildlife.
- Based on wildlife habitat protection, the desired width of riparian buffers range from 40 to 600 feet (12 to 180 m) for wildlife and bird species in Connecticut (CRJC,

2001).Mayer et al. 2005 reviewed a number of peer-reviewed studies concerned with the relationship between riparian buffer width and nitrogen removal capacity effectiveness. He reported mean forest buffers of 240 feet (73 m) from the reviewed studies, with minimum of 35 feet (10 m) and maximum of 720 feet (220 m). Federally recommended buffer widths vary from 23 to 328feet (7 to 100 m), which covers the expected width of a buffer for significantly removing nitrogen (Mayes et al. 2006).

- Lee at al. 2004 reviewed provincial, territorial and state guidelines for establishing riparian forest buffer zones in Canada and United States and reported a mean buffer from 50 to 95 feet (15 to 29 m) for different water body types when both countries were combined. Arizona was not included in the results of this paper, because no riparian management guidelines were provided to the authors (Lee et al. 2004).

Instead of rigid buffer widths, an approach of mapping potential riparian areas based on a combination of stream network and topology, used by the Wyoming Gap Analysis Project (Merrill et al. 1996) and by the West Virginia Gap Analysis Project (Stranger et al. 2000), was adopted for this part of the regional characterization of Arizona. This approach was considered more appropriate than the approach of creating buffers with different widths, because it incorporates the topology and results in realistic shapes of riparian areas. The inputs used in this spatial model included (Figure 1):

1. 1:100,000 perennial streams network and lake databases obtained from the Arizona State Land Department, Arizona Land Sources Information System, both published in 1993
2. Digital Elevation Model (DEM) at 30 m resolution , obtained from U.S. Geological Survey DEM data , with filled sinks
3. Percent slope, derived from the DEM data

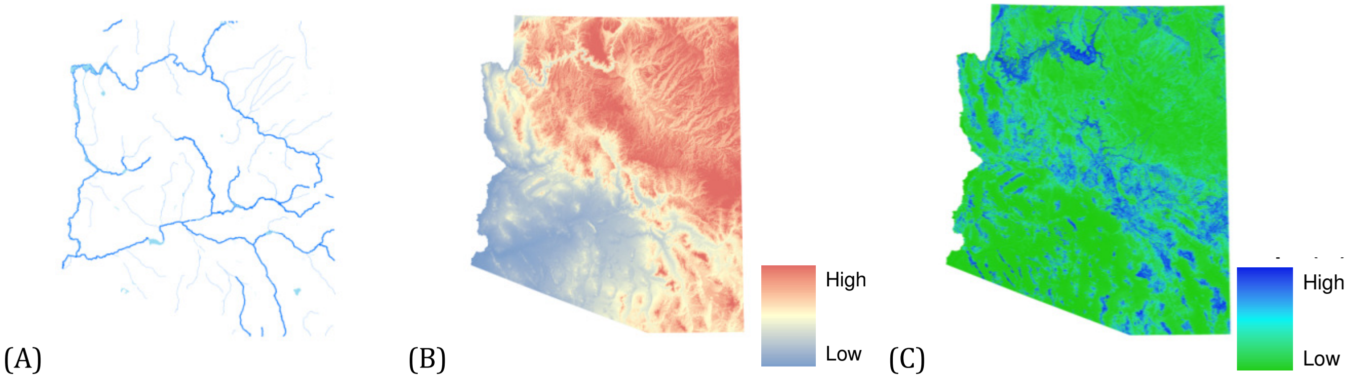

Figure 1. Input datasets for PATHDISTANCE modeling approach of riparian areas: (A) hydrology – rivers and water bodies; (B) elevation data; (C) percent slope.

-*First*, the major rivers and main basin rivers were selected from the statewide dataset of perennial streams. Polygons classified as ephemeral, inundation, lake, reservoir, streams and marsh/swamp in the lake database were separated to represent the water bodies in Arizona.

-*Then*, the PATHDISTANCE module in ArcInfo (ARCGIS 9.3.1) was used separately for each river and water body category to create a surface of the relative cost of traveling upslope from the stream. Elevation data were used in the PATHDISTANCE modeling to calculate more accurately cell–to cell distance.

-The result of the PATHDISTANCE module was a continuous surface with abruptly increasing relative cost for steeper slopes indicating that the higher cost associated with areas further away from river and water bodies and at higher elevation. The areas with high PATHDISTANCE values are less likely to support riparian vegetation and wildlife.

-To determine the extent of potential riparian areas we examined different thresholds for the PATHDISTANCE values and decided on threshold of 1000 for all river and water body categories. Areas with values below the threshold were considered to be reasonable approximations of riparian areas.

-*Finally*, we excluded all water bodies (lakes, reservoirs, etc.) from the delineated areas from the PATHDISTANCE module to determine the final extent of potential riparian areas surrounding perennial rivers and water bodies in Arizona.

2.2 Geophysical potential for riparian woody vegetation

In this section we examine which areas within the identified riparian zones have the potential to support riparian vegetation based on geology, landform and soil type.

In this part of the analysis we used a riparian vegetation dataset obtained from the Arizona State Land Department, Arizona Land Resources Information System (1994). The riparian vegetation types defined by the spatial datasets are reported in Table 1 and shown in Figure 2. Cottonwood/willow, conifer/oak, mesquite and mixed broadleaf were considered to have current native woody tree vegetation cover and were the primary focus of this analysis.

Table 1. Riparian vegetation types in Arizona and their area (acres) and percent of the total area.

Vegetation Class	Riparian veg. type	Area (acres)	Percent (%) of the total
Riparian Tree Cover	Cottonwood/Willow	29,979	18
	Mixed Broadleaf	14,624	9
	Conifer/Oak	4,923	3
	Mesquite	1,108	1
Other Woody Vegetation Cover	Mountain Scrub	58,689	35
	Russian Olive	3,240	2
	Tamarisk	1,204	1
	Strand	54	0
Agriculture	Agriculture	10,368	6
Other Wetland	Wet Meadow	632	0
	Marsh	630	0
Other	Flood Scoured	18,028	11
	Areas not Ground Verified	13,041	6
	Total area of riparian vegetation	**166,521**	**100**

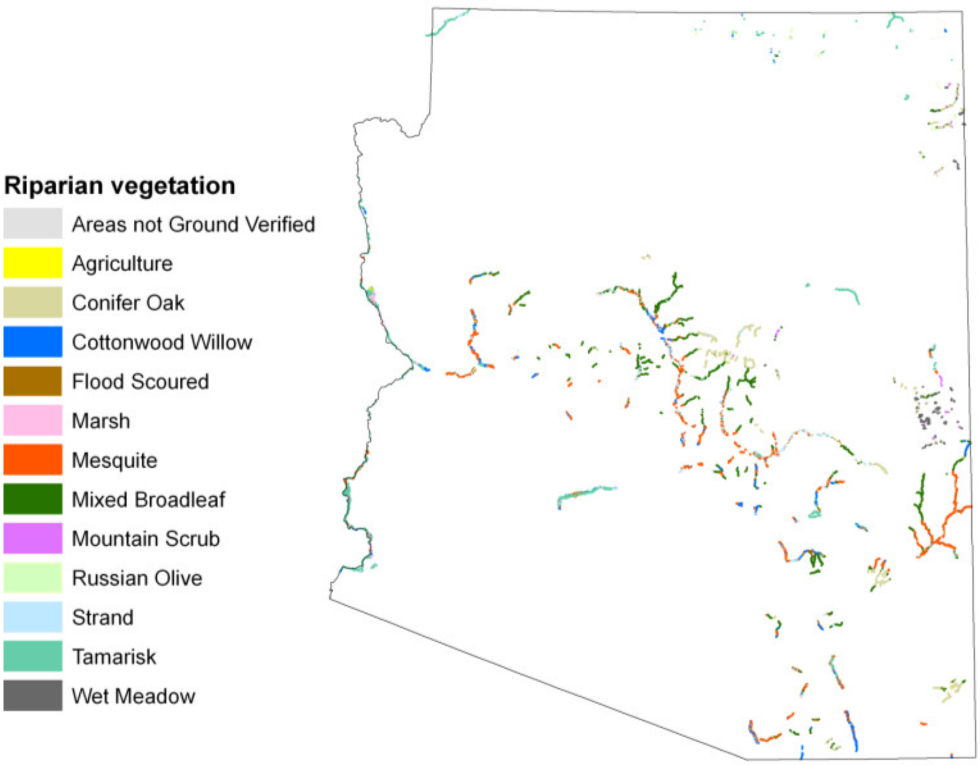

Figure 2. Distribution of riparian vegetation across Arizona according to a dataset obtained from the Arizona State Land Department.

The following databases were used to determine geophysical potential:

1. A digital database of geology for Arizona developed by Hirschberg and Pitts, 2000 (Figure 3) with information on geological formations, i.e. unconsolidated sediments, sedimentary rocks, metasedimentary rocks, intrusive rocks, extrusive rocks, metamorphic rocks, water or ice.
2. A digital dataset of landforms developed by Manis et al. (2001) for Arizona (Figure 4). The landforms dataset defines different landform types based on slope angles and aspects, landform positions, hydrological relationships and microclimatic parameters. Parameters influencing the surface and sub-surface water movement, and evaporative water loss versus water retention within local watershed were considered in the modeling of the landform types.
3. Soil type classes were obtained from the STATSGO2 database developed by the National Cooperative Soil Survey and distributed by the Natural Resources Conservation Service (formerly Soil Conservation Service) of the U.S. Department of Agriculture (Figure 5).

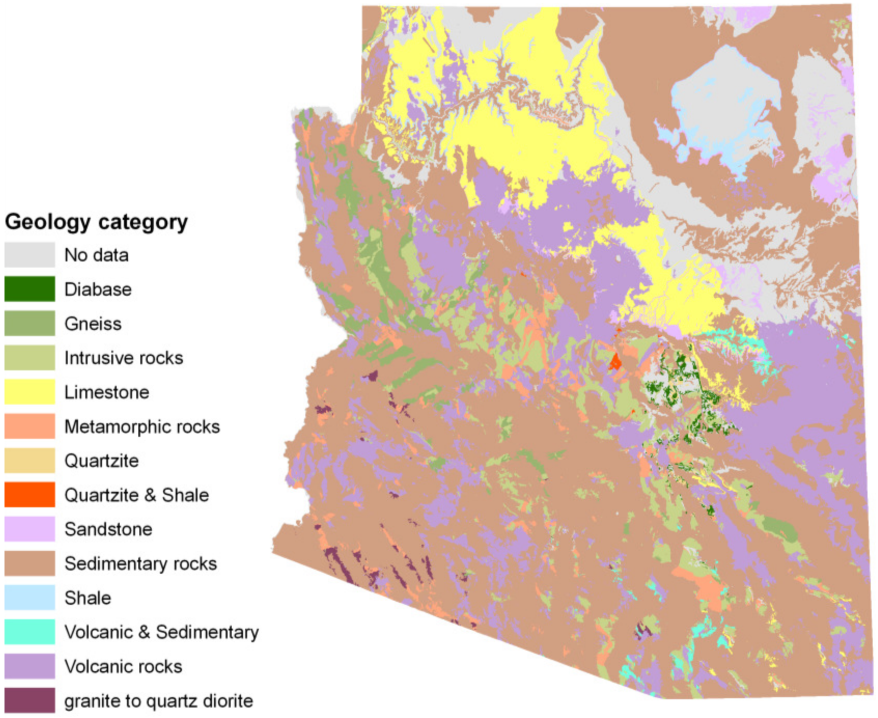

Figure 3. Geological formations across Arizona.

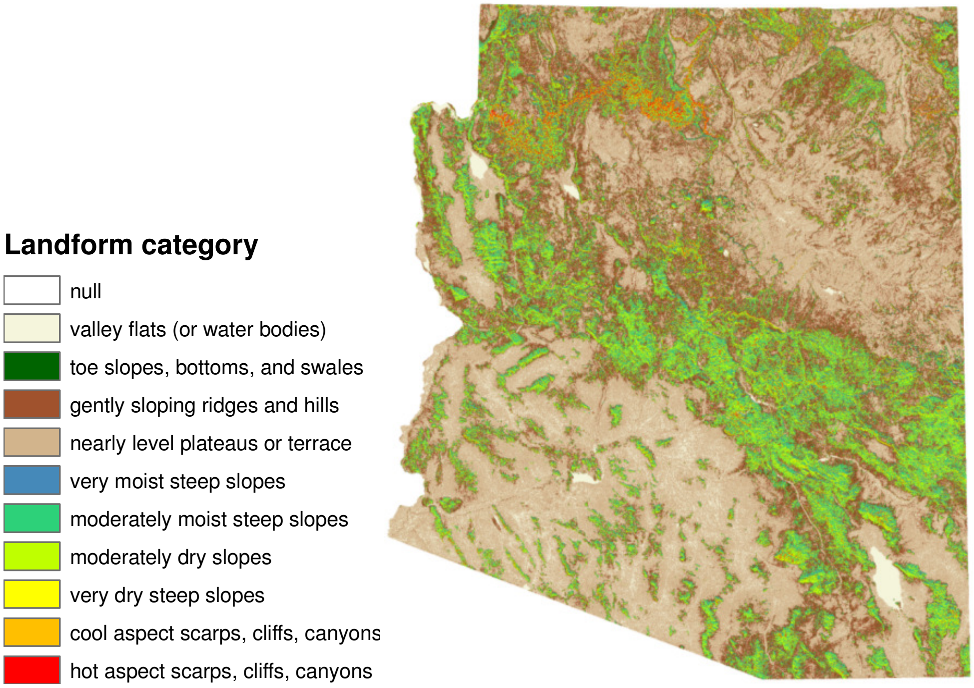

Figure 4. Landform categories across Arizona.

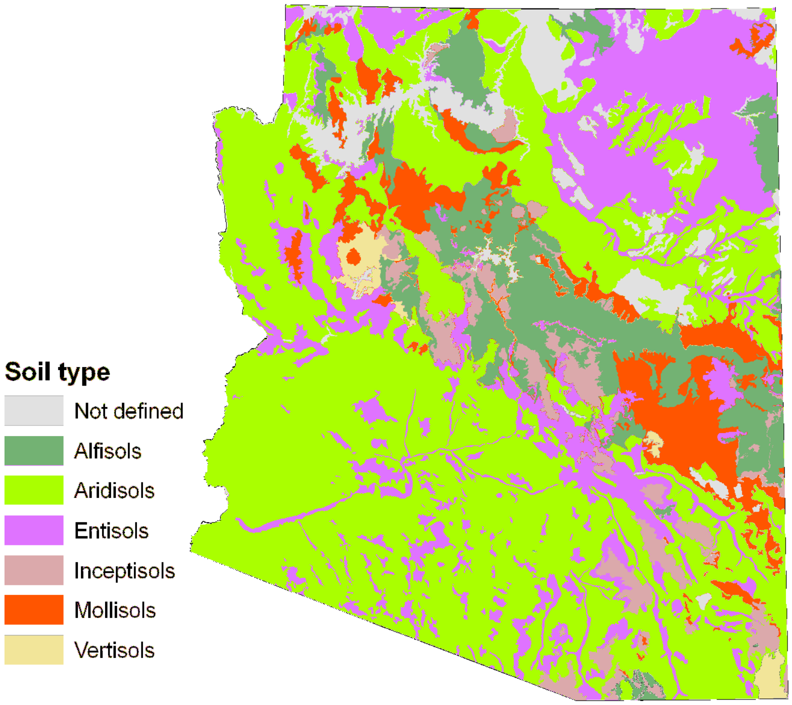

Figure 5. Soil types across Arizona according to STATSGO2 dataset.

For each database the percentage of the native woody tree riparian vegetation type per class/category was used to create a factor map for the modeled riparian areas.

Separate factor maps for geology, landforms and soil type were created for each of the riparian woody vegetation types (cottonwood/willow, conifer/oak, mesquite and mixed broadleaf); these factor maps were combined using a weighted average approach to create a single geophysical potential map for each of the riparian woody vegetation types.

2.3 Identifying opportunities for carbon sequestration through forestation

To identify the opportunities for carbon sequestration through forestation activities, we first identified areas suitable for forestation for each of the woody riparian types and then assigned the associated rates of carbon sequestration for 20, 40 and 80 years. Data on carbon stocks in riparian areas in southwest of the US are very sparse. Applying standard forest growth rates will lead to overestimations of carbon stocks. We used measurements of mesquite, willow and cottonwood riparian areas along the Lower Colorado River in 2007 collected by Winrock International to assign carbon sequestration rates for 20, 40 and 80 years (Pearson et al., 2007). This allowed us to estimate the potential carbon sequestration of a forestation project for these years.

To identify the areas that have potential for forestation we first overlaid the landcover categories from the National Landcover Dataset (NLCD) for 2001 with the potential riparian areas mapped under the first objective of this analysis. With this step we identified potential riparian areas that are occupied by the shrub/scrub category and could be used for forestation activities.

Then, we combined the riparian areas occupied by shrub/scrub with the geophysical potential map for each of the native woody vegetation types. According to Arizona's Riparian Areas web site[1], riparian vegetation can be characterized into three broad ecosystems based on the elevation for the southwestern United States. These three elevation categories are as follows: (1) less than 3280 ft (1000 m), (2) between 3288 and 6560 ft (1000-2000 m) and (3) greater than 6560 ft (2000 m). Therefore, we stratified the geophysical potential scores on shrub/scrubland cover category by elevation categories to refine the extent of areas suitable for sustaining riparian woody vegetation.

Carbon stocks were assigned for woody riparian tree and potential carbon sequestration from forestation of riparian areas was calculated for 20, 40 and 80 years.

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[1] Arizona's Riparian Areas is a module developed by University of Arizona to provide general information for riparian areas of Arizona. More information at http://ag.arizona.edu/extension/riparian/intro.html

3.0 Project Results

3.1. Modeling the extent of potential riparian areas

We used a modeling approach that incorporates river and water bodies as well as elevation and slope to model the extent of the riparian areas. This model resulted in predicting the potential riparian area in natural shapes rather than creating buffers around the rivers. Figure 6 shows the extent of the modeled potential riparian areas in Arizona. The total modeled area was estimated at 3 million acres (1.2 million ha), which is approximately 4% of the total area of Arizona (Figure 6).

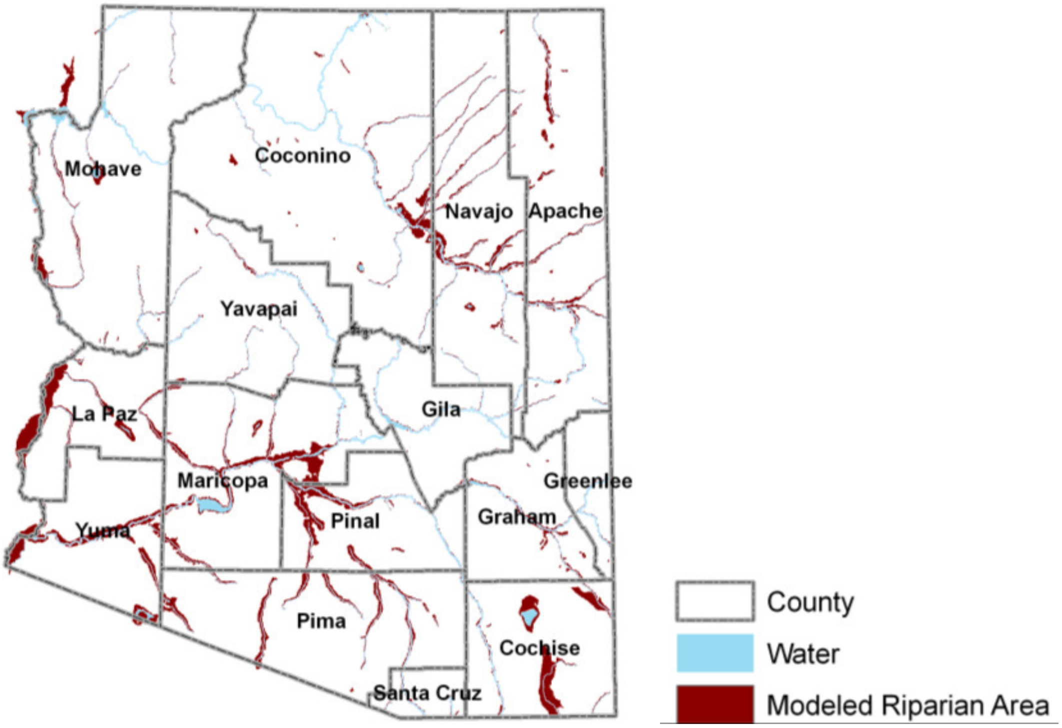


Figure 6. Extent of the potential riparian areas for Arizona modeled with PATHDISTANCE model.

The results showed that Yuma, La Paz and Pinal County have the largest extent of potential riparian area as a percent of the total county area – 10%, 9% and 9% respectively (Table 2). The county of Maricopa resulted in the largest area of potential riparian areas with approximately 450 thousand acres, which accounted for 8% of the total county area. Potential riparian areas for both Greenlee and Gila Counties, accounted for only about 1% of county area.

Table 2. Distribution of the potential riparian area per county and total county area (acres)

County name	County area	Potential riparian area	Percent of the area
	Acres		
Yuma	3,541,487	342,376	10%
La Paz	2,886,287	262,363	9%

Pinal	3,435,172	296,649	9%
Cochise	3,966,683	312,370	8%
Maricopa	5,902,022	448,549	8%
Pima	5,893,335	306,982	5%
Navajo	6,394,555	245,394	4%
Apache	7,161,887	194,347	3%
Graham	2,985,730	76,705	3%
Santa Cruz	796,230	19,140	2%
Mohave	8,634,681	157,628	2%
Coconino	11,932,379	202,261	2%
Yavapai	5,204,838	63,277	1%
Greenlee	1,178,381	11,352	1%
Gila	3,055,321	25,314	1%
Totals	72,968,987	2,964,706	4%

3.2. Geophysical potential for riparian woody vegetation

For this analysis the four riparian woody tree vegetation types were considered: cottonwood/willow, conifer/oak, mesquite and mixed broadleaf. We calculated the distribution of these four vegetation types across landform, rock formation and soil type classes.

3.2.1. Landform

Figure 7 shows the distribution of riparian vegetation types on different landform classes and Table 3 reports specific percentages of native woody vegetation classes within each landform class. For example, cottonwood/willow and mesquite are mostly spread on flat valleys, leveled plateaus or terraces and gently rolling slope ridges and hills, while mixed broadleaf and conifer/oak are common for gently sloping ridges as well as for moderately dry and moderately moist steep slopes.

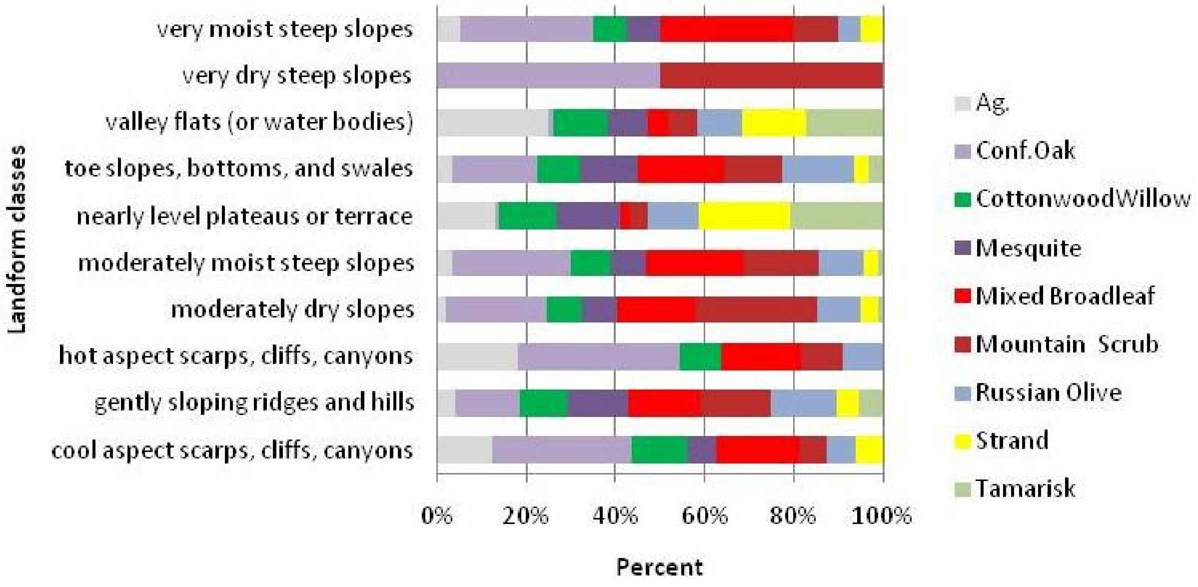


Figure 7. Distribution of riparian vegetation types per landform positional class.

Table 3. Percent of native woody riparian vegetation types per landform class.

Landform positional classes	Confer Oak	Cottonwood/ willow	Mesquite	Mixed Broadleaf
Cool aspect scarps, cliffs, canyons	5%	2%	1%	3%
Gently sloping ridges and hills	22%	16%	21%	24%
Hot aspect scarps, cliffs, canyons	4%	1%	0%	2%
Moderately dry slopes	23%	8%	8%	18%
Moderately moist steep slopes	24%	8%	7%	20%
Nearly level plateaus or terrace	1%	34%	37%	5%
Toe slopes, bottoms, and swales	6%	3%	4%	6%
Valley flats (or water bodies)	2%	24%	18%	9%
Very dry steep slopes	1%	0%	0%	0%
Very moist steep slopes	12%	3%	3%	12%

3.2.2. Rock Formation

The distribution of each vegetation class per rock formation class is shown in Figure 8 and the specific percent of native woody vegetation classes within each landform class is reported in Table 4.

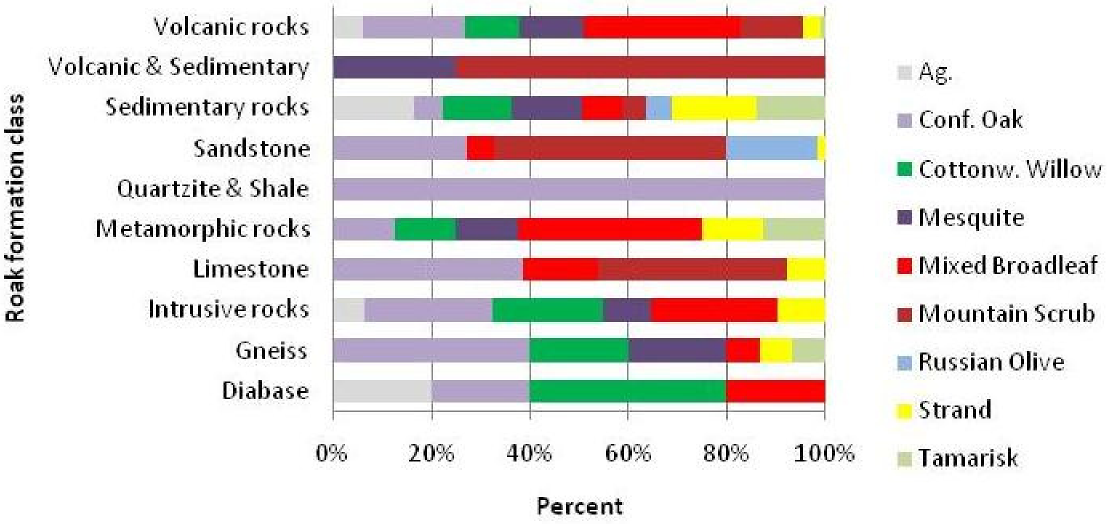


Figure 8. Distribution of riparian vegetation types per rock formation class.

Table 4. Percent of native woody riparian vegetation type per landform (rock formation) class.

Landform class	Confer Oak	Cottonwood Willow	Mesquite	Mixed Broadleaf
Diabase	1%	2%	0%	1%
Gneiss	6%	3%	3%	1%
Intrusive rocks	8%	7%	3%	8%
Limestone	5%	0%	0%	2%
Metamorphic rocks	1%	1%	1%	3%

Quartzite	0%	0%	0%	0%
Quartzite & Shale	1%	0%	0%	0%
Sandstone	19%	0%	0%	4%
Sedimentary rocks	30%	72%	73%	42%
Shale	0%	0%	0%	0%
Volcanic & Sedimentary	0%	0%	1%	0%
Volcanic rocks	24%	13%	15%	37%

3.2.3. Soil Type

The distribution of each vegetation class per soil class is shown in Figure 9 and the specific percent of the native woody vegetation types within each soil type class is reported in Table 5.

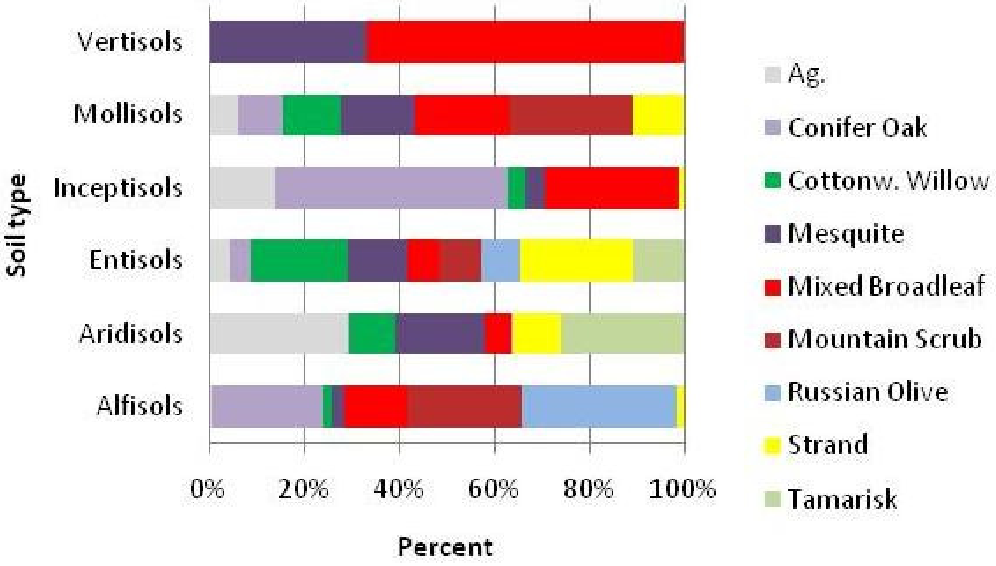


Figure 9. Distribution of riparian vegetation type per soil type.

Table 5. Percent of native woody riparian vegetation per soil type.

Soil Order	Conifer /oak	Cottonwood Willow	Mesquite	Mixed Broadleaf
Alfisols	40%	**3%**	4%	23%
Aridisols	1%	**22%**	44%	13%
Entisols	12%	**57%**	35%	19%
Inceptisols	38%	**3%**	3%	22%
Mollisols	6%	**8%**	10%	13%
Vertisols	0%	**0%**	1%	2%

3.2.4. Geophysical Potential Maps

Percentage information from Table 3, 4 and 5 were used to create landform, geology and soil factor maps, which were combined using weighted averages to create a single geophysical potential map for each native woody vegetation type. Figure 10 shows the geophysical potential map for conifer/oak, cottonwood/willow, mesquite and mixed broadleaf vegetation for area south of Scottsdale, AZ.

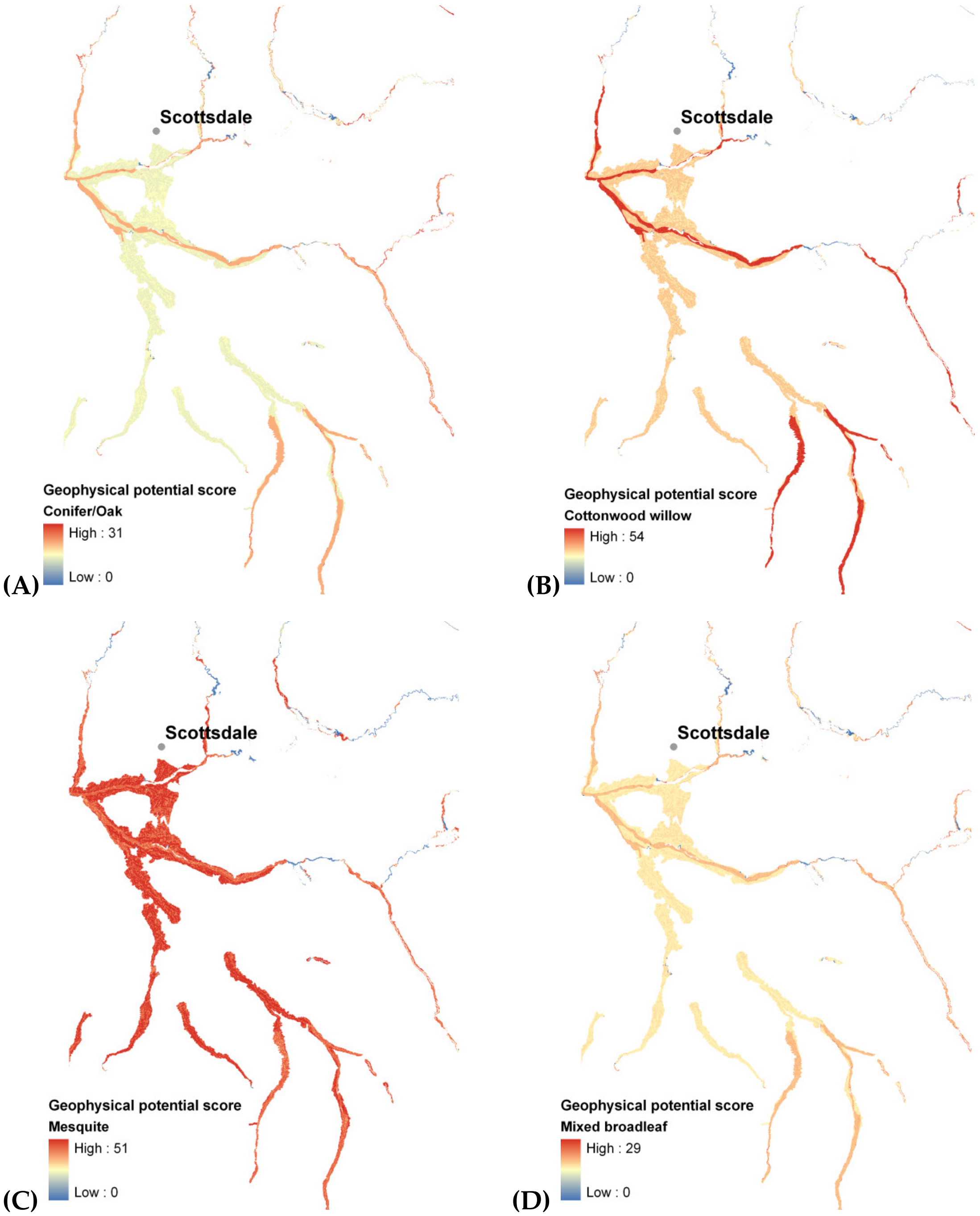


Figure 10. Example of geophysical potential map for (A) conifer/oak, (B) cottonwood/willow, (C) mesquite, and (D) mixed broadleaf vegetation.

3.3. Identifying opportunities for carbon sequestration through forestation

The National Land Cover Dataset (NLCD) for 2001 has a total of 15 categories for the state of Arizona. We aggregated the four developed classes, three forest classes and two wetland classes into developed area, forest and wetland classes, respectively. The distribution of the nine aggregated land cover classes across the modeled potential riparian areas is shown in Figure 11.

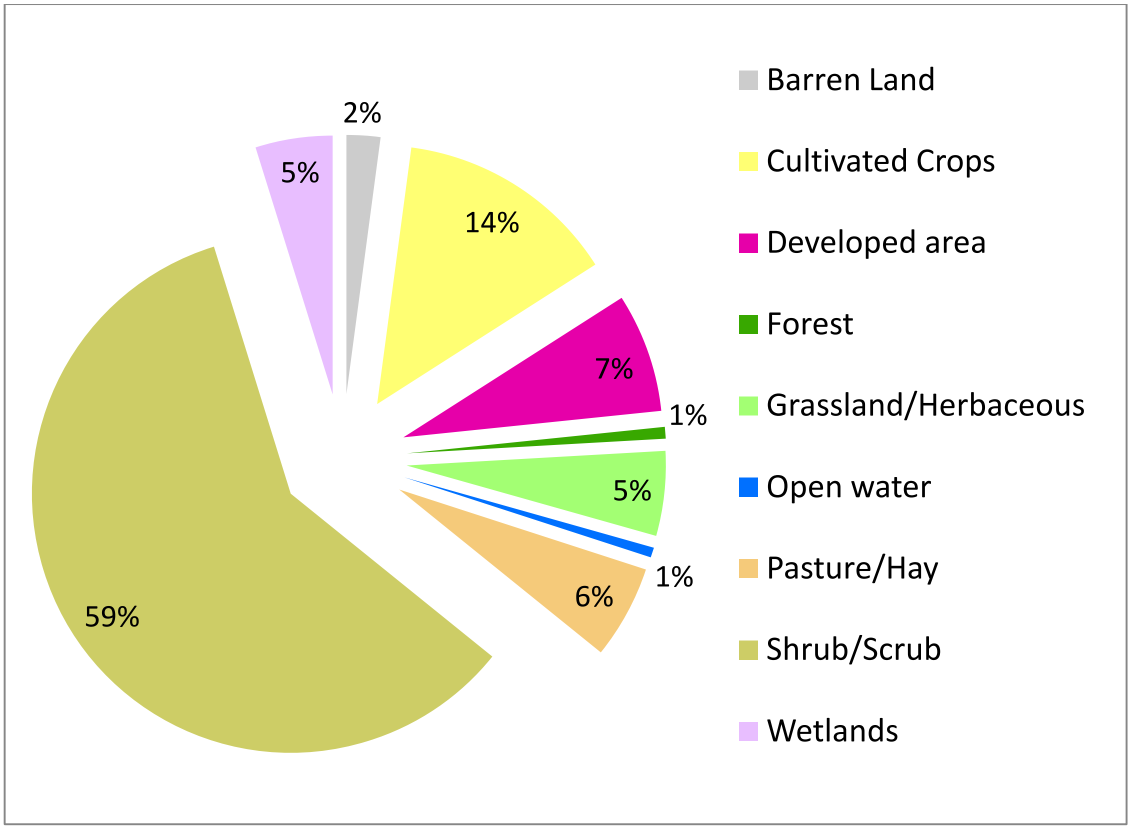
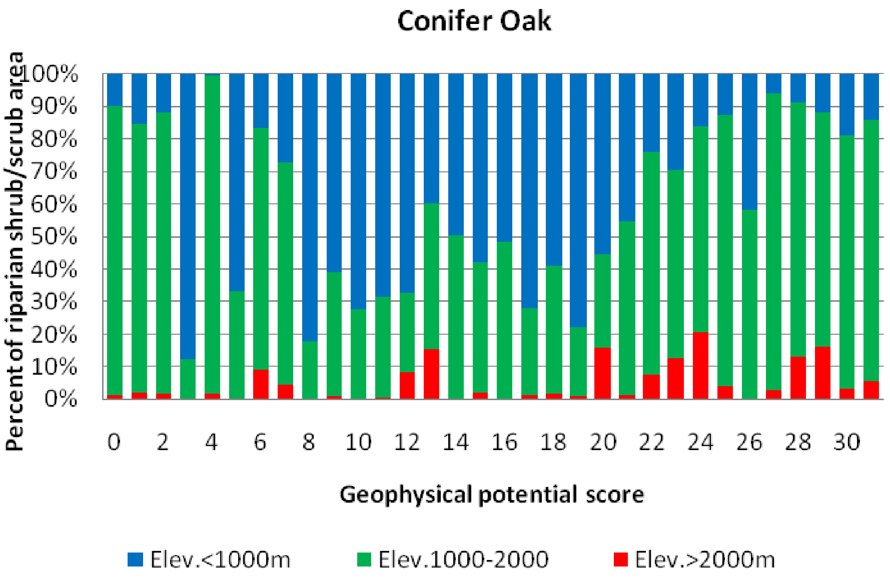
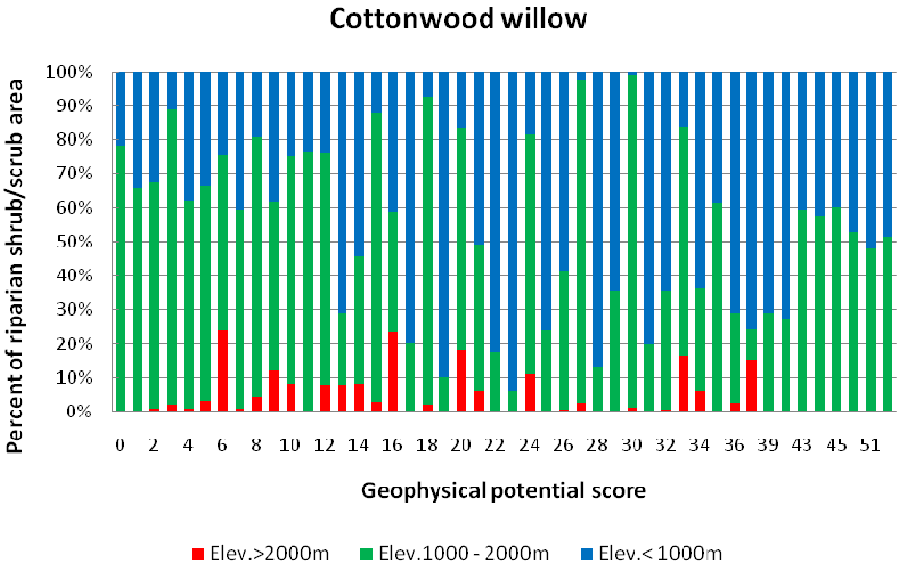


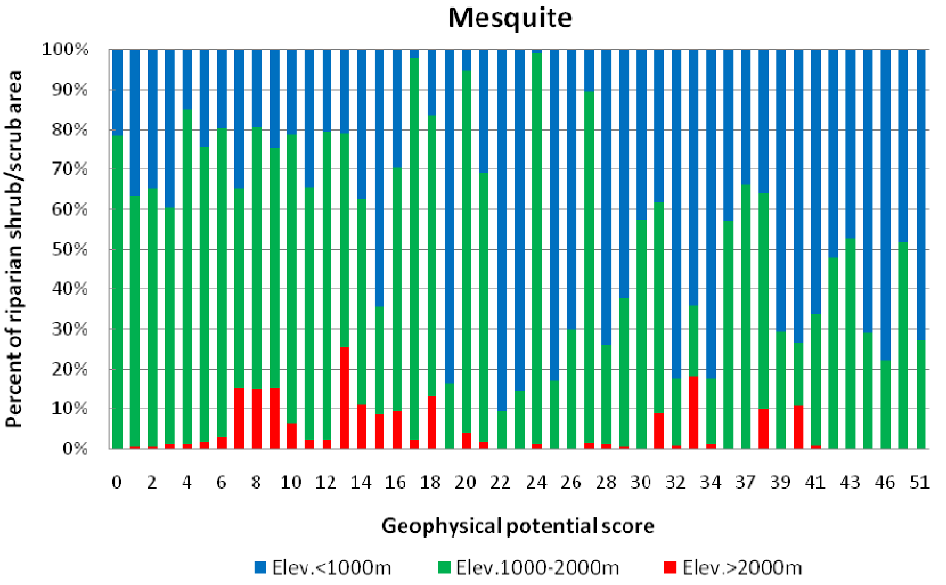
Figure 11. Percent distribution of the aggregated nine land cover classes from NLCD 2001 across modeled potential riparian areas.

The area occupied by shrub/scrub category, representing more than 59% of the modeled potential riparian areas, was extracted as the baseline cover with the greatest economic opportunity for forestation.

Geophysical potential scores for conifer/oak, cottonwood/willow, mesquite and mixed broadleaf on shrub/scrub land cover category were analyzed across the tree elevation strata – (1) less than 3280 ft (1000 m), (2) between 3288 and 6560 ft (1000-2000 m) and (3) greater than 6560 ft (2000 m). Figure 12 reports the percent of area occupied by shrub/scrub land cover category per geophysical likelihood score and per elevation stratum for each of the four native woody riparian vegetation types.


Conifer Oak
Percent of riparian shrub/scrub area
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Geophysical potential score
Elev.<1000m
Elev.1000-2000
Elev.>2000m


Cottonwood willow
Percent of riparian shrub/scrub area
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 39 43 45 51
Geophysical potential score
Elev.>2000m
Elev.1000 - 2000m
Elev.< 1000m



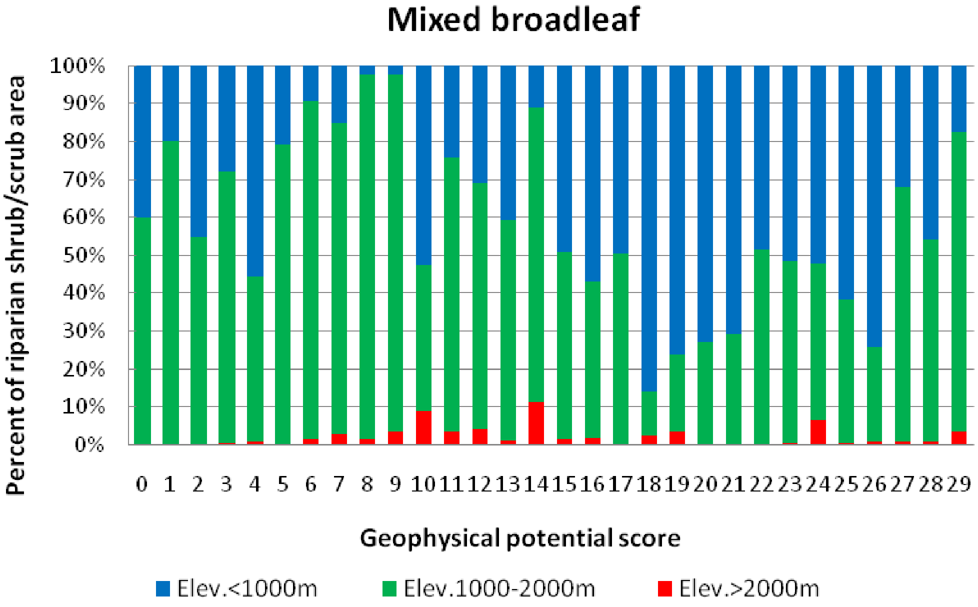


Figure 12. Percent distribution of area occupied by shrub/scrub land cover category across the geophysical likelihood score per elevation strata for (top to bottom) conifer/oak, cottonwood/willow, mesquite and mixed broadleaf.

We refined the area available for forestation on shrub/scrub riparian land by dividing the geophysical scores for each woody vegetation riparian type into four equal intervals to represent low, moderate, high and very high class of geophysical potential. We considered area suitable for forestation with the four woody vegetation riparian types only for the latter two geophysical potential classes (high and very high) per elevation stratum (Table 6).

Total area, on high and very high geophysical potential class, identified for forestation with cottonwood/willow and mesquite trees was estimated to be 1.6 million acres (647 thousand ha), with mixed broadleaf trees was estimated to1.5 million acres (607 thousand ha), and with conifer/oak trees was estimated to 69 thousand acres (27 thousand ha). The results show that 88% of the total area for cottonwood/willow, 87% for mesquite, 33% for mixed broadleaf, and just 10% for conifer/oak are located on very high geophysical potential class.

Table 6. Final riparian area (acres) identified as suitable for forestation with conifer/oak, cottonwood/willow, mesquite and mixed broadleaf woody riparian vegetation types on high and very high geophysical potential.

	Conifer/Oak		**Cottonwood/Willow**		**Mesquite**		**Mixed broadleaf**	
Elevation category	**High Potential**	**Very High Potential**	**High Potential**	**Very High Potential**	**High Potential**	**Very High Potential**	**High Potential**	**Very High Potential**
	Acres							
1000m	34,944	1,012	29,245	928,357	36,785	927,434	716,603	247,504
1000-2000	25,703	5,146	158,818	502,088	170,837	501,639	283,843	244,503
>2000m	1,483	648	3,801	2,176	2,947	1,847	4,000	1,633
Totals per class	62,130	6,806	191,864	1,432,621	210,569	1,430,920	1,004,446	493,641
Grand totals	**68,939**		**1,624,486**		**1,641,490**		**1,498,087**	

Table 7 reports the area identified as suitable for forestation for each of the woody riparian vegetation types per county. Pima County has the largest potential of 249 thousand acres (100 thousand ha) for planting either cottonwood/willow or mesquite, Navajo county has the largest potential of 99 thousand acres (40 thousand ha) for planting mixed broadleaf species, and Yavapai County has the largest potential of 2,000 acres (800 ha) for planting conifer/oak.

Table 7. Very high geophysical potential riparian area (acres) identified for forestation with conifer/oak, cottonwood/willow, mesquite and mixed broadleaf woody riparian vegetation types reported by county.

County Name	Conifer/oak	Cottonwood/willow	Mesquite	Mixed broadleaf
Apache	556	77,468	77,173	70,971
Cochise	63	212,856	212,893	27,262
Coconino	171	27,355	26,606	21,562
Gila	1,360	10,585	10,180	7,694
Graham	93	36,901	36,904	28,332
Greenlee	481	5,984	6,204	6,122
La Paz		99,019	99,031	5,142
Maricopa	54	185,561	184,884	67,617
Mohave		82,728	83,157	9,626
Navajo	1,629	134,637	134,561	**99,338**
Pima		**249,420**	**249,430**	50,496
Pinal		141,157	141,223	40,529
Santa Cruz	335	9,559	9,619	7,487
Yavapai	**2,062**	36,096	35,588	13,097
Yuma		123,225	123,337	38,362

3.4. Potential Carbon Stocks

Thirty-five measurement plots were recorded along the lower Colorado Rivers by the Winrock team (Pearson et al., 2007) and from the data collected for mesquite, willow and cottonwood riparian areas, the growth curve was developed (Figure 13 and Table 8).

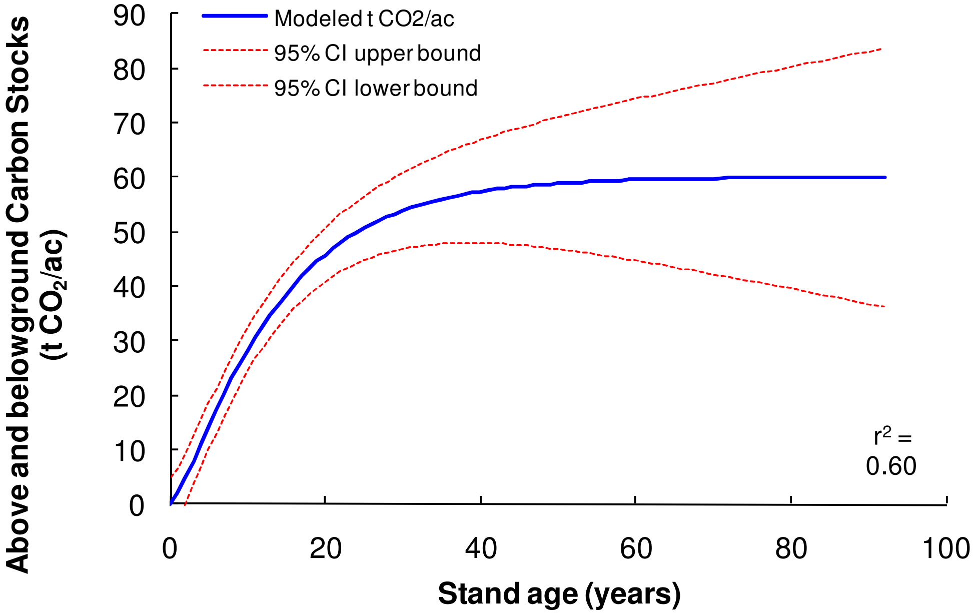


Figure 13. Estimated carbon sequestration for riparian areas in Arizona derived from field measurements along the Lower Colorado River

Table 8. Estimated carbon sequestration for riparian areas in Arizona derived from field measurements along the Lower Colorado River

Years	**Expected Sequestration**		
	t CO_2e/acre		
0	0	+/-	*4.8*
5	14	+/-	*4.2*
10	28	+/-	*4.0*
15	39	+/-	*4.2*
20	46	+/-	*4.9*
25	51	+/-	*5.9*
30	54	+/-	*7.0*
35	56	+/-	*8.2*
40	57	+/-	*9.5*
45	58	+/-	*10.8*
50	59	+/-	*12.1*
55	59	+/-	*13.5*
60	60	+/-	*14.8*
65	60	+/-	*16.2*
70	60	+/-	*18.1*
75	60	+/-	*20.9*
80	60	+/-	*23.7*

Due to the paucity of data at this time we are unable to provide separate carbon accumulation rates for the four proposed woody tree vegetation types: conifer/oak, cottonwood/willow, mesquite and mixed broadleaf. It is likely that the curve used would be conservative for areas with high water availability and particularly for areas dominated by cottonwood.

3.5. Potential Carbon Sequestration Through Forestation of Riparian Areas

The total amount of carbon that could be sequestered by forestation of riparian areas with high and very high geophysical potential at all three time periods varies by native woody riparian vegetation type (Table 9). The analysis showed that areas defined as suitable for forestation with conifer/oak (69 thousand acres) on high and very high geophysical potential classes could sequester more than 4 million t CO_2e after 80 years. Riparian areas identified as suitable for growing cottonwood /willow, mesquite and mixed broadleaf species a higher potential to sequester carbon after 80 years, 97 million, 98 million and 89 million CO_2e, respectively.

Table 9. Potential riparian area for forestation, carbon accumulation rates, and total carbon sequestration for 20, 40 and 80 years forestation project activity.

Native woody riparian vegetation	Potential category	Potential area for forestation (acres)	Carbon sequestration rate (t CO_2e/acre) at age of:			Total carbon sequestration (t CO_2e) at project year (x 1 000)		
			20	40	80	20	40	80
Conifer/oak	High	62,130	46	57	60	2,858	3,541	3,728
	Very High	6,806				313	388	408
Cottonwood/ willow	High	191,864	46	57	60	8,826	10,936	11,512
	Very High	1,432,621				65,901	81,659	85,957
Mesquite	High	210,569	46	57	60	9,686	12,002	12,634
	Very High	1,430,920				65,822	81,562	85,855
Mixed broadleaf	High	1,004,446	46	57	60	46,205	57,253	60,267
	Very High	493,641				22,707	28,138	29,618

4.0 Conclusions and Recommendations

4.1 Conclusions

The approach used to map the extent of the riparian areas for the state of Arizona is robust because it allows calculating a spatial surface of relative cost of moving from the stream or water source up into the stream valley, accounting for slope and elevation. The relative cost increases abruptly with steeper slope as well as with areas located further from the water source by distance or elevation. These areas may be less likely to support riparian vegetation and wildlife. Using this method, the areas mapped as potential riparian areas have more natural shape. The area mapped as riparian areas is sensitive to selecting the threshold for the relative cost surface. In this analysis we used a threshold of 1000 units of the relative cost.

This method resulted in mapping approximately 3 million acres (1.2 million ha) of riparian areas across the state of Arizona, which accounted for 4% of the total state area. The result showed that Yuma, La Paz and Pinal County have the largest extent of potential riparian area as a percent of the total county area – 10%, 9% and 9% respectively while Greenlee and Gila County have the least extent of potential riparian area as a percent of the total county area - approximately 1%.

In this analysis we used geology, landform and soil type to evaluate the geophysical potential for growing native woody riparian trees such as conifer/oak, cottonwood/willow, mesquite and mixed broadleaf. The locations of these native woody riparian trees allowed us to calibrate the model and to predict the geophysical potential for the geology, landform and soil type classes across the remained riparian areas. The geophysical potential or likelihood maps in Figure 9 clearly indicate the areas with high values for landform, geology (rock formation) and soil factors.

The analysis illustrated that approximately 59% of the mapped riparian area was occupied by shrub/scrub according to the NLCD 2001 across the whole range of the geophysical potential scores for the native woody riparian vegetation. Considering equal interval class partition of the geophysical potential scores for each of the native woody vegetation, we selected riparian areas currently occupied by shrub/scrub in the high and very high geophysical potential class.
Due to the scarcity of carbon data for these native riparian tree species we used previously collected carbon data of mesquite, willow and cottonwood riparian areas along the Lower Colorado River in 2007 (Pearson et al., 2007) to estimate the carbon rate at 20 , 40 and 80 years. The analysis identified that approximately 1.4 million acres (566 thousand ha) are suitable for forestation with cottonwood/willow or mesquite, which potential for sequestering 97 and 98 million t CO_2e, respectively after 80 years. Area suitable for forestation with mixed broadleaf species was estimated at 500 thousand acres (202 thousand ha) with carbon sequestration potential of 89 million t CO_2e after 80 years, while the area suitable for forestation with conifer/oak was estimated at only 7 thousand acres (3 thousand ha), resulting in potential carbon sequestration of only 4 million t CO_2e after 80 years.

4.2 Recommendations

The preliminary analysis presented in this report highlighted the needs of further research with regarding restoration of riparian areas. Further research and analysis is needed particularly in the following areas:

4.2.1. Threshold selection of the relative cost surface

More in depth analysis and empirical data collection are needed to help select the correct threshold of the relative cost surface created through PATHDISTANCE. The current analysis considered only one value threshold for identifying the extent of the riparian areas, while in reality different values of threshold of the relative cost could be needed for mapping precisely the extent of the riparian areas. Aerial photographs or high resolution images can be used to develop a relationship between the value of the relative cost surface and the furthest and closest distance of riparian area edge per river class and/or elevation.

4.2.2. Collection of empirical data

The current analysis used equal interval to separate geophysical potential scores into low, moderate, high and very high classes. Additional empirical data should be collected though field work and/or from aerial photograph or high resolution images to develop a relationship between the geophysical potential scores and location of existing native woody vegetation. This will allow for accurate determination of the interval of geophysical potential scores representative for each of the native woody vegetation. The riparian vegetation data used in this analysis did not provided enough information to develop such relationship.

4.2.3. Cross discipline analysis

Forestation of the identified riparian areas will function not only as a carbon sink, but will be important in preserving water quality, maintaining stream integrity, providing wildlife habitat, and controlling flood and storm water runoff. Therefore, the selection of sites that could be afforested within the identified riparian areas should consider all these additional functions of riparian forest. For example, information and data produced by the Arizona statewide freshwater assessment by the Nature Conservancy could be considered when selecting sites for forestation.

Based on the funds available, it is recommended that these further analysis and data collection are carried out at county level. As indicated from this analysis Pima, Navajo and Yavapai counties have the largest estimated areas suitable for forestation with cottonwood/willow and mesquite, mixed broadleaf and conifer/oak, respectively and could be a good candidate for further analysis.

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BASELINE GREENHOUSE GAS EMISSIONS AND REMOVALS FOR FOREST AND AGRICULTURAL LANDS IN ARIZONA

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DOE Contract No.: DE-FC26-05NT42593

Contract Period: October 1, 2005 - May 11, 2011

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Abstract

The project described in *Baseline Greenhouse Gas Emissions and Removals for Forest and Agricultural Lands in Arizona* sought to quantify the baseline of changes in carbon stocks on forest and agricultural lands in Arizona for the 1990s. These baselines provide an estimate of the emissions and removals of greenhouse gases attributable to changes in the use and management of land and are useful for identifying where major opportunities could exist in Arizona for enhancing carbon stocks and/or reducing carbon sources to potentially reduce greenhouse gas emissions.

The analysis revealed that forests were responsible for a net removal of carbon dioxide from the atmosphere of 0.9 million metric tons of carbon dioxide per year (MMTCO$_2$/yr) between 1987 and 1997, and that agricultural lands were responsible for a net emission of 0.04 MMTCO$_2$/yr. On non-federal lands emissions from forests caused by development were estimated at 0.0145–0.0152 MMTCO$_2$/yr, and between 1990 and 1996 154,000 acres of forest and rangeland were burned by fires with an estimated emission of 0.47 MMTCO$_2$eq/yr. Nitrous oxide (N$_2$O) and methane (CH$_4$) emissions (in CO$_2$ eq) from agricultural lands are more than 100 times higher than carbon emission due to land-use change.

Keywords: Carbon sequestration, carbon storage, carbon dioxide, greenhouse gas, emissions, forest fire, agriculture, Arizona, WESTCARB, Regional Carbon Sequestration Partnership

Executive Summary

Introduction

This study is one of a series of carbon sequestration research projects conducted by the West Coast Regional Carbon Sequestration Partnership (WESTCARB), which is managed and co-funded by the California Energy Commission.

Purpose

This WESTCARB project derived a baseline of carbon emissions and removals for Arizona's forest and agricultural lands.

Project Objective

This project sought to establish the baseline carbon stocks and changes in stocks for the forest and agricultural sectors in Arizona during the most recent 10-year period for which data are available (generally the 1990s). Such baselines can assist in identifying opportunities where carbon removals (sequestration) in each sector might be increased, or carbon emissions decreased, through changes in land use and management.

Project Outcomes

Baseline for Forest Lands

The forest baseline is separated into three component parts: a general forests baseline, a baseline effect of development, and a baseline effect from fire. The general forests baseline is presented at the state level for all forestlands, based on U.S. Department of Agriculture's Forest Service data, detailing change in forest area and change in carbon stocks, but with no attribution to the causes for the change. Using additional databases, the specific cases of emissions associated with development and emissions associated with fire are further examined.

General Forestlands Baseline

Between 1987 and 1997 there was an estimated increase in Arizona's forest area of 0.5 million acres (ac), or 0.2 million hectares (ha), a mean of 54,000 ac (22,000 ha) per year. This is equivalent to an increase of 9 million metric tons carbon dioxide (CO_2) equivalent ($MMTCO_2e$), or 0.92 $MMTCO_2e$/yr between 1987 and 1997.

The estimated increase in carbon stocks of 0.92 $MMTCO_2e$/yr is substantially lower than the estimated sequestration in soil and forests reported by the Arizona Climate Change Advisory Group of 6.7 $MMTCO_2e$ in 2000. However, some of this divergence can be accounted for by the inclusion of soil carbon sequestration in the Climate Change Advisory Group analysis. In addition, there is some uncertainty on whether the carbon is artificially inflated due to a U.S. Department of Agriculture Forest Service change in forest definition from 10 percent cover to 5 percent cover in the study period.

Baseline Effect of Development on Forest Lands

The baseline for emissions from development was created using land use data from the National Resources Inventory of the United States Department of Agriculture and carbon data derived from the U.S. Department of Agriculture's Forest Service Forest Inventory and Analysis Database for the period 1987 to 1997. Because of data limitations, the analysis is limited to non-federal lands and to the gross CO_2 emissions from aboveground live-tree biomass on conversion of non-federal forestland to developed land uses. Because the focus is on non-federal lands, the analyses should be used only to explore decisions on private lands.

Between 1987 and 1997 3,499 ac (1,416 ha) of non-federal forest in Arizona were converted to development, which is equal to just 350 ac (140 ha) per year. All of this area was located in the north part of the state. For gross carbon emissions, two scenarios were considered. Under Scenario 1 all tree biomass in the converted area was immediately emitted as carbon dioxide. Under Scenario 2, for developed areas of less than 10 ac (4 ha), it was assumed that 50 percent of the carbon was retained in the form of residual trees.

Under Scenario 1 an estimated 152,000 tons of CO_2 equivalent (t CO_2e) were emitted due to development, or 15,200 t CO_2e/yr. Under Scenario 2, 145,000 t CO_2e were emitted, or 14,500 t CO_2e/yr.

These emissions compare with the estimated gross sequestration from forests in Arizona of 0.92 $MMTCO_2$e/yr between 1987 and 1997 and gross emissions for the state of 99 $MMTCO_2$e/yr (from Arizona Climate Change Advisory Group). Emissions from deforestation therefore represent a fraction of a percentage of the total emissions in the state.

Baseline Effect of Fire on Forest Lands

The emissions from fire were examined through overlaying the wildfire database for Arizona on the National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer satellite imagery showing change in normalized differential vegetation index . (The normalized differential vegetation index measures "greenness" of landscapes; greenness decreases immediately after fire). This process determined the location, size, and intensity of fires between 1990 and 1996. Carbon values were applied to these fires using data from the U.S. Forest Service Forest's Forest Inventory and Analysis Database and proportional emissions from the detailed baseline fire analysis for California. The analysis considered all forests and rangelands in Arizona, federal and non-federal.

Across the seven years analyzed, fires with a total area of 1.08 million ac (437,700 ha) were recorded. This is equivalent to 154,000 ac/yr or 62,500 hectares per year (ha/yr). Emissions totaling 904,000 tons of carbon or 3.3 $MMTCO_2$e were estimated to have occurred from fire during the analysis period. This is equivalent to an emission of 0.47 $MMTCO_2$e/yr.

Eighty-five percent of the burned area was on rangelands, but 42 percent of the emissions were from the 15 percent of burned area that was forest. Fire incidence varied by year, with high emissions in 1993 to 1996 (> 168,000 t C) and low emissions between 1991 and 1992 (< 23,000 t C). Fires occurred throughout Arizona during the study period, and there was no apparent geographical relationship between either area burned or carbon emissions from fire and geographic location.

These emissions compare with the estimated gross sequestration from forests in Arizona of 0.92 MMTCO$_2$e/yr between 1987 and 1997 (see above) and gross emissions for the state of 99 MMTCO$_2$e/yr (from Arizona Climate Change Advisory Group). During the analysis period, emissions from fire therefore represented only about 0.5 percent of the state's total emissions.

Baseline for Agricultural Lands

Agricultural land area in Arizona amounts to about 1.5 percent of the total land area. The state lost agricultural land area during 1987–1997 through conversion to other land uses, in particular to urban development/transportation and from retiring agricultural land from cultivation. In some counties, the area of woody cropland actually increased, but these increases were more than offset by decreases in non-woody cropland. Accompanying these losses in area were losses in standing carbon stocks on agricultural land, so that conversion of agricultural land to other uses was responsible for a net annual source (emission) of CO_2 to the atmosphere. Losses of agricultural carbon stocks over the 1987–1997 period were estimated at 99,000 tons. The estimated net annual source from Arizona agricultural lands was 0.04 MMTCO$_2$eq.

Although the primary focus of this report is on emissions of CO_2 from agricultural land conversion, those emissions represent only a portion of the total greenhouse gas emissions attributable to the agricultural sector. The primary non-CO_2 greenhouse gases associated with agricultural activities are nitrous oxide (N_2O) and methane (CH_4). Nitrous oxide (emitted from agricultural soils, especially after fertilizer application) has approximately 296 times the global warming potential of CO_2, and methane (emitted by livestock and through manure management) has approximately 23 times the global warming potential of CO_2. Examination of data from Arizona indicated that GHG emissions from N_2O and CH_4 in the agricultural sector dwarf the annual CO_2 source from agricultural land conversion. In fact, CO_2 emissions from land conversion represented less than 1 percent of the total CO_2 and non-CO_2 greenhouse gas emissions attributable to the agricultural sector.

Conclusions

The authors drew the following general conclusions from this research:

General Forests Baseline

- An estimated 219,000 ha (541,000 ac) of forest on federal and non-federal lands were gained in Arizona between 1987 and 1997 at a rate of 21,935 ha/yr (54,201 ac/yr). These gains are equivalent to 0.28 percent of the forest area per year between 1987 and 1997.
- A gross sequestration of an estimated 9.2 million metric tons CO_2 equivalent (MMTCO$_2$e) occurred between 1987 and 1997 (0.92 MMTCO$_2$e/yr) and 42.7 MMTCO$_2$e (7.1 MMTCO$_2$e/yr) between 1997 and 2003.

- The sequestration rate estimated in a previous study for the State of Arizona in 2000 exceeds the rate predicted in this study, probably due to methodological and terminological differences.
- Carbon sinks could potentially offset as much as 7 percent of Arizona's emissions.
- For just non-federal forested lands, there was a net loss of 69,000 ha (170,000 ac). Ninety percent of the loss in forested area occurs in the northern counties of the state.

Development Baseline

- An estimated 1,416 ha (3,499 ac) were lost to development in Arizona between 1987 and 1997 at a rate of 142 ha (351 ac) per year. This forest loss is equivalent to a gross emission of between 0.145 and 0.152 million metric tons of CO_2 equivalent, or 0.0145 to 0.0152 $MMTCO_2e$ per year. The emissions were exclusively in the north part of the state.
- Emissions from deforestation represent a fraction of a percent of the state's total emissions.

Fire Baseline

- Across the seven years analyzed, researchers recorded fires with a total area of 437,700 ha (1.08 million ac)—equivalent to 62,500 ha/yr or 154,000 ac/yr. Emissions totaling 904,000 tons of carbon or 3.3 $MMTCO_2e$ were estimated to have occurred from fire during that period—equivalent to an emission of 0.47 $MMTCO_2e$/yr.
- Eighty-five percent of the burnt area was on rangelands, but 42 percent of the emissions were from the 15 percent of burned area that was forest. Fire incidence varied by year with high emissions in 1993 to 1996 (> 168,000 t C) and low emissions between 1991 and 1992 (< 23,000 t C).

Agricultural Baseline

- In 1997, agricultural land represented 1.5 percent of the total land area, and non-woody crops were 93 percent of all agricultural land. Both woody and non-woody cropland are concentrated in the southern counties.
- Statewide, there was a loss of agricultural land of 6.6 percent between 1987 and 1997.
- Total carbon stocks in all agricultural land types in Arizona were estimated at 1 million tons. Between 1987 and 1997, there was a total loss of about 99,000 tons of carbon, or 9.4 percent of the carbon stored in agricultural lands in 1987.
- In CO_2 equivalent terms, total agricultural carbon stocks in Arizona in 1997 were 3.5 $MMTCO_2eq$, and the net loss 1987–1997 disregarding non-CO_2 greenhouse gas emissions was 0.4 $MMTCO_2eq$—equivalent to an annual source of 0.04 $MMTCO_2eq$.
- Non-CO_2 greenhouse gas emissions from N_2O (emitted from agricultural soils after fertilizer application) and CH_4 (from livestock and manure management) dwarf the annual CO_2 source from agricultural land conversion in Arizona.

1.0 Introduction and Background Information

1.1. General Approach

This baseline document's purpose is to examine changes in land use and the associated emissions or sequestration of carbon for forest and agricultural lands in the State of Arizona.

Separate baseline analyses are included here for forestlands and agricultural lands. The agricultural land study follows the same principles as the California baseline study (Brown et al. 2004). For forestlands, the California baseline study was based on California-specific interpreted satellite imagery that detailed the scale of change, vegetation type, and cause of change. Because no comparable data is available for Arizona, the research team instead relied predominantly on two national datasets (see Section 1.2). The consequence of using generalized broad-scale datasets is that the outcome is less certain than that achieved for California.

The forest baseline includes a state-level analysis on the change in area and carbon stocks in all forestland, plus a county-level analysis of changes on non-federal forestland. Also included are specific case studies on emissions due to development and fire.

1.2. Datasets Used in the Analysis

Two datasets are used repeatedly through the baseline analyses: the National Resources Inventory (NRI) database and the U.S. Forest Service Forest Inventory and Analysis (FIA) database.

1.2.1. The National Resources Inventory

The National Resources Inventory is conducted by the U.S. Department of Agriculture - National Resources Conservation Service (NRCS). The NRI is a scientifically designed survey of the nation's soil, water, and other related resources with the purpose of assessing conditions and trends. The NRI contains data only on non-federal lands and water bodies. As noted in the Users' Manual (NRCS 2000), the NRI data are useful in developing estimates of natural resource conditions and in conducting geospatial and temporal analyses of these conditions (however, the location of the survey plots is not given in the database). In these baseline analyses, NRI data were used for estimates of area because NRI data is available across the WESTCARB states, wide in coverage, and available for multiple points in time and multiple classes of land use.

Because NRI data come from sample surveys, it is important to have a sufficient sample size for a reliable estimate. The NRI Users' Manual does not recommend that the data be used for county-level analysis because of sample size issues. To be conservative, here analyses are reported at the state level. County-level results are given for illustrative purposes only.

National Resources Inventory analyses are for the time period 1987 to 1997. More recently the NRI has switched to annual reporting, but these data are not yet publicly available.

1.2.2. The Forest Inventory and Analysis Database

Forest biomass was estimated using the U.S. Forest Service Forest Inventory and Analysis database. Following Acts of Congress in 1928 and 1974, the USFS has been systematically collecting data via the FIA on U.S. forests.

The FIA data is composed of a hierarchy of the following nine tables: SURVEY, COUNTY, PLOT, SUBPLOT, CONDITION, TREE, SEEDLING, SITETREE, and BOUNDARY. Examples of plot-level records include: State, County, Plot number, Owner, Forest type, Stand age, Site productivity, and Slope. Examples of tree-level records include: State, County, Plot number, Tree number, Diameter at breast height (DBH), Crown class, Volume, Growth, and Expansion Factors (which allow extension from values per plot to per acre). Diameters are included in the database for all trees with DBH > 1 inch. Creating links between the different hierarchies of the database and utilizing the expansion factors allows the user to explore a variety of topics related to biomass stocks in trees.

In this baseline study, data were downloaded from the FIA website on the scale of individual trees within plots within each county within each state. Using the biomass regressions of Jenkins et al. (2003), DBH was converted to biomass for each tree. Area expansion factors (plot to acre), metric conversions, and summation were used to calculate biomass in metric tons per hectare. In the fire baseline, forests are consolidated by forest type which is a plot-level characteristic.

1.3. Geographical Subdivision of the State

In this forest baseline study, the state was subdivided into two regions. These regions were based on FIA ″units″ but are convenient due to climatic, topographic, and vegetation similarities within units (Table 1-1). Both the forest and agricultural baselines include county-level analyses; counties in Arizona are shown in Figure 1-1.

Table 1-1. Two Arizona regions with the component counties detailed

Region	Counties
Southern	Cochise, Graham, Greenlee, La Paz, Maricopa, Pima, Pinal, Santa Cruz, Yuma
Northern	Apache, Coconino, Gila, Mohave, Navajo, Yavapai

Figure 1-1. Arizona counties

Source: Digital Map Store, http://county-map.digital-topo-maps.com/arizona.shtml

2.0 Baselines for Forestlands in Arizona

2.1. Introduction

This chapter presents a baseline for emissions and sequestration in the forests of Arizona. *Forest* is defined here (as in the FIA and NRI) as land with a greater than 10% stocking of trees.

This chapter is presented in three sections.

Section 2.2 presents a general forest baseline, detailing changes in forest area and in carbon stocks in Arizona's forests with an estimate of annual sequestration/emissions. A state level total is presented for all forests with county level detail only for non-federal lands.

The remaining sections present case studies of individual causes of emissions from forests. These case studies should not be considered as an addition to the general baseline (Section 2.2) but as subsets of it. Emissions from fire or development will have formed part of the total emissions from forests that are presented, or alternatively will have decreased the total estimated sequestration presented from forests.

Section 2.3 presents the case study of emissions caused by development on forestland.

Section 2.4 presents the case study of emissions caused by fire on forestland.

2.2. General Forestlands Baseline

2.2.1. State Level Analysis for all Forestlands

The United States Department of Agriculture (USDA) Forest Service published a baseline for forests in Arizona between 1987 and 1997 (Birdsey and Lewis 2003). Estimates are based on forest inventory data collected by the Forest Service's FIA Unit. Determination of the location of tree measurement plots and changes in land area were assessed using high altitude photography. Where forest inventory was not available, estimates of land use change were derived from the National Resources Inventory.

Between 1987 and 1997, Birdsey and Lewis (2003) estimated a net change in forest area for Arizona from 7.8 million ha in 1987 to 8.1 million hectares in 1997. This is a total gain of 219,345 ha (an increase of 2.8%), which averages out to 21,935 ha/yr (an increase of 0.28%/yr).

Across the state Birdsey and Lewis calculated a mean forest carbon stock density of 42.7 t C/ha in 1987 and 41.9 t C/ha in 1997, or a loss of 0.8 t C/ha over the ten years.

Combining the area data with the carbon density data gives a total stock on forestland in Arizona in 1987 and 1997 and a change in stock between the two dates. The stock in 1987 was estimated as 335 million t C and this grew to 337.6 million t C in 1997. This is equal to a total gain of 2.5 million tons of carbon (a gain of 0.75%), which averages out to 251,700 tons of carbon per year (a gain of 0.075%/yr).

2.2.2. Changes in Forest Area on Private Land

The above section gives the overall picture of changes in area and carbon stocks for the whole state, without any reference to the causes of change. Of particular interest in relation to changes in forest use and management is the potential to conserve significant quantities of carbon in forests under threat for conversion to other uses; particularly development. It is argued that most forest conversion would come from private lands. It is not expected that widespread deforestation is occurring on public lands, though some afforestation may be overlooked. Here is detailed a baseline at the county level for the change in area in privately owned forests in Arizona.

The change in land use associated with forests on Arizona's private lands was analyzed from the NRI. Two dates were used that reported data at the county scale of resolution: the most recent publicly available data for 1997 and for 1987. At the state level all forested land was estimated in 1987 and 1997, as well as the broad destination or origin of land that changed from or to forest in the same time period (Table 2-2-1).

Table 2-2-1. Change in area between 1987 and 1997 for non-federal forestland in Arizona

Area (ha)	Unchanged[1]	Lost to[2]	Gained from[3]
Unchanged	1,644,498		
Development		1,416	
Pasture/Rangeland		102,915	58,803
Farmland/Agriculture			283
Strip mines		23,392	
Other		40	
1987 Total			**1,772,262**
1997 Total			**1,703,585**

[1] *Unchanged* refers to areas remaining forest between 1987 and 1997.
[2] *Lost to* refers to areas lost from forest to other land use categories between 1987 and 1997.
[3] *Gained from* refers to areas becoming forest between 1987 and 1997.

In Arizona, forest area decreased by 68,677 ha in the ten years from 1987 and 1997, or an average of 6,868 ha/yr. Of the total area of forest in 1987, 93.9% remained unchanged as forest ten years later in 1997. There was a loss of 127,764 ha principally to rangeland and to strip mining, and a gain of 59,086 ha back from rangeland. Only 1,416 ha of forest were converted to development (see Section 2.3).

County-Level Changes in Forest Area

National Resources Inventory data is not designed for use at the county level; results are given here for illustrative purposes. Two-thirds of the counties in the State of Arizona contained measured areas of forest. The six most northerly counties (Apache, Coconino, Gila, Mohave, Navajo, and Yavapai), which represent 58% of the area of the state, contained 95% of the forest area. Across the state, 40% of counties experienced a loss in forest area between 1987 and 1997 and 20% gained forest area. Large losses (> 10,000 ha) occurred in Apache, Cochise, Coconino, and Gila counties, while Navajo County gained almost 20,000 ha of forest area (Tables 2-2-2 and 2-2-3).

Table 2-2-2. Area of non-federal forestland in Arizona in 1987 and 1997 and change between the two dates

Area (ha)	County Area (ha)	1987	1997	Change
Apache	2,902,050	706,809	690,782	(16,026)
Cochise	1,597,880	12,384		(12,384)
Coconino	4,821,891	189,238	142,819	(46,419)
Gila	1,234,829	100,608	82,316	(18,292)
Graham	1,198,987	70,782	70,782	-
Greenlee	478,371			-
La Paz	1,165,483	1,052	5,990	4,937
Maricopa	2,383,602			-
Mohave	3,447,699	294,217	293,893	(324)
Navajo	2,577,862	396,363	416,113	19,749
Pima	2,379,232			-
Pinal	1,390,719			-
Santa Cruz	320,546		243	243
Yavapai	2,103,925	809	648	(162)
Yuma	1,428,143			-
TOTAL		**1,772,262**	**1,703,586**	**(68,678)**

Table 2-2-3. Area of non-federal forestland in 1987 and 1997 and change between two dates for two Arizona regions

	Area	(ha)	Change
	1987	1997	Area
Northern	1,688,044	1,626,570	**(61,474)**
Southern	84,218	77,014	**(7,204)**

2.2.3. Conclusions

An estimated 219,000 ha of forest on federal and non-federal lands were gained in Arizona between 1987 and 1997 at a rate of 21,935 ha/yr. These gains are equivalent to 0.28% of the forest area per year between 1987 and 1997.

A gross sequestration of an estimated 9.2 million metric tons CO_2 equivalent (MMTCO$_2$e) occurred between 1987 and 1997 (0.92 MMTCO$_2$e/yr) and 42.7 MMTCO$_2$e (7.1 MMTCO$_2$e/yr) between 1997 and 2003.

This sequestration compares with the estimated sequestration of 6.7 MMTCO$_2$e in soil and forest sinks for the State of Arizona in 2000 (Bailie and Lazarus 2005).

The sequestration rate estimated by Bailie and Lazarus (2005) clearly exceeds the rate predicted here. An explanation could be the inclusion of soil organic carbon sequestration and sequestration in the forest floor and in coarse woody debris in the study of Bailie and Lazarus (2005). Alternatively, it is possible that a change in the definition of forest by the USFS from a cover of 10% to a cover of 5% could have artificially inflated the forest area during the study, artificially elevating the estimated sequestration.

The gross emissions for Arizona (excluding sinks) for the year 2000 were estimated as 99 MMTCO_2e (Bailie and Lazarus 2005). Sinks, therefore, potentially can offset as much as 7% of the state's emissions.

For just non-federal forested lands, there was a net loss of 69,000 ha. Ninety percent of the loss in forested area occurs in the northern counties of the state.

2.3. Development Baseline

2.3.1. General Approach

This section provides a baseline for the emissions of carbon attributable to development of forest lands in Arizona. This analysis should be considered a subset of the general forest baseline: the emissions due to development will form part of wider changes in carbon stocks in the state. If this development analysis is added to the analysis of the general forest baseline, then double counting will occur.

Forest land development is examined only for private lands; it is not expected that widespread development is occurring on public land. Changes in stocks are only changes in aboveground tree biomass, because of uncertainties surrounding both the absolute level of carbon in other carbon pools and whether or not development will cause emissions from these pools.

As in the general forest baseline, changes in forest area due to development were based on NRI data for changes in land use. Carbon stocks and changes in those stocks were derived from FIA data. For the purposes of this study, development includes three NRI categories:

- Urban / 10 acres or larger
- Urban / small built-up (< 10 acres). The category *Urban/small built-up* will be referred to as *small-scale development.*
- Transportation (e.g., roads, airports)

Statistical confidence can only be maintained in results given at the state level, because of the design of the NRI database. Results are given here at the county level merely for illustrative purposes.

2.3.2. Changes in Area at the State and County Level

Between 1987 and 1997, 1,416 ha of non-federal forest were lost in Arizona due to development, or 142 ha per year. The loss over ten years is equivalent to 0.08% of the total forest area present in the state in 1987. Of the total area lost to development, 9% could be considered small-scale development (Table 2-3-1).

Table 2-3-1. Non-federal forest area between 1987 and 1997 in Arizona. Area in hectares.

	Unchanged[1]	Lost to[2]	Gained from[3]
Unchanged	1,644,498		
Development		1,416	
% small scale		9%	
Pasture/Rangeland		102,915	58,803
Farmland/Agriculture			283
Strip Mines		23,392	
Other		40	
1987 Total			**1,772,262**
1997 Total			**1,703,585**

[1] *Unchanged* refers to areas remaining forest between 1987 and 1997.
[2] *Lost to* refers to areas lost from forest to other land use categories between 1987 and 1997.
[3] *Gained from* refers to areas becoming forest between 1987 and 1997.

National Resources Inventory data is not designed for use at the county level; results are given here for illustrative purposes. Losses in non-federal forest area between 1987 and 1997 only occurred in three counties in Arizona (Apache, Coconino, Yavapai), all in the state's northern portion (Figure 2-3-1 and Table 2-3-2). These counties, however, account for 33% of the state's area and 49% of the forested area.

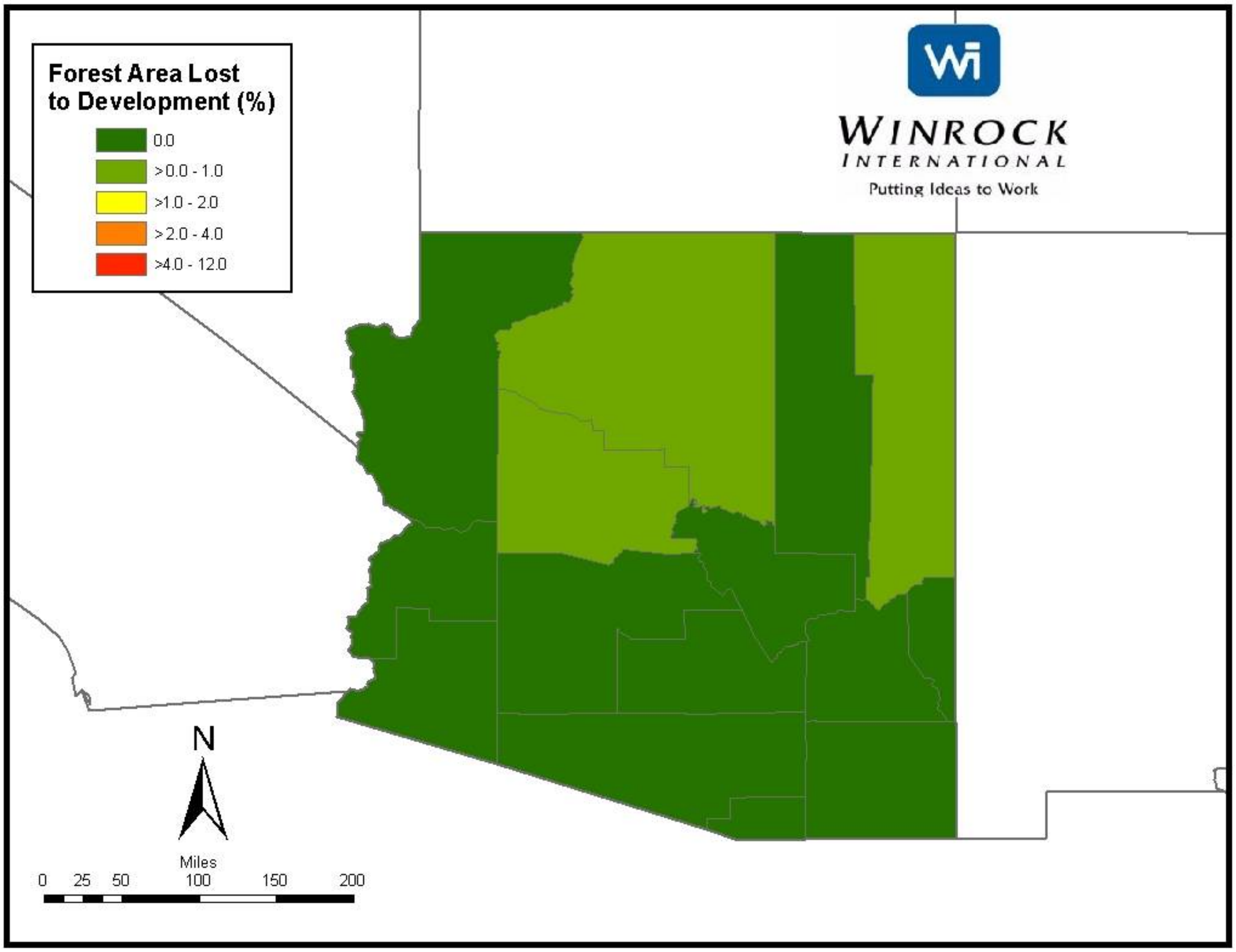

Figure 2-3-1. Loss in non-federal forest area between 1987 and 1997 as a percentage of total non-federal forest area in the county

Table 2-3-2. County-level data on area of non-federal forest in 1997, area of forest lost to development between 1987 and 1997, and % of losses that were small-scale

County	Population	County Area (ha)	Non-Fed Forest area 1997 (ha)	Area Lost to development (ha)	% small scale
Apache	69,423	2,902,050	690,782	121	
Cochise	117,755	1,597,880			
Coconino	116,320	4,821,891	142,819	1,133	11%*
Gila	51,335	1,234,829	82,316	0	
Graham	33,489	1,198,987	70,782	0	
Greenlee	8,547	478,371			
La Paz	19,715	1,165,483	5,990	0	
Maricopa	3,072,149	2,383,602			
Mohave	155,032	3,447,699	293,893	0	
Navajo	97,470	2,577,862	416,113	0	
Pima	843,746	2,379,232			
Pinal	179,727	1,390,719			
Santa Cruz	38,381	320,546	243	0	
Yavapai	167,517	2,103,925	648	162	
Yuma	160,026	1,428,143			
TOTAL			**1,703,586**	**1,416**	9%

*Note: The 11% represents small-scale development for Coconino County; the 9% in the Total represents the percentage of area lost to small-scale development across the state.

2.3.3. Carbon Stocks

Estimates of carbon stocks in live tree biomass were derived from the FIA database. For Arizona, the research team used FIA data from the 2003 inventory because no FIA data exists for dates representing a midpoint of the analysis period 1987–1997, and the previous inventory in 1985 is considered to be rather out of date for this period.

The FIA data were consolidated at the FIA Unit level. Biomass carbon estimates were derived from the measurements of tree DBH for all trees in inventory plots using the allometric equations of Jenkins et al. (2003), scaled up to a per-hectare basis using the plot-area expansion factors (Table 2-3-3).

To be conservative, aboveground tree biomass alone was considered. The rate of emission of carbon stored in roots and soil organic matter is slow and poorly understood, especially when it is considered that some of the developed areas will be capped with concrete. Wood products are also not included, as it is not clear what proportion of the cut trees would be harvested for products, nor what products would be produced (firewood and even paper can be rapidly emitted).

Table 2-3-3. Mean aboveground tree carbon stock (from 2003 FIA data) for each region of Arizona with the number of plots and the confidence interval around the stock estimate

Region	Mean (t C/ha)	95% CI (t C/ha)	# plots	Counties
Southern	18.1	3.31	264	Cochise, Graham, Greenlee, La Paz, Maricopa, Pima, Pinal, Santa Cruz, Yuma
Northern	29.2	2.09	816	Apache, Coconino, Gila, Mohave, Navajo, Yavapai

2.3.4. Carbon Emissions from Development

Two carbon emission scenarios are considered here. In both cases FIA data from federal and non-federal forests are applied to NRI land cover estimates for non-federal forests.

- Scenario 1 assumes that all carbon present on the land in aboveground tree biomass is lost when development occurs.
- Scenario 2 assumes that when small-scale development occurs, a significant proportion of the trees remain during and after the process of development. As examples, these may be trees surrounding residential properties or trees on golf courses. Therefore, in this scenario, the research team assumed that for Transportation and Urban/10 acres or larger, all carbon is lost, but for Urban/small built-up, only 50% of the carbon stocks are emitted.

Emissions discussed here for conversion of forestland to development are gross emissions from aboveground tree biomass only. Total emissions from development over the ten-year period were estimated as 41,300 t C under Scenario 1 and 39,600 t C under Scenario 2. This is equivalent to 4,135 and 3,957 t C per year, respectively. The difference is small because only 9% of the total development change is attributed to small-scale development. Emissions by county are summarized in Figure 2-3-2 and Table 2-3-4.

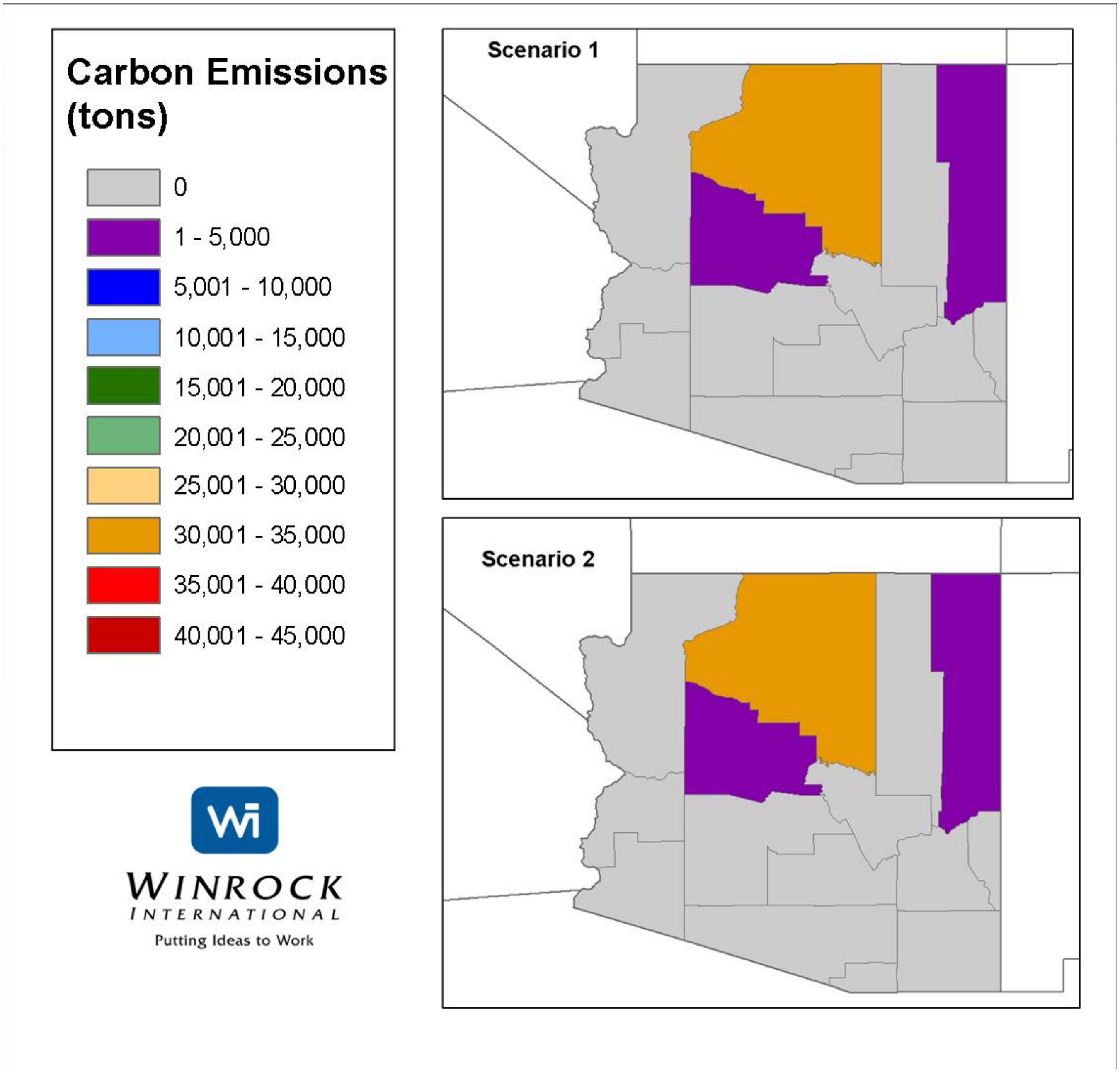

Figure 2-3-2. Carbon emissions under the two scenarios at the county level across Arizona

Table 2-3-4. County-level estimates on the emissions between 1987 and 1997 due to development. Scenario 2 is more conservative, assuming that trees are not clear-cut during small-scale development

County	Population	County Area (ha)	Non-Fed Forest Area 1997 (ha)	Carbon emissions (t C) Scenario 1	Scenario 2
Apache	69,423	2,902,050	690,782	3,544	3544
Cochise	117,755	1,597,880			
Coconino	116,320	4,821,891	142,819	33,077	31,305
Gila	51,335	1,234,829	82,316		
Graham	33,489	1,198,987	70,782		
Greenlee	8,547	478,371			
La Paz	19,715	1,165,483	5,990		
Maricopa	3,072,149	2,383,602			
Mohave	155,032	3,447,699	293,893		
Navajo	97,470	2,577,862	416,113		
Pima	843,746	2,379,232			
Pinal	179,727	1,390,719			
Santa Cruz	38,381	320,546	243		
Yavapai	167,517	2,103,925	648	4,725	4,725
Yuma	160,026	1,428,143			
TOTAL	**5,130,632**	**29,431,219**	**1,703,586**	**41,346**	**39,574**

The carbon emissions as a result of development mirror the loss in forest area. All losses occurred in the northern region of the state (Table 2-3-5). The loss to development over ten years represents less than 0.1% of the total area of forest land in Arizona, and consequently a low level of emissions for a large state.

Table 2-3-5. Region-level summary of loss in area and carbon emissions between 1987 and 1997 due to development. Scenario 2 is more conservative assuming that trees are not clear-cut during small-scale development.

Region	Area lost (ha)	Carbon emissions (t C) Scenario 1	Scenario 2
Southern	0	0	0
Northern	1,416	41,346	39,574

This loss to development is equal to an annual loss in area across the state of just 142 ha with annual CO_2 equivalent emissions of between 14,500 and 15,200 metric tons of CO_2e (Table 2-3-6).

Table 2-3-6. Region-level summary of annual loss in area and carbon dioxide equivalent emissions between 1987 and 1997 due to development. Scenario 2 is more conservative, assuming that trees are not clear-cut during small-scale development.

Region	Annual Area lost (ha/yr)	Annual carbon emissions ($MMTCO_2e/yr$)	
		Scenario 1	Scenario 2
Southern	0	0	0
Northern	142	0.0152	0.0145

2.3.5. Additional Considerations

Emissions discussed here for conversion of forestland to development are gross emissions from aboveground tree biomass only.

Gross versus Net Emissions

The analysis presented above represents gross changes. The only consideration was of emissions from losses of forest to development.

Where gains of forest were made from development (none in Arizona), this was not considered.

The destination of biomass upon development is also not considered. The assumption is made that all carbon is immediately emitted. In reality this is unlikely to be the case. Some of the wood is likely to ultimately become firewood, some will be left to decompose, and some may be used as timber and will have a longer existence as wood products. Regardless, all trees cut for development will ultimately be emitted to the atmosphere as CO_2 or CO_2 equivalents. Instead of including any delay here, it is assumed that the CO_2 is emitted immediately.

Other Carbon Pools

Aboveground tree biomass was the only carbon pool considered in this analysis. The reason behind this decision was the uncertainty involved in other pools generally, and specifically in the case of development.

Soil carbon is particularly uncertain. If the land is capped by concrete it is unlikely that soil carbon will be affected at all. If grasses are planted there is even the possibility that development could lead to an increase in soil carbon.

For similar reasons, roots are also uncertain. The rate at which roots decompose is very poorly known and even less is known about the diminished rate if the roots are buried beneath concrete or tarmac.

Dead wood and litter are likely to be emitted either immediately upon development or through time as decomposition occurs. However, there is no clear relationship between aboveground tree biomass and these pools, and the uncertainty involved with any assumption would be very large.

Non-CO_2 greenhouse gas emissions are also unknown. If site preparation occurs through burning, there will be emissions of methane and nitrous oxide (both potent GHGs). If site preparation involves drainage there will be emissions of methane. Without specific site-by-site information it is not possible to make these estimations.

2.3.6. Conclusions

An estimated 1,416 ha were lost to development in Arizona between 1987 and 1997 at a rate of 142 ha per year. This forest loss is equivalent to a gross emission of between 0.145 and 0.152 million metric tons of CO_2 equivalent, or 0.0145 to 0.0152 $MMTCO_2e$ per year.

The emissions were exclusively in the north part of the state, in the counties of Apache, Coconino, and Yavapai.

These emissions compare with the estimated gross sequestration from forests in Arizona of 0.92 $MMTCO_2e$/yr between 1987 and 1997 (Section 2.2) and gross emissions for the state of 99 $MMTCO_2e$/yr (Bailie and Lazarus 2005). Emissions from deforestation therefore represent a fraction of a percent of the state's total emissions.

2.4. Fire Baseline

In this fire analysis the emissions caused by fire between 1990 and 1996 are estimated. These emissions are part of the general forest baseline (Section 2.2). Without emissions from fire, the general forest baseline would be raised by an amount equal to these emissions.

This baseline, unlike the general forest baseline and the development emissions baseline contains an analysis of rangelands as well as forests.

There are two components to a fire emissions analysis. It is necessary to know both the area that is burnt and the amount of biomass that is volatilized into GHGs per area. Knowledge of these components permits an estimation of total fire-derived emissions.

The period 1990 to 1996 was chosen for this analysis, because these study dates represent the most recent, consistent complete coverage (although a partial dataset exists for 1997–2003). Complete coverage is essential in order to be able to make state-level conclusions on the fire impact.

2.4.1. Methods for Assessing Biomass Volatilized

Background

The effects of fire on carbon stocks are dependent on the intensity of the fire. An intense fire will destroy biomass and release a great proportion of the carbon to the atmosphere, while a less intense fire will even fail to kill the majority of the trees. Here fires are divided into three potential intensities: high, medium, and low.

As illustrated in Figure 2-4-1, pre-fire carbon has five potential destinations during and after a fire. The first proportion will survive the fire to continue as live vegetation; a second proportion will be volatilized during the fire and immediately released to the atmosphere; and the remainder will be divided between the pools of dead wood, soot, and charcoal. Soot and charcoal are stable forms of carbon and can remain unchanged for hundreds of years; in contrast dead wood decomposes over time.

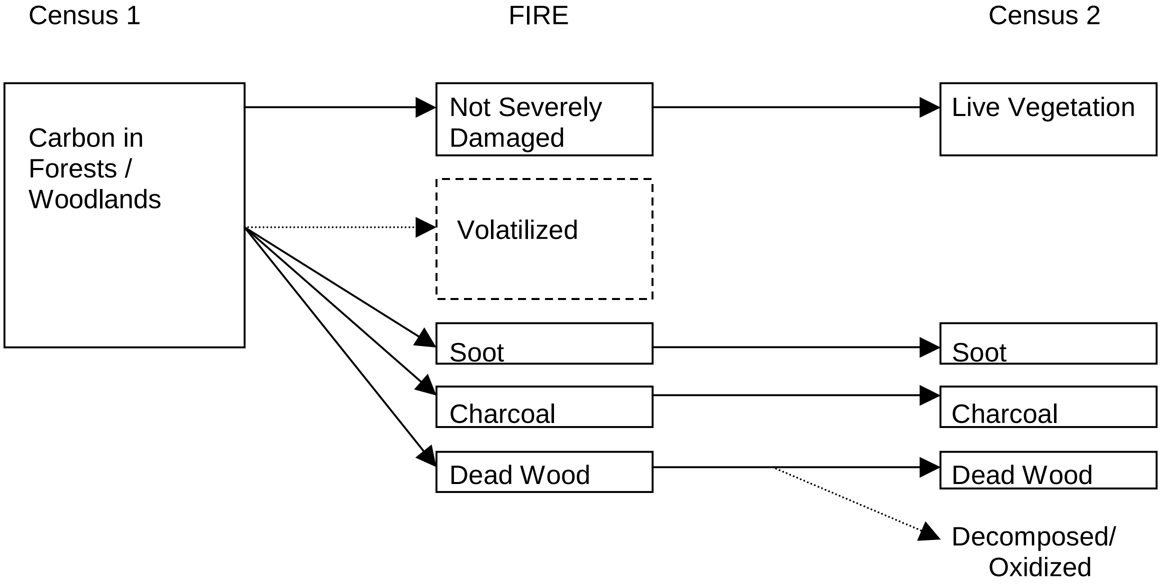

Figure 2-4-1. Flow diagram illustrating the various destinations of pre-burn carbon after a fire

The basis for this baseline analysis was the detailed study conducted for California (Brown et al. 2004). Under the California baseline analysis, changes in canopy coverage (measured from satellite imagery) were recorded through time for forest types and causes (including fire) were assigned. The study assumed (based on expert opinion) that the high, medium, and low intensities are associated with the magnitude of change in crown cover, so that a large decrease in crown cover would be due to a high-intensity fire or a small decrease would be caused by a low-intensity fire.

The midpoint of each decrease in canopy coverage class was assumed to be the proportion of the vegetation killed by the fire. The proportion volatilized is dependent on fire intensity (60% by a high-intensity fire, 40% by a mid-intensity fire, and 20% by a low-intensity fire) (McNaughton et al. 1998; Carvalho et al. 2001). If the volatilized proportion is subtracted from the midpoint of the decrease, then the remaining fraction is the dead wood, soot, and charcoal pool. This fraction was divided using the following proportions: 22% charcoal, 44% soot, and 32% dead wood (Comery 1981; Raison et al. 1985; Fearnside et al. 1993; Neary et al. 1996).

Approach for Calculations

This study' aim was to determine the loss in biomass as a result of fire in Arizona. The California study used data on the area affected by fire in classes of initial and post-fire crown cover and forest type. The degree of reduction in crown cover was used to indicate the intensity of the fire. The research team also had the biomass associated with each crown cover class, so a change between two cover classes could be represented as a loss in carbon. In contrast, in

Arizona available data included only forest type and an indication of fire intensity from fire extent and change in spectral reflectance.

The approach for this study was therefore to use the California data to determine the percentage loss in biomass that occurs as a result of a high-, medium-, or a low-intensity fire in each of the forest types. The percentage loss is then applied to Arizona-specific biomass numbers for comparable forest types.

The source of biomass values is the Arizona 2003 inventory of the forest inventory and analysis database (FIADB). These were split between forest types. In all cases, Arizona FIA data was divided by the five forest/woodland types (Douglas Fir, Fir-Spruce, Other Conifer (typically Ponderosa Pine), Hardwood Forest, and Hardwood Rangeland (typically oak savannah and pinyon-juniper) (Table 2-4-1) at the county level. The division by forest/woodland type was used to align the Arizona analysis with the original California study (Brown et al. 2004).

Table 2-4-1. Forest types for fire baseline analysis cross-walked with FIA forest type

California-analysis forest type	FIA forest type
Douglas Fir	Douglas Fir
Fir Spruce	White fir, Red fir, Noble fir, Pacific silver fir, Engelmann spruce, Engelmann spruce/Subalpine fir, Grand fir, Subalpine fir, Blue spruce, Sitka spruce
Other Conifer	Port-Orford cedar, Ponderosa pine, Western white pine, Jeffrey pine/Coulter pine/big cone Douglas-fir, Mountain hemlock, Lodgepole pine, Western hemlock, Western redcedar, Alaska yellow cedar, Western larch, Misc. western softwoods
Hardwoods - forest	Cottonwood, Willow, Oregon Ash, Aspen, Red alder, Bigleaf maple, Tanoak, Giant chinkapin, Pacific Madrone
Hardwood - rangeland	Western juniper, California black oak, Oregon white oak, Canyon live oak/Interior live oak, California laurel, Misc. western hardwood woodlands, Intermountain maple woodland, Juniper woodland, Pinyon juniper woodland, Rocky mountain juniper, Deciduous oak woodland, Mesquite woodland

The FIA data was further split into regions—Northern and Southern—with the assumption that the climatic variation would lead to variation in biomass that would refine the estimates. The split of counties between regions is listed in Table 1-1.

The mean biomass stocks were calculated from Arizona FIA data by region and forest type (Table 2-4-2).

Table 2-4-2. Mean biomass stock by forest type and region

Forest type	Mean biomass (t biomass/ha)	
	Northern	Southern
Douglas Fir	175.6	153.8
Fir Spruce	244.2	
Other Conifer	118.6	107.7
Hardwood	159.1	
Range Hardwood	43.8	31.8

Biomass Loss through Fire

To calculate the emissions through fire, the research team used results from the California analysis (Brown et al. 2004), taking the estimated stocks for each forest type at each of the four canopy density classes, plus the net emissions for each forest type/canopy density class/fire intensity class. Finally the emissions were calculated as a proportion of the original biomass and the results expressed as a percentage.

Because no canopy cover class data exists for Arizona, a mean emission percentage that excludes canopy cover is required. This was achieved by weighting the emission percentages by the proportion of forest in each canopy class in the most representative region of California (North Sierra).

The proportions by forest type by region by fire intensity were then multiplied by the biomass by forest type by region to give estimated biomass lost through emissions from fire (Tables 2-4-3 and 2-4-4).

Table 2-4-3. Mean emissions (in t CO_2e/ha) from a high-, mid-, and low-intensity fire in the Northern Region of Arizona

Forest type	High	Mid	Low
Douglas Fir	145.0	62.5	25.1
Fir Spruce	263.5	112.9	45.5
Other Conifer	80.7	53.5	26.6
Hardwood	141.2	61.1	24.6
Range Hardwood	27.4	11.8	4.8

Table 2-4-4. Mean emissions (in t CO_2e/ha) from a high-, mid-, and low-intensity fire in the Southern Region of Arizona

Forest type	High	Mid	Low
Douglas Fir	126.9	54.8	22.0
Fir Spruce	0.0	0.0	0.0
Other Conifer	73.2	48.6	24.2
Hardwood	0.0	0.0	0.0
Range Hardwood	31.4	13.5	5.4

Non-Tree Vegetation

Biomass numbers for non-tree vegetation (primarily shrubs and grasses in rangelands) are taken from the literature and Winrock International experience (Table 2-4-5).

Table 2-4-5. Estimates of pre-fire biomass stocks in non-tree vegetation

Vegetation type	Biomass carbon (t C/ha)	Source
Wet Grasslands	5.9	Prichard et al. 2000
Mesic Grasslands	2.4	Brown and Archer 1999
Xeric Grasslands	0.6	Winrock unpublished data
Shrublands	5.1	Martin et al. 1981
Desert scrub	2.6	Winrock unpublished data

Here the conservative assumption is made that 50% of the pre-fire biomass in non-tree vegetation is volatilized to be emitted as carbon dioxide.

2.4.2. Methods for Assessing Area Impacted by Fire and Fire Intensity

Satellite-based analysis is a practical method of quantifying area burned primarily due to the dangerous nature and the wide geographic extent of wildfires. The state reports the location and size of recorded fires but with no measure of fire intensity, nor with the location of the boundaries of the fire. It is necessary to know fire intensity to estimate emissions, and the precise location is necessary for a correlation with a database of vegetation species. The approach for this analysis was to estimate the extent of fires at known fire locations, through delineating areas with a change in reflectance on multiple satellite images—that is, pre-fire and post-fire images.

A common measurement of vegetation from satellite imagery is the Normalized Difference Vegetation Index (NDVI). Very low values of NDVI (0.1 and below) correspond to barren areas of soil without vegetation or of sand, rock, or snow. Moderate values represent shrub and grassland (0.2 to 0.3), while high values indicate forests (0.6 to 0.8).

Databases

The **NDVI** was calculated from 1.1 kilometer (km) pixel resolution NOAA Advanced Very High Resolution Radiometer (AVHRR) 10-day composite images. The temporal frameset covered the month of September and spanned 1990–2003 (except 1994). This encompassed the NOAA 11, 14, and 16 satellites. September was chosen for the analysis time frame because it is toward the end of the fire season and the burned areas are not yet affected by regrowth. Only one September 1994 composite was produced for 1994, due to the failure of the AVHRR sensor aboard NOAA-11. As a result, the imagery for 1994 along with fire data was dropped from the analysis because of data inconsistencies in image values and incomplete temporal coverage from sensor failures.

The **wildfire database for Arizona** encompassed a total of 23,242 occurrences that vary from less than one acre to many thousand acres. Fires for the study period with a final size greater than 2,000 ac were identified for NDVI postfire burn detection analysis to quantify area burned. For state lands, 5,602 fires occurred between 1990 and 1996; for federal lands, 17,636 fires occurred between 1990 and 1996. Each fire record included a unique identification with a global positioning system (GPS) point location, date, and final extent in acres. There was no geographic information system (GIS) polygon representing the extent of the fire in the original database so it was not possible to precisely locate the extent of the fire from these records, so the research team used the approach described below.

Mapping Methods

Fire Identification

This analysis used a postfire burn detection method to quantify area burned by wildfires. The NDVI was calculated from the water vapor-corrected band 10 (visible, 0.58–0.68 micrometer [μm]) and band 11 (near infrared, 0.725–1.10 μm).

$$\text{NDVI} = (\text{ch } 11 - \text{ch } 10)/(\text{ch } 11 + \text{ch } 10)$$

To obtain a single September NDVI for each year of the study period, three (or in some years four) 10-day composites were averaged into a single image (NDVI_y). These September images were then averaged into a 13-year historical NDVI reference image (NDVI_m).

The NDVI reflectance values are bimodal, ranging from -1.0 to 1.0. Positive values reflect vegetation or "greenness," and negative values indicate soil or non-vegetated areas. Values close to 1 are "greener" than values close to 0, and values close to -1 are more barren than values close to 0. When vegetation is burned, a rise in channel 10 reflectance and a decrease in channel 11 reflectance occurs. The degree of change (NDVI_d) was measured by subtracting NDVI_y from NDVI_m

$$\text{NDVI}_y - \text{NDVI}_m = \text{NDVI}_d$$

Each individual annual September image was subtracted from the reference image and potential fire locations were identified. In NDVI difference imagery, positive values indicate an increase in "greenness" from NDVI_m, and negative values indicate a decrease. For burned area-identification purposes, all positive values were removed, along with negative values greater than -0.05. The result was an image containing areas of concentrated vegetation decrease. The fire location data was then overlaid to confirm the changes as potential fires.

Fire Extent

The extent of fires listed as having over 2,000 ac in final size were mapped by visual interpretation from the changes seen in NDVI_d with assistance from the fire's GPS location and extent information (Figure 2-4-2).

The wildfire mapping process consisted of creating polygons that represent the extent of the burn area. Fires were first divided into big and small, based on final extent. Fires with a final extent of < 2,000 ac or 8 pixels were labeled as small fires. For AVHRR imagery, 1 pixel = 100 ha = 247.5 ac. Areas of vegetation that had a decrease in $NDVI_d$ greater than 8 pixels and a corresponding fire greater than 2,000 ac were digitized using the "heads up method."[1] The area digitized was then compared with the reported fire extent.

All fires with less than 2,000 ac burned were classified as too small to display a change in the AVHRR imagery. For these fires, a buffer was calculated and added to the fire point based on the GPS point (which was considered the center of the fire) and the radius (which was derived from the size reported in the original record).

Additionally, if a fire that was larger than 2,000 ac could not be mapped by visual interpretation, it was mapped by the buffering method.

In the case of the fires that occurred in 1994, they were mapped using the images from 1995.

Fire Severity

For the fires that occurred in forested lands, three classes of burn severity were identified: low, medium, and high (Figure 2-4-2). Again, the intensity was evaluated separately depending on the fire mapping method. For the fires that were identified using the imagery, the value of burn severity corresponded with the value of the difference in NDVI. The rationale is that the more negative the difference between the actual NDVI and the mean NDVI, the more severe is the fire. As a result, one fire can include areas with different burn severities. Small fires (< 2,000 ac) were arbitrarily considered to experience a low burn fire severity, since there was no image data to consistently support the estimation.

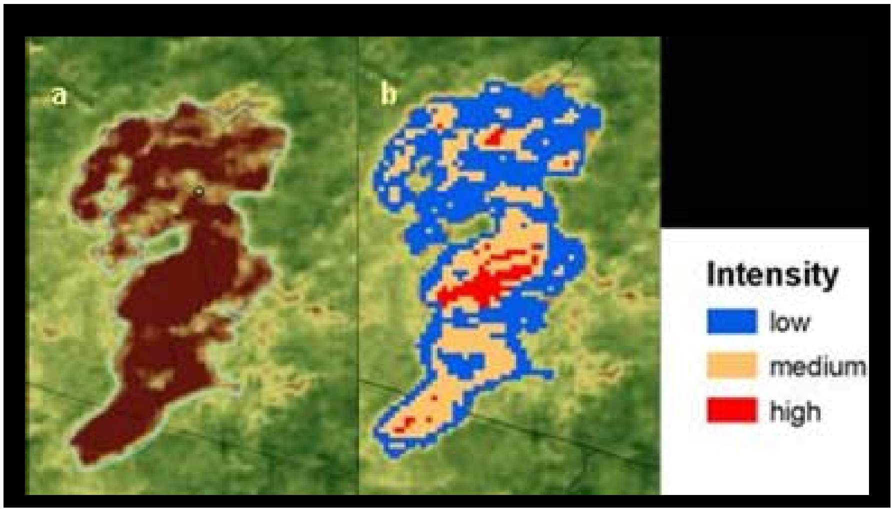

Figure 2-4-2. Illustration of the mapping method. In (a), the point location from the state or federal database is established; a fire boundary is then created and compared to the fire area reported with the point location. In (b), the fire intensity through the burn area is calculated using NDVI values.

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[1] "Heads up" digitizing refers to on screen digitizing. It is referred to as "heads up" because the analyst focuses on the screen, as opposed to a digitizing tablet.

Land Cover Affected by Fire

Finally, the fire maps were crossed with the land cover maps, making it possible to estimate the amount of land cover type/forest type that was affected by fires.

2.4.3. Results

Across the seven years analyzed, researchers recorded fires with a total area of 1.08 million ac (437,700 ha), as illustrated in Figure 2-4-3. This is equivalent to 154,000 ac/yr (62,500 ha/yr).

Emissions totaling 904,000 tons of carbon, or 3.3 $MMTCO_2e$, were estimated to have occurred from fire during the analysis period. This is equivalent to an emission of 0.47 $MMTCO_2e$/yr.

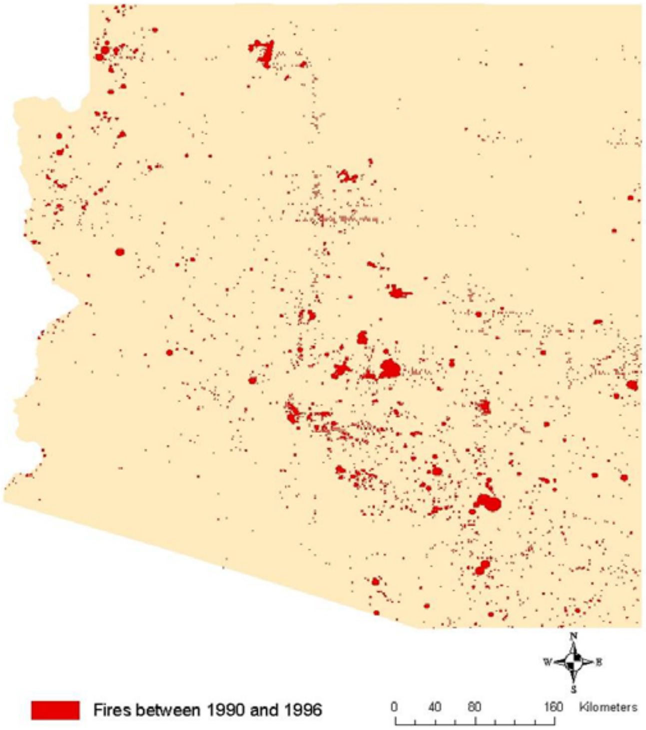

Figure 2-4-3. The location and extent of fires in Arizona between 1990 and 1996

Eighty percent of the fires occurred on rangelands with only 14% in forests (Table 2-4-6).[2] Because of the higher biomass loss from forests during fire, almost 42% of the total emissions from fire originated in the 14% of fire area that was in forest.

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[2] The remaining fire area was on developed, agricultural, or barren land.

Table 2-4-6. Area burned and carbon emissions in forests and in rangeland across the analysis period

Area Type	Area burned (ha)	Emissions (t C)
Forest	62,388	375,637
Rangeland	351,891	528,725

The annual emissions ranged between 22,000 tons of carbon and 218,000 tons of carbon (Table 2-4-7 and Figure 2-4-3). The lowest emissions occurred in 1991 and 1992, when just 14,000 and 18,000 ha were burned. The highest emission was in 1996, when 67,000 ha burned; however, the largest area burned in 1993 and 1995, but a greater proportion of these fires occurred in low biomass systems (that is, rangelands with no trees). The largest fires and highest emission came in the later years of the analysis, but more years of data would be needed to consider whether there is a trend to increase in fire coverage and emissions.

Table 2-4-7. Area burned and carbon emissions per year across the analysis period

YEAR	Area burned (ha)	% Forest	Emissions (t C)
1990	34,909	38	111,273
1991	14,215	10	22,352
1992	17,907	5	22,612
1993	109,510	6	168,611
1994	90,476	16	177,601
1995	103,145	7	183,898
1996	67,490	26	218,014
TOTAL	437,652		904,361

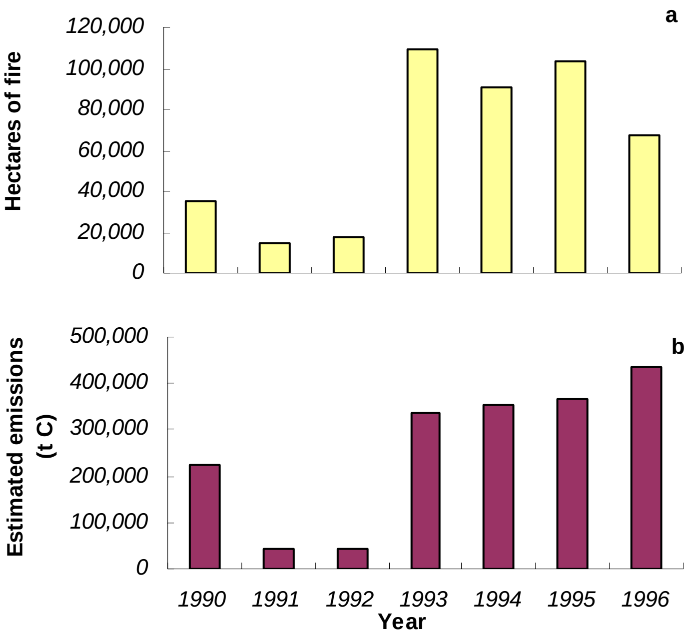

Figure 2-4-4. Area affected by fire and estimated emissions from fire across the study period

Fires occurred throughout Arizona during the study period and there was no apparent geographical relationship between either area burned or carbon emissions from fire and geographic location (Figures 2-4-4 and 2-4-5). As shown in Table 2-4-8, the highest emissions occurred in Coconino and Gila Counties. The largest total areas burned were located in Maricopa and Mohave Counties.

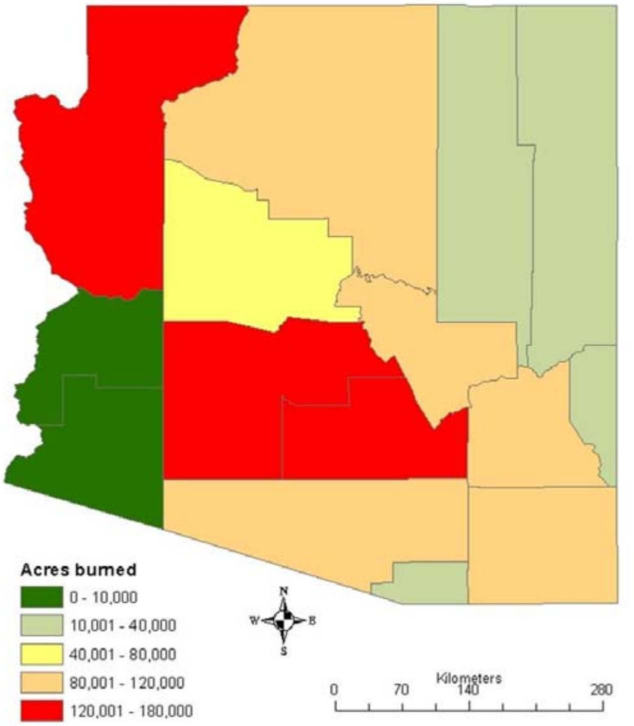

Figure 2-4-5. Area burned (in acres), at the county level, between 1990 and 1996

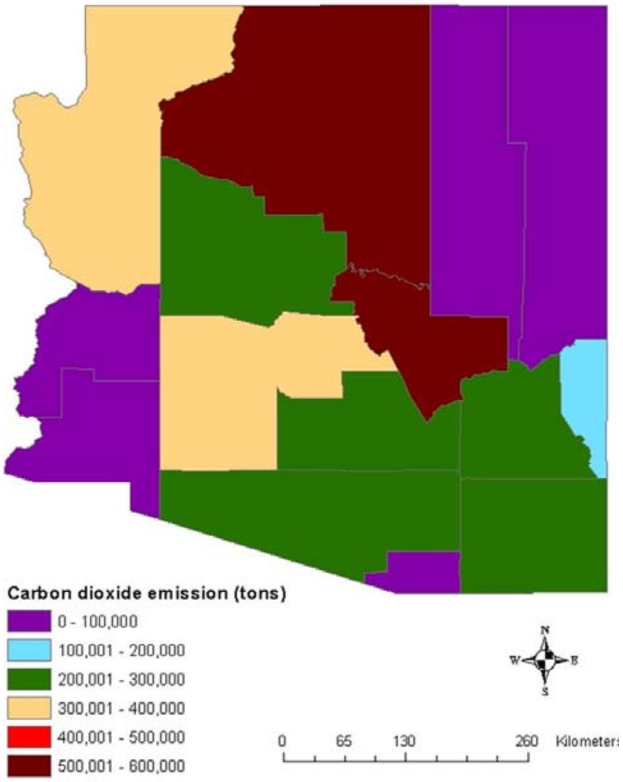

Figure 2-4-6. Metric tons of carbon dioxide emitted, at the county level, between 1990 and 1996

Table 2-4-8. Area burned and carbon emissions per county across the analysis period

County	County Area (ha)	Area burned (ha)	Emissions (t C)
Apache	2,902,050	5,723	14,698
Cochise	1,597,880	36,664	74,279
Coconino	4,821,891	38,221	137,097
Gila	1,234,829	35,485	143,832
Graham	1,198,987	37,391	77,270
Greenlee	478,371	12,396	50,734
La Paz	1,165,483	2,334	2,703
Maricopa	2,383,602	61,479	84,341
Mohave	3,447,699	71,075	94,615
Navajo	2,577,862	5,342	24,481
Pima	2,379,232	48,316	64,908
Pinal	1,390,719	55,492	73,271
Santa Cruz	320,546	4,483	4,549
Yavapai	2,103,925	22,300	56,528
Yuma	1,428,143	950	1,056
TOTAL	29,431,219	437,651	904,362

2.4.4. Uncertainties

The carbon values to which percentage emission factors are applied are averaged values across all FIA plots in a forest type/region combination. Consequently, the same average value is used to represent forests with very high carbon stocks or very low carbon stocks. Fires will occur in forests regardless of starting carbon stock, yet it is possible that the forests with the very lowest carbon stocks (for example in the year immediately after clear-cut logging) may not have enough biomass to sustain a fire. The emissions reported here may therefore be a small *overestimate,* for if the very lowest biomass plots are excluded from the FIA analysis the mean will be raised and consequently, the estimated emissions will be as well.

The calculated emissions presented here are conservatively limited to just aboveground tree biomass and therefore represent an *underestimation* of total emissions. Carbon stored in other pools will combust and be emitted through fire. However, the research team has no detailed source that will link the region and forest type-specific FIA data on aboveground tree biomass with similar data on other carbon pools.

Fire will directly impact dead wood, litter, shrubs, and herbs (though even these pools may not be completely volatilized in low-severity fires [e.g., Skinner 2002]). The influence of fire on soil carbon or the carbon stored in roots is less clear. When a tree is killed, the roots will not be burned but will become dead material that will decompose at a rate that is not well understood. A very intense fire will affect soil carbon, though it is not fully understood what proportion of soil carbon is volatilized, nor to what depth the impact penetrates.

The research team consulted the literature to get an indication of the scale of potential additional emissions for pools not included here. Smithwick et al. (2002) took measurements of all carbon pools across 43 stands at seven sites in Washington and Oregon. The authors divided their measurements into three regions: Coastal, Cascades, and Eastern. The results from the dry pine forests of Eastern Oregon are presented here to represent the forests in Arizona. Values for roots were not taken from Smithwick et al. (2002); roots were estimated more directly by using the temperate forest allometric equation of Cairns et al. (1997), which calculates belowground biomass from aboveground biomass. The amount of additional biomass carbon as a percentage of aboveground live tree biomass carbon stocks is given in Table 2-4-9.

Table 2-4-9. Relative increase in stocks that would result from adding each of the additional carbon pools to live aboveground trees

	Litter	Dead Wood	Shrubs	Herbs	Roots	Soil Carbon
Arizona	22%	23%	0.38%	0.09%	25%–31%	43%

The measurements of Smithwick et al (2002) were in old-growth forests. In younger forests lower absolute amounts of dead wood might be expected together with similar quantities of litter, shrubs, and herbs. Therefore a lower proportion of dead wood and a higher proportion of litter, shrubs, and herbs might be expected in younger forests.

Here, as an indication of potential additions, the values of Smithwick et al. (2002) are used. An addition of litter, dead wood, shrubs, and herbs (assuming that these pools are volatilized at the same proportion as live aboveground trees) results in an additional emission over the study period equal to 206,936 tons of carbon, or an additional 23%.

2.4.5. Conclusions

Across the seven years analyzed, fires with a total area of 437,700 ha (1.08 million ac) were recorded. This is equivalent to 62,500 ha/yr or 154,000 ac/yr. Emissions totaling 904,000 tons of carbon or 3.3 MMTCO$_2$e were estimated to have occurred from fire during the analysis period. This is equivalent to an emission of 0.47 MMTCO$_2$e/yr.

Eighty-five percent of the burnt area was on rangelands but 42% of the emissions were from the 15% of burned area that was forest. Fire incidence varied by year with high emissions in 1993 to 1996 (> 168,000 t C) and low emissions between 1991 and 1992 (< 23,000 t C). Fires occurred throughout Arizona during the study period, and there was no apparent geographical relationship between either area burned or carbon emissions from fire and geographic location.

3.0 Baseline for Agricultural Lands in Arizona

3.1. General Approach

The goal of this part of the research was to quantify the baseline of changes in carbon stocks in the Arizona agricultural sector for the decade of the 1990s. Baselines provide an estimate of the emissions and removals of GHGs caused by changes in the use and management of land. The focus of this report is on emissions and removals of carbon dioxide and not on non-CO_2 greenhouse gases. Baselines are useful for identifying where, within the landscape of a state, opportunities exist for enhancing carbon stocks and/or reducing carbon sources to mitigate GHG emissions.

The baseline for the agricultural sector depends on two types of data: (1) the total area of agricultural land, and area of each of the major agricultural land-use types, through time, and (2) the carbon stocks in each land-use type. Areas and changes in area of agricultural lands are based primarily on the NRI database for the period 1987–1997. Carbon stock estimates for various agricultural land-use types were derived from consultation with experts in local universities and from the literature in combination with standard methods. The analysis is conducted for the entire state of Arizona at the county scale of resolution.

3.1.1. Classification of Agricultural Land

In this study, NRI data were used for estimates of area because of the NRI's relative strength in agricultural surveys compared with other sources of data. The coverage of NRI data is wider and is available across the states for multiple points in time and for multiple classes of agriculture.

In this analysis, agricultural land is equated to cropland as defined in the NRI (NRCS 2000). The NRI recognizes two categories of cropland: cultivated and non-cultivated. Cultivated cropland includes small grains and row crops, hay and pasture with cropping history, and horticulture with double cropping (meaning horticulture with crops planted under the trees). Non-cultivated cropland includes horticulture without double cropping and hay without cropping history. Grazing lands are included under the analyses of rangelands in Chapter 2.

The distinction between cultivated and non-cultivated crops is not useful for the purpose of (aboveground) carbon analysis, which depends instead on biomass models based on the growth form of the vegetation. Therefore, the specific land-use categories from NRI were regrouped for this analysis into categories related to the growth form of the crop. All horticulture lands, with or without double cropping, were reclassified as woody cropland. The rest of the croplands, including hay, row crops, and small grains, were considered to be non-woody crops (Table 3-1).

Table 3-1. NRI categories and subcategories in Arizona

Broad classification	Detailed classification	NRI classification
INCLUDED AS AGRICULTURE IN THIS CHAPTER		
Perennial woody crops	Fruit orchards	Fruit orchards
	Nut orchards	Nut orchards
	Vineyards	Vineyards
	Bush crops	Bush crops
	Berry crops	Berry crops
	Other horticulture	Other horticulture
Annual non-woody crops	Row / close crops	Row/Corn
		Row/Sorghum
		Row/Soybeans
		Row/Cotton
		Row/Peanuts
		Row/Tobacco
		Row/Sugar beets
		Row/Potatoes
		Row/Other veg/truck crops
		Row/All other row crops
		Row/Sunflower
		Close/Wheat
		Close/Oats
		Close/Rice
		Close/Barley
		Close/All other close grown
		Hay/Grass
		Hay/Legume
		Hay/Legume-grass
		Other crop/Summer fallow
		Other crop/Aquaculture
		Other crop/Other-set-aside, etc.
FOCUS OF CHAPTER 2		
Pasture / rangeland	Pasture / rangeland	Pasture/Grass
		Pasture/Legume
		Pasture/Grass-forbs-legumes
		Rangeland
Forest	Forest	Forestland/Grazed
		Forestland/Not grazed

Table 3-1. (cont'd)

Broad classification	Detailed classification	NRI classification
OTHER CATEGORIES		
Urban / transportation	Urban / transportation	Urban/10 acres or larger Urban/Small built-up Transportation
Other	Other	Other farmland/Farmsteads Other farmland/Other land Other farmland/CRP land Barren/Salt flats Barren/Bare exposed rock Barren/Strip mines Barren/Beaches Barren/Sand dunes Barren/Mixed barren lands Barren/Mud flats Barren/River wash Barren/Oil wasteland Barren/Other barren land Other rural/Permanent snow-ice Other rural/Marshland All other land Water/Body 2–40 acres Water/Body less than 2 acres Water/Streams < 66 ft. wide Water/Streams 66–660 ft. wide Water/Large

CRP = Conservation Reserve Program

3.1.2. Limitations of the NRI Database

Despite the general acceptance of NRI for agricultural resource analysis, it is important to note its limitations. First, the samples were taken from non-federal lands only, while in the West Coast states, federal lands occupy half or more of the total land area. Second, the data are not from a complete census, but rather from a statistically sound sampling design. Finally, the NRI's classification of land cover/land-use types may not be consistent with other classification schemes commonly used in land cover/land use analysis; for example, the classification in USGS National Land Cover Classification system.

For this chapter's purpose, however, these limitations have virtually no effect on the analysis, because the data are only being used for the agricultural sector, where lands are privately owned, easy to classify, and statistically well reported.

The NRI reports a margin of error for the 1997 reporting (equivalent to a 95% confidence interval) of ±9% for its sampling of areas of cultivated cropland.

3.1.3. Area and Change in Area of Agricultural Land

The research team reclassified the NRI data for each state into the broad classes shown in Table 3-1 and then calculated the areas for each class for 1987 and 1997. Although 1992 data were available, a similar analysis for California, where the change over two five-year periods (1987–1992 and 1992–1997) was included, indicated that using two periods did not appear to add any further insights into the dynamics of land-use and carbon stock change (Brown et al. 2004). Thus this study only examined the change over the 10-year period 1987 to 1997.

3.1.4. Carbon Density of Agricultural Land

The baseline analysis for the agricultural sector focuses on carbon in vegetation only, including above- and belowground (roots) components. Carbon in vegetation is estimated as 50% of the biomass of the vegetation.

Carbon Stocks for Non-Woody and Woody Crops

A difficulty in estimating the biomass of non-woody annual crops is caused by the seasonal change of the vegetation. During the non-growing season, there is little biomass in annual crops, while at the peak of the growing season just before harvest, biomass can be high. Considering that litter production is usually low in these crops, peak biomass is assumed to be equivalent to the annual primary production of the crops on the land. In many cases the majority of the biomass (or production) is removed from the field at harvest. An approximate temporal average of the biomass was used to derive the carbon stock. The biomass in cultivated non-woody crops was estimated based on three data sources: (1) crop biomass from the U.S. Department of Agriculture – National Agriculture Statistics Service (USDA NASS, see www.usda.gov/nass/sso-rpts.htm), (2) length and timing of harvest cycles, and (3) the relative abundance of each crop type.

Carbon stocks of horticultural crops have less seasonal variation, but data on carbon stocks for these crops are scarce. Yield data from the USDA NASS represents only the biomass of the harvest—a useful estimate of peak biomass for non-woody crops, but only a small portion of the standing biomass for woody crops. Thus estimates were instead derived from consultation with extension agents, university researchers, and government officials in combination with literature searches, principally to determine typical stocking densities (number of trees per unit area), tree diameters, and tree heights. Biomass could then be estimated from tree diameter and height using a regression equation (Winrock unpublished). The stocking densities were combined with estimates of biomass per plant to arrive at an estimate of biomass carbon density in metric t C/ha. For fruit orchards and bush fruits, multiple crop types were included, and the relative abundance of each crop type in the state, derived from USDA NASS, determined the area-weighted mean carbon stock that was used in this analysis (Table 3-2).

Table 3-2. Estimates of the average carbon stock (t C/ha) for each of the crop types in Arizona

Crop type	Average C stock (t C/ha)
Fruit orchards	17.3
Nut orchards	10.8
Vineyards	4.3
Bush fruits	-
Berry fruits	-
Other horticulture	4.5
Non-woody crops	1.5

Soil carbon stocks are not included in this report because the research team assumed that most agricultural land has been under cultivation long enough that changes in soil carbon would be minimal to non-existent under current practices. The stability of soil carbon on cultivated land was confirmed by the study of DeClerck and Singer (2003), who showed that the percent change in soil carbon under row crops in California remained constant over an approximate period of 50 years. Interestingly, DeClerck and Singer also found the same trend for tree crops, but an increase in soil carbon over the past 50 years for soils under viticulture (about a 1.7-fold increase) and pasture (about a 1.6-fold increase). These results are difficult to apply in baseline determination because the results were reported as an increase in percent carbon with no indication of changes in soil bulk density; calculating changes in carbon stocks requires not only the change in percent carbon but also the change in soil bulk density.

Estimates of the carbon stocks in non-agricultural lands (such as urban/transportation, and all of the “other” class) are assumed to be zero. This assumption is probably reasonable for “other,” because this contains mostly barren lands, but for urban/transportation there is likely to be more carbon than in non-woody croplands. Urban development often contains significantly more (but unknown) amount of biomass in trees and shrubs that homeowners and local municipalities plant than in the agricultural lands that they replace. This is an area of further research—estimating the amount of carbon in biomass of urban areas as a function of density and other factors.

Change in Stocks

When a change in agricultural land use occurred, it was assumed in this analysis that the entire carbon stocks in vegetation present before the change would be emitted into the atmosphere as carbon dioxide. This is a reasonable assumption given the necessity to clear the land to plant alternative crops or initiate urban development.

Regarding changes in land use to agricultural crops, it is assumed that the change occurred at the midpoint of the period under analysis (in 1992), five years before 1997, and five years after

1987. For non-woody crops such as vineyards, bush and berry crops, and other horticulture crops, it is reasonable to assume that in five years these crop types will have reached their predicted steady-state biomass. The same assumption cannot be applied to orchards, which will take longer than five years to attain their maximal biomass. Instead, the biomass accumulation that might have occurred in five years of growth for fruit and nut orchards was estimated based on conservative estimations of stocking density, tree heights, and diameters at five years age (Table 3-3).

Table 3-3. The estimated average biomass carbon accumulation after five years of growth for fruit and nut orchards in Arizona (t C/ha)

Location	Average biomass carbon accumulation
Fruit orchards	1.6
Nut orchards	0.4

In addition, it can be expected that fruit orchards and nut orchards will continue to accumulate biomass for many years. The research team therefore applied an average biomass accumulation to areas of orchards that remained constant over the ten years of the analysis. The rate of biomass accumulation was determined by estimating the stocks at years 40 and 60 and dividing the difference by 20 to get an annual accumulation. The annual accumulation was multiplied by 10 to give an accumulation for the ten years 1987 to 1997 (Table 3-4).

Table 3-4. The estimated average biomass carbon accumulation over 10 years of growth for fruit and nut orchards in Arizona (t C/ha). This growth rate is for existing orchards; that is, for areas unaffected by land-use change.

Location	Average biomass carbon accumulation
Fruit orchards	3.4
Nut orchards	2.1

3.1.5. Uncertainty

Uncertainty in NRI Data

The estimated margin of error (95% confidence interval) for the area of cultivated cropland in 1997 is 12.6% for Arizona (NRCS 2000). For areas presented at finer scales (that is, at the county level or for a specific crop) or for changes in area, the margin of error will be significantly higher.

Uncertainty in Carbon Stock Data

To evaluate the confidence in the estimated carbon stocks, ranges were determined (Table 3-5) based on the ranges in diameter, height, biomass, and planting density provided by the data sources consulted, as described in Section 3.1.4.

Table 3-5. Estimated ranges in average carbon stock for each crop type in Arizona (t C/ha)

Crop type	Range in C stocks (t C/ha)
Fruit orchards	12.9–26.1
Nut orchards	4.4–23.5
Vineyards	2.4–6.7
Bush fruits	–
Berry fruits	–
Other horticulture	3.4–5.7
Non-woody crops	1.0–2.0

Weighting the deviations from the mean by area and carbon stock gave a mean deviation value for carbon stocks of 42%.

3.2. Results

3.2.1. *Statewide Land Use and Land Use Change 1987–1997*

The total area of Arizona is 29.53 million ha, of which 57% is covered by the NRI and the remainder is federal land falling outside the scope of the NRI.

In 1997 agricultural land in Arizona, including both perennial woody and annual non-woody lands, was estimated at 438,289 ha, or 1.5% of the land area of the state (Figure 3-1). The area of woody cropland was 6.9% of the total area under agricultural cultivation.

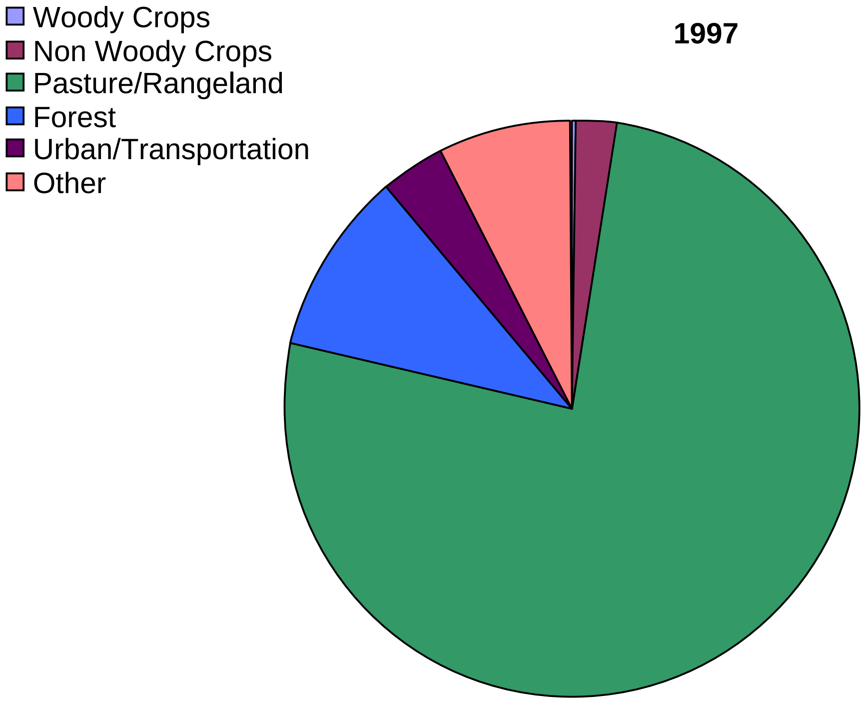

Figure 3-1. Proportional area for land uses in Arizona in 1997, based on NRI data (non-federal lands only)

Table 3-6. Areas (ha) and changes in areas (ha) for lands in Arizona from the NRI dataset

	1987	1997	Change	% Change
Woody crops				
Fruit orchards	16,229	17,766	1,537	+9.5
Nut orchards	8,660	7,648	-1,012	-11.7
Vineyards	4,492	4,654	162	+3.6
Bush crops	-	-	-	-
Berry crops	-	-	-	-
Other horticulture	-	-	-	-
Total woody crops	29,381	30,068	687	+2.3
Non-woody crops				
Row/Close crops	439,667	408,221	-31,446	-7.2
Other land uses				
Pasture/Rangeland	12,991,477	12,906,045	-85,432	-0.7
Forest	1,772,262	1,703,585	-68,677	-3.9
Urban/Transportation	514,536	603,570	89,034	+17.3
Other	1,198,357	1,294,190	95,833	+8.0
TOTAL	16,945,680	16,945,680		

Overall, agricultural land in Arizona experienced a 6.6% (30,759 ha) loss in area during the 10-year period from 1987–1997. However, this loss included a 7.2% loss in area of non-woody crops and a 2.3% increase in area of woody crops (Table 3-6 and Figure 3-2). In the same time period there were small decreases in the area of pasture/rangeland (0.7%) and non-federal forest (3.9%), and increases in the area of urban/transportation (17.3%) and the Other category (8.0%).

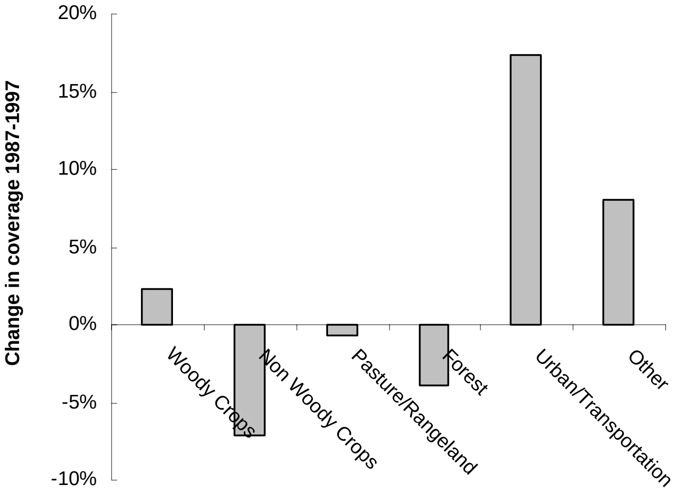

Figure 3-2. Proportional change in area between 1987 and 1997 for broad land uses in Arizona

3.2.2. Changes in Specific Land-Use Type

As shown in Figure 3-3, agricultural land in Arizona is dominated by non-woody crop types (93%). Among the woody crops, fruit orchards make up 59%, nut orchards 25%, and vineyards 15%.

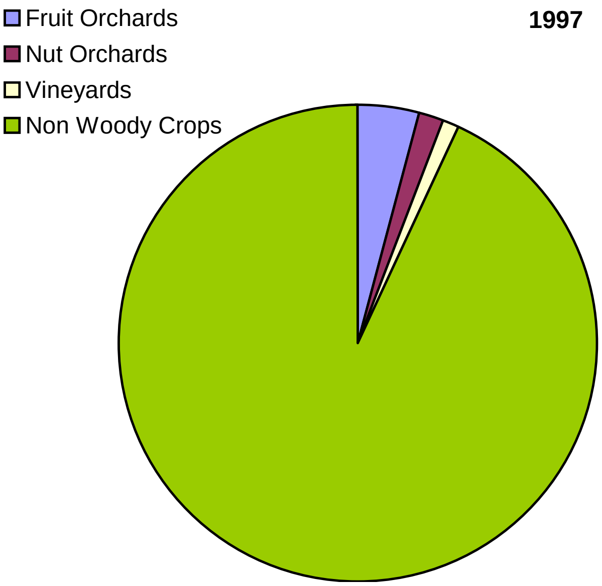

Figure 3-3. Proportional coverage of each agricultural land-use in Arizona in 1997

The 2.3% increase in area of woody crops between 1987 and 1997 was composed of a 9.5% increase in fruit orchards (1,537 ha) and a 3.6% increase in vineyards (162 ha), balanced by a 11.7% decrease in nut orchards (1,012 ha) (Table 3-6 and Figure 3-4).

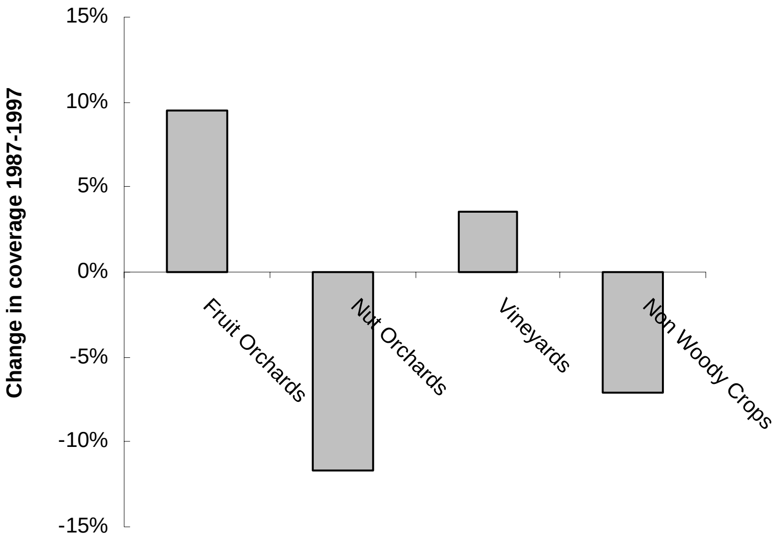

Figure 3-4. Proportional change in area between 1987 and 1997 for agricultural land uses in Arizona

There was a net loss in area in each of the land uses to development—the Urban/Transportation NRI land class (Table 3-7). The greatest loss was from pasture/rangeland to development (65,805 ha), although this was balanced by a loss in forest to pasture/rangeland (44,112 ha). The loss in forest to pasture runs contrary to the sentiment among ranchers that mesquite and juniper are encroaching on grasslands (pers. comm. Melanie Lenart, University of Arizona). However, it should be remembered that NRI classifies oak and juniper woodlands (and any areas with less than 10% crown cover) as rangeland.

The decrease in area of nut orchards resulted in an increase in non-woody crops (202 ha), forest (283 ha), and development (526 ha). Non-woody crops gained area from fruit orchards (81 ha), nut orchards (202 ha), and rangeland (3602 ha) but lost area to development (14,488 ha) and the Other category (20,842 ha).

3.2.3. County-Level Estimate of Agricultural Land Area

The NRI data is not designed for use at the county level; results are given here for illustrative purposes. Woody cropland is concentrated in the south of the state, but even in this region it is never a dominant component of the landscape (< 0.5% by area) (Figure 3-5a). Non-woody crops are also concentrated to the south but are more dominant than woody crops, occupying up to almost 9% of some counties (Figure 3-5b). The counties with the greatest coverage of non-woody crops include Maricopa and Pinal, with 115,900 ha and 124,200 ha, respectively, in 1997 (Table 3-8).

Only six counties recorded net changes in area of woody crops (Figure 3-6a). Losses in area occurred in Cochise, Graham, Yuma, and Pima and gains occurred in Maricopa and Pinal. Losses in area of non-woody crops were recorded in all but two counties: Mohave and Pinal (Figure 3-6b and Table 3-8).

3.2.4. Carbon Stocks of Agricultural Land During 1987–1997

The total estimated carbon stock in the vegetation of all Arizona agricultural crops is approximately 1 million tons. In the ten-year period between 1987 and 1997, the carbon stock decreased by 98,900 tons, caused by the conversion of agricultural land to alternative uses. Of this total, just over 47,000 tons were lost from non-woody crops and 51,700 tons were lost from woody crops (Table 2-4). This represents a loss of 7.2% of the carbon in non-woody crops and of 13.1% in carbon in woody crops, for a total loss from agriculture in Arizona proportional to 9.4% of the carbon stored in 1987. The main source of the loss was from fruit orchards (a loss of 57,500 t C), which far exceeded small gains in carbon stored in nut orchards and vineyards (Table 3-9 and Figure 3-7).

Table 3-7. Land-use change transition matrix, showing the source and direction of changes in Arizona 1987–1997. A negative sign indicates a net loss of area from the land use in the row to the land use in the column.

Land-Use Type	Unchanged	Fruit Orchards	Nut Orchards	Vineyards	Non-Woody Crops	Rangeland	Forest	Urban / Transportation	Other	TOTAL CHANGE
Fruit Orchards	10,198				-81	6,435		-3,238	-1,578	1,538
Nut Orchards	7,649				-202		-283	-526		-1,011
Vineyards	4,492								162	162
Non-Woody Crops	381,834	81	202			3,602		-14,488	-20,842	-31,445
Rangeland	12,768,771	-6,435			-3,602		44,112	-65,805	-53,704	-85,434
Forest	1,644,498					-44,112		-1,416	-23,149	-68,677

Table 3-8. The county level coverage (ha) for specific agricultural land uses and the change in coverage in Arizona, 1987 to 1997

County	High-carbon Crops						Low-carbon Crops		TOTALS	
	Fruit Orchards		Nut Orchards		Vineyards		Non-Woody crops			
	1987	1997	1987	1997	1987	1997	1987	1997	1987	1997
Apache							2,469	2,266	2,469	2,266
Cochise	1,052	1,012	445	445			47,876	40,227	49,373	41,684
Coconino							283	243	283	243
Gila							1,214	243	1,214	243
Graham	486	243					18,454	16,350	18,940	16,593
Greenlee							1,497	931	1,497	931
La Paz							28,693	23,756	28,693	23,756
Maricopa	7,285	10,805			728	728	121,653	115,866	129,666	127,399
Mohave							971	1,174	971	1,174
Navajo							1,255	364	1,255	364
Pima			5,787	4,775			12,101	11,251	17,888	16,026
Pinal	2,307	2,307	1,052	1,052	3,764	3,926	123,353	124,162	130,476	131,447
Santa Cruz							1,821	809	1,821	809
Yavapai							2,550	2,104	2,550	2,104
Yuma	5,099	3,399	1,376	1,376			75,477	68,475	81,952	73,250
TOTAL	16,229	17,766	8,660	7,648	4,492	4,654	439,667	408,221	469,048	438,289

Table 3-9. Carbon stocks (t C) and changes in carbon stocks (t C) for land-use types in Arizona

	1987	1997	Change
Woody crops			
Fruit orchards	280,753	223,216	-57,537
Nut orchards	93,534	98,670	5,136
Vineyards	19,316	20,012	697
Bush crops	-	-	-
Berry crops	-	-	-
Other horticulture	-	-	-
Total woody crops	393,603	341,898	-51,705
Non-woody crops			
Row / Close crops	659,501	612,332	-47,169
TOTAL	1,053,104	954,230	-98,874

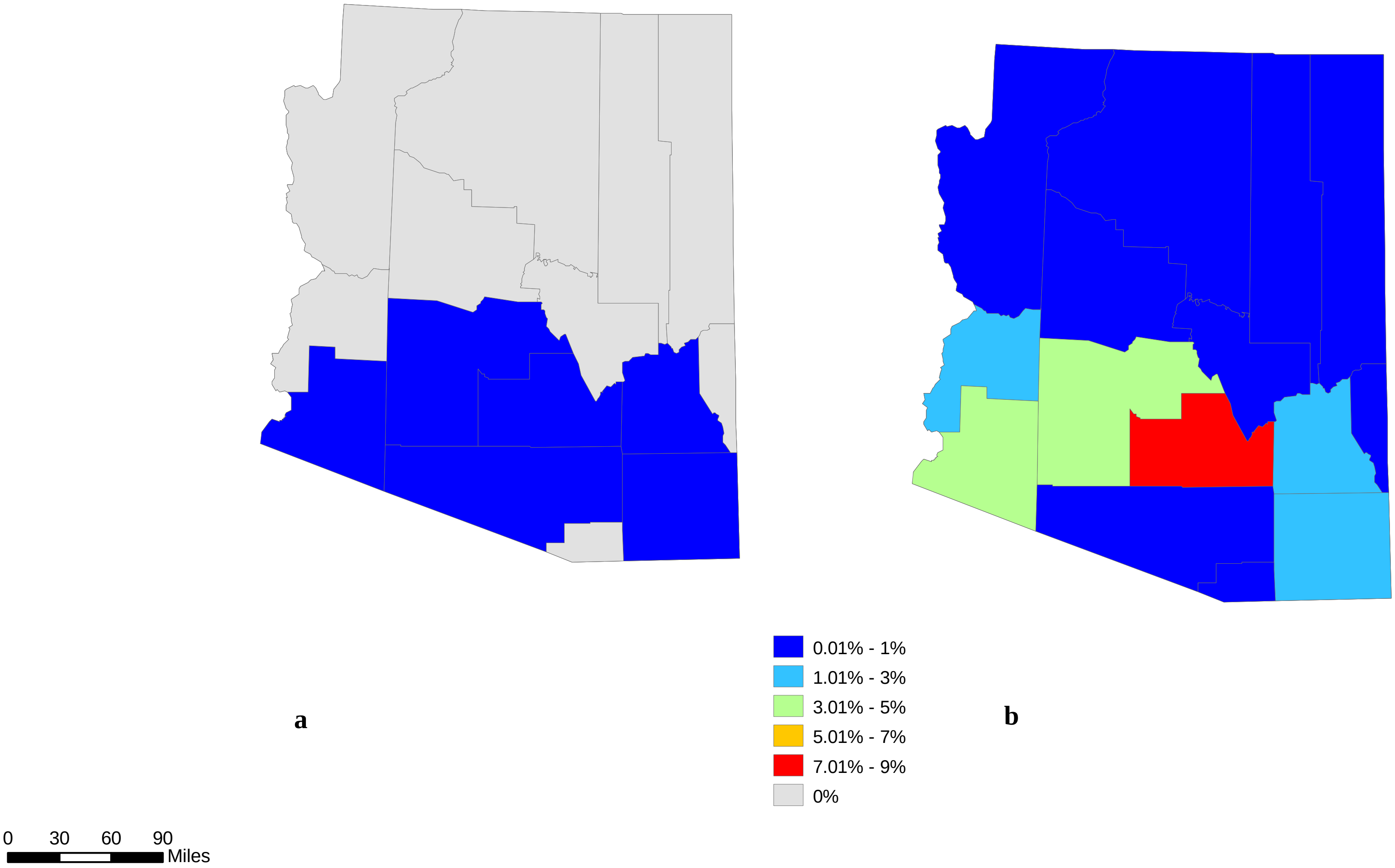

Figure 3-5. Land use by county in Arizona, 1997, showing distribution of (a) woody and (b) non-woody cropland. Values indicate the percentage of total land area in each county occupied by each class of agricultural land

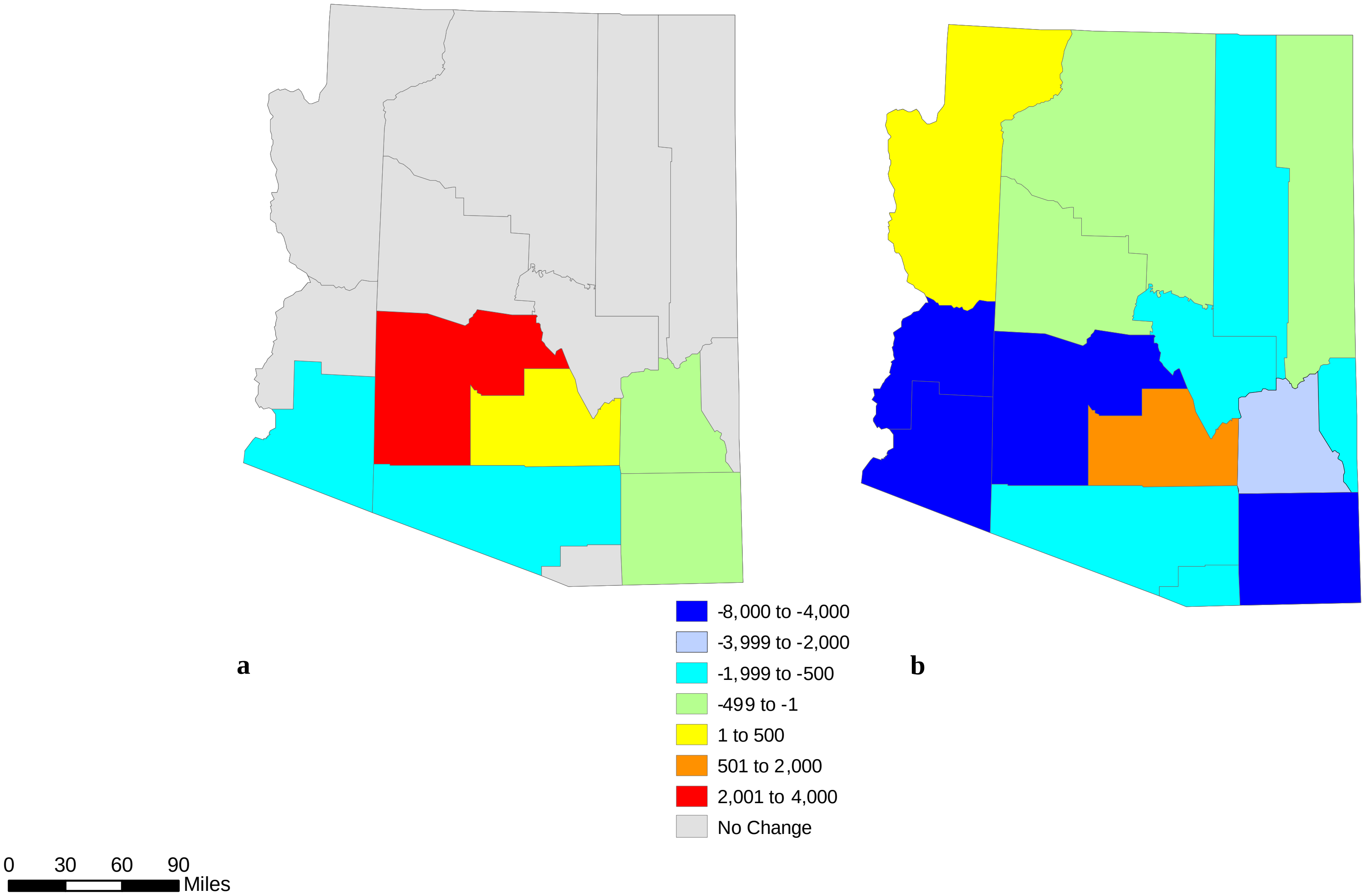

Figure 3-6. Land use change by county in Arizona, 1987 to 1997, showing distribution of change in area in (a) woody and (b) non-woody cropland. Values indicate change in hectares; a minus sign indicates a loss in area from 1987 to 1997; a plus sign indicates a gain in area in the same period.

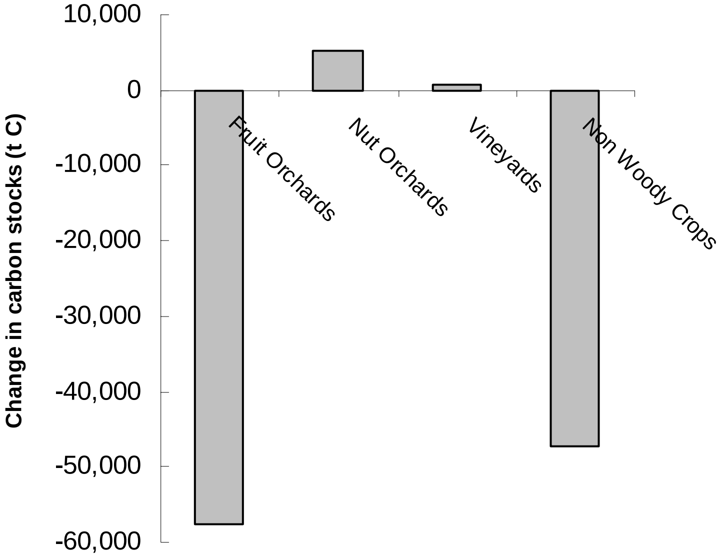

Figure 3-7. Changes in carbon stock (t C) across crop types in Arizona between 1987 and 1997

Large losses in carbon resulted from conversion of cropland to development (83,400 t C) and other land changes (60,900 t C). No changes were recorded from cropland to forestland or vice versa. Gains in carbon in cropland between 1987 and 1997 resulted from the conversion of rangeland to fruit orchards and non-woody crops (11,900 t C). Of the gross gains in carbon in fruit orchards, 74% was from growth of existing orchards and 26% was from growth in new plantings. There was no expansion in the area of nut orchards and consequently 100% of the gains in carbon were from growth in existing orchards (Table 3-9).

When converted to CO_2 equivalents, the total stocks in 1997 on agricultural land in Arizona are estimated at 3.5 $MMtCO_2eq$ (Table 3-10). There was a net loss of 0.4 $MMtCO_2eq$ between 1987 and 1997. This is equal to an annual source of 0.04 $MMtCO_2eq$. Thirty-six percent of the stocks are estimated to be in woody vegetation. Both woody and non-woody vegetation represented an annual source of 0.02 $MMtCO_2eq$.

Table 3-10. Carbon stocks on agricultural land and their change (million tons of CO_2 equivalent, $MMTCO_2e$)

Date	Agricultural Land	Woody	Non-woody
1987	3.9	1.4	2.4
1997	3.5	1.3	2.2
1987–1997	-0.4	-0.2	-0.2

Table 3-11. The land use origins and destinations of changes in carbon stocks in agriculture in Arizona between 1987 and 1997. A negative sign indicates a net loss of carbon stocks from the land use in the row to the land use in the column

Land-Use Type	Growth of existing stands	Fruit Orchards	Nut Orchards	Vineyards	Non-Woody Crops	Rangeland	Forest	Urban / Transportation	Other	TOTAL CHANGE
Fruit Orchards	34,675				-15,379	6,483		-56,010	-27,305	-57,536
Nut Orchards	16,063				-2,185			-5,682	-3,060	5,136
Vineyards									697	697
Non-Woody Crops		122	303			5,403		-21,732	-31,263	-47,168

3.2.5. *Carbon Stocks of Agricultural Land by County*

The losses of carbon stocks from non-woody crops were spread through all but two counties in the state (Mohave and Pinal counties). In contrast, the net losses from woody crops were limited to four counties (Graham, Maricopa, Pima, and Yuma), with the losses of 29,900 and 34,900 tons of carbon from fruit orchards coming from single counties (Maricopa and Yuma, respectively) (Table 3-12 and Figure 3-8).

Table 3-12. Change in carbon stocks (t C) between 1987 and 1997 by crop types for counties in Arizona

County	Woody Crops			Non-woody Crops	
	Fruit Orchards	Nut Orchards	Vineyards	Row / Close crops	TOTAL
Apache	0	0	0	-305	-305
Cochise	2,740	935	0	-11,474	-7,799
Coconino	0	0	0	-60	-60
Gila	0	0	0	-1,457	-1,457
Graham	-3,376	0	0	-3,156	-6,532
Greenlee	0	0	0	-849	-849
La Paz	0	0	0	-7,406	-7,406
Maricopa	-29,892	0	0	-8,681	-38,573
Mohave	0	0	0	305	305
Navajo	0	0	0	-1,337	-1,337
Pima	0	-899	0	-1,275	-2,174
Pinal	7,844	2,210	697	1,214	11,965
Santa Cruz	0	0	0	-1,518	-1,518
Yavapai	0	0	0	-669	-669
Yuma	-34,853	2,889	0	-10,503	-42,467
TOTAL	-57,537	5,135	697	-47,171	-98,876

3.3. Non-CO_2 Greenhouse Gas Emissions

The primary non-CO_2 greenhouse gas emitted from croplands is nitrous oxide (N_2O), with approximately 296 times the global warming potential of CO_2. Nitrous oxide is emitted from agricultural soils especially after fertilizer application. A second important non-CO_2 gas is methane (CH_4), with approximately 23 times the global warming potential of CO_2. Methane is emitted during manure management and through livestock enteric fermentation.

The Arizona Climate Change Advisory Group (Bailie and Lazarus 2005) report an annual emission from agricultural sources (manure management, fertilizer use, and livestock [enteric fermentation]) of 4.2 $MMTCO_2e$ for the year 2000. This is more than 100 times the total estimated here for CO_2 emissions attributable to agricultural land conversion (0.036 $MMTCO_2e$/yr). The CO_2 equivalents from nitrous oxide and methane thus make up more than 99% of the total summed annual sources estimated for Arizona’s agricultural sector.

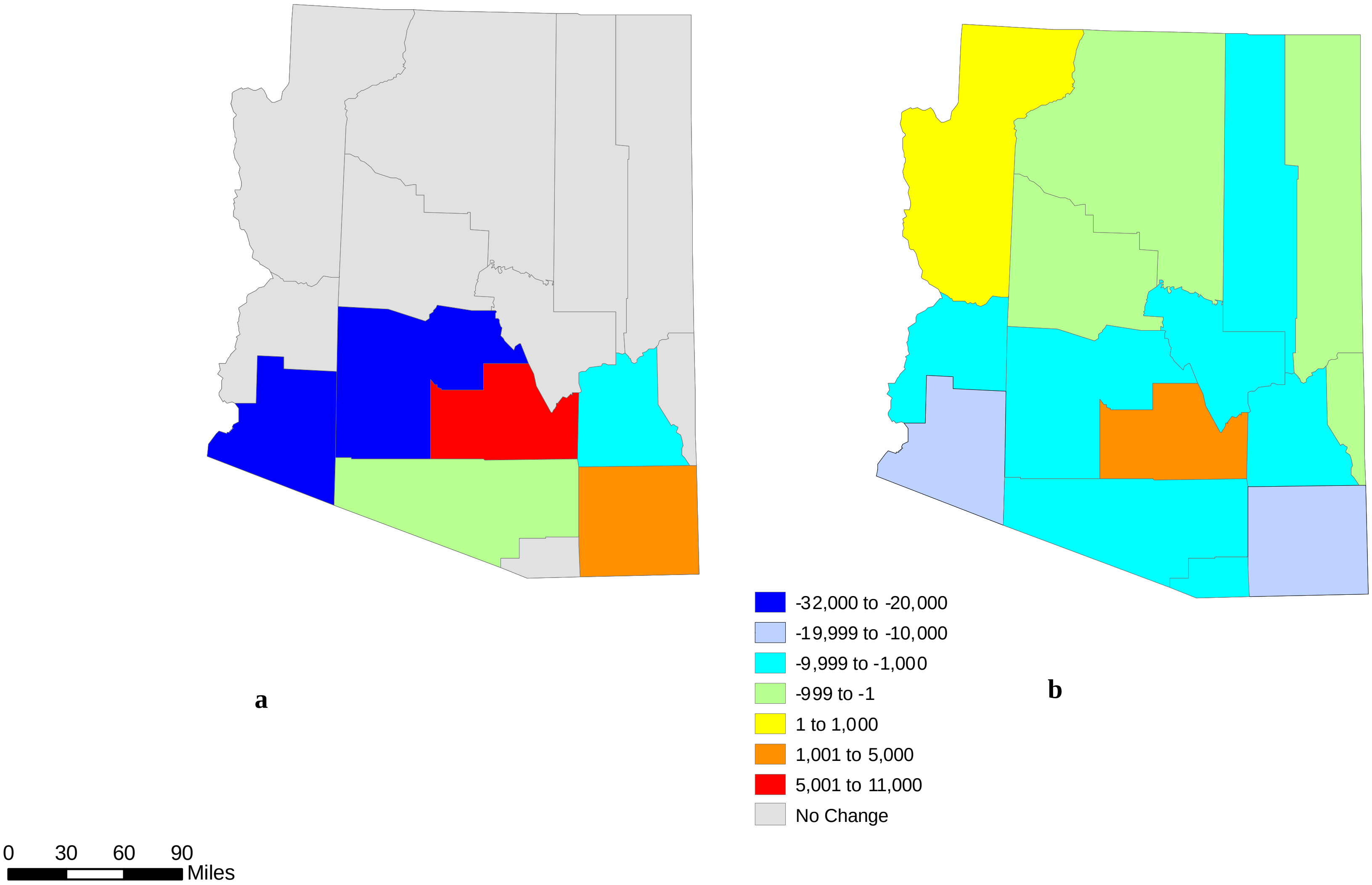

Figure 3-8. county-scale change in carbon stocks, 1987 to 1997, in (a) high-carbon crops (orchards and vineyards, and in (b) low-carbon crops (non-woody crops in Arizona. Values in tons of carbon

3.4. Chapter 3 Conclusions

Agricultural land in Arizona in 1997 represented 1.5% of the total land area, and non-woody crops were 93% of all agricultural land. Both woody and non-woody cropland are concentrated in the southern counties, with non-woody cropland totaling up to 9% of the total land area but woody cropland making up less than 0.5% of the land area in these counties. Statewide, there was a loss of agricultural land of 6.6% between 1987 and 1997, including a 7.2% decrease in non-woody cropland and a 2.3% increase in woody cropland. All land uses lost area over the period through conversion to urban development/transportation.

Total carbon stocks in all agricultural land types in Arizona were estimated at 1 million tons. Between 1987 and 1997, there was a total loss of about 99,000 tons of carbon, or 9.4% of the carbon stored in agricultural lands in 1987 (7.2% loss of the carbon stocks in non-woody crops and 13.1% of the carbon stocks in woody crops). The greatest losses came from conversion of fruit orchards and non-woody crops to urban development, and the greatest gains from conversion of rangeland to fruit orchards and non-woody crops. In CO_2 equivalent terms, total agricultural carbon stocks in Arizona in 1997 were 3.5 $MMTCO_2eq$, and the net loss 1987–1997 disregarding non-CO_2 greenhouse gas emissions was 0.4 $MMTCO_2eq$—equivalent to an annual source of 0.04 $MMTCO_2eq$. At the county level of analysis, all but two counties lost carbon through conversion of non-woody cropland to other land uses, but only five lost carbon through conversion of woody cropland. The greatest losses were in Maricopa and Yuma counties.

Non-CO_2 greenhouse gas emissions from N_2O (emitted from agricultural soils after fertilizer application) and CH_4 (from livestock and manure management) dwarf the annual CO_2 source from agricultural land conversion in Arizona.

Table 3-13 summarizes changes in agricultural land area and carbon stocks for Arizona between 1987 and 1997.

Table 3-13. Summary of agricultural land area and changes in area, carbon stocks, and changes in stocks, for Arizona 1987–1997

Parameter	Units	Arizona
Proportion of agricultural land to total land	%	1.5
Change in agricultural land area, 1987–1997	Hectares (%)	-30,759 (6.6%)
Change in woody cropland area		+687 (2.3%)
Change in non-woody cropland area		-31,446 (7.2%)
Total carbon stocks in agricultural land, 1997	MMTCO$_2$e	3.5
Change in carbon stocks in agricultural land	MMTCO$_2$e	-0.4
Estimated net annual source (emissions) from agricultural lands, disregarding non-CO$_2$ greenhouse gas emissions	MMTCO$_2$e	-0.04
From woody cropland		-0.02
From non-woody cropland		-0.02
Estimated net annual source from non-CO$_2$ greenhouse gas emissions, 2000	MMTCO$_2$e	4.2

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5.0 Glossary

AVHRR	Advanced Very High Resolution Radiometer
CH_4	methane
CO_2	carbon dioxide
CRP	Conservation Reserve Program
DBH	diameter at breast height
FIA	U.S. Forest Service Forest Inventory and Analysis
FIADB	forest inventory and analysis database
GHG	greenhouse gas
GIS	geographic information system
GPS	global positioning system
km	kilometer
$MMTCO_2e$	million metric tons CO_2 equivalent
N_2O	nitrous oxide
NASS	National Agriculture Statistics Service
NDVI	normalized differential vegetation index
NOAA	National Oceanic and Atmospheric Administration
NRCS	U. S. Department of Agriculture - National Resources Conservation Service
NRI	National Resource Inventory
OSU	Oregon State University
t CO_2e	tons of CO_2 equivalent
μm	micrometer
USDA	United States Department of Agriculture
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
WESTCARB	West Coast Regional Carbon Sequestration Partnership

WEST COAST REGIONAL CARBON SEQUESTRATION PARTNERSHIP
westcarb.org

PROJECT IDEA NOTE: AFFORESTATION/RESTORATION OF RIPARIAN AREAS ALONG SANTA CRUZ RIVER, ARIZONA USA

Casarim, F., T. Pearson, S. Petrova, K. Goslee, and S. Brown

Winrock International

DOE Contract No.: DE-FC26-05NT42593
Contract Period: October 1, 2005 - May 11, 2011

Table of Contents

Abstract

Riparian forests are crucial ecosystems linking the aquatic and the terrestrial environment. As a result, these riverine systems process large fluxes of energy, nutrients and life at various spatial and temporal scales. This project idea is for the revegetation of approximately 2,634 acres of riparian lands along the middle and lower reaches of the Santa Cruz River in the U.S. Five different properties were chosen for the implementation of this project. The revegetation project would generate a wide array of social and environmental benefits, such as: carbon sequestration, maintenance of water quality and quantity, fish and wildlife habitat enhancement, and aesthetics and human recreation improvement. In terms of sequestered carbon, the project would result in the uptake of as much as 150,000 tons of CO_2e from the atmosphere by 2050. Unfortunately, the implementation of this project was considered unfeasible in economic terms. Prices of the verifiable emission reductions (VER) would have to reach levels that are unlikely in the near future. For this project to break-even between costs and benefits (IRR = 0%) the price of the negotiated VER would have to reach US$ 67.00. Assuming a current estimate of US$ 7.00 it is unlikely this project can be implemented only using revenues from carbon sequestration.

Key words: Santa Cruz River, riparian forest, revegetation, carbon sequestration

Executive Summary

This project idea note is for a potential project for the revegetation of riparian areas along the Santa Cruz River in Arizona. The Santa Cruz River forms a bi-national ecosystem that has its headwaters in the United States, flows southward crossing into the Sonora desert in Northern Mexico and turns and reenters the U.S. just east of Nogales. This unique system supports tall and shaded forests in an arid climate, forming an oasis for vegetation, wildlife and people. Unfortunately, the riparian forests along the Santa Cruz have been historically mismanaged due to agricultural land expansion and are mostly inexistent from the borders of the river.

This project aims to analyze the viability of revegetating the riparian forests using the revenues generated from carbon credits as a result of the carbon sequestered by the established trees. The goal is to quantify the amount of carbon sequestered and potential revenues from credits in a regulatory market. As proposed, this project intends to revegetate a total of 2,634 hectares of land distributed over 5 different properties in the Southern portion (within the United States border) of the river.

The implementation of this project would generate the following direct social and environmental benefits to the local communities:

- Water quality maintenance;
- Storm water regulation and storage;
- Biodiversity maintenance and habitat enhancement;
- Sediment and nutrient retention;
- Improvement of human recreational activities; and
- Improvement of landscape aesthetics.

The establishment of this project would result in the sequestration of over 150,000 t CO_2e over its entire duration of 40 years. The uptake of carbon would be greater in the early growth stages of established vegetation and would slowly decrease over time. Costs of establishment however, as a result of the vast area to be revegetated, were estimated to be large, at the order of $4.7 million at the beginning of the project. Over time as plants uptake carbon and credits can be generated, this project would be able to balance costs with benefits.

To break-even between investments and revenues (internal rate of return – IRR ≥ 0%) in the 20 years subsequent its implementation the negotiated price of the Verified Emission Reductions (VERs or carbon credits) would have to be at the order of $67.00 per t CO_2e. This price is high because the project would have to operate for 5 years without crediting, as carbon sequestered would be dedicated to pay off emissions from removing existing vegetation during the project implementation process.

Due to the high cost of implementation, this project was considered not economically feasible. Current market prices for VERs of US$7.00 would have to rise to a level unlikely in today's or any near future market ($110.00) in order for the IRR of the project to reach over 5%. Therefore it was concluded that this project is not practical in economic terms if only using revenues generated from carbon offsets.

1.0 Introduction

1.1 Background and Overview

This project aims to reforest and restore native riparian forests along the Santa Cruz River in Southern Arizona. Riparian forests are unique systems because they connect the aquatic and terrestrial environments. Riparian forests of this river are degraded due to human presence. Yet, twenty-two threatened and endangered species make their home within the Santa Cruz basin, highlighting the importance of this green oasis in the arid landscape of the Southwestern United States.

Five (5) different areas within Pima and Santa Cruz counties accounting for a total of 2,634 acres are included in this afforestation/restoration project. The project will improve the integrity and functionality of the Santa Cruz River, ensuring a healthy stream system and maintaining the river's provision of societal goods and services, such as:

- Carbon sequestration;
- Water quality maintenance;
- Storm water regulation and storage;
- Biodiversity maintenance;
- Fish and wildlife habitat enhancement;
- Sediment and nutrient retention and soil integrity protection;
- Local microclimate regulation;
- Improvement of human recreational activities; and
- Improvement of landscape aesthetics.

1.2 Project Objectives

The main goal of this project is to restore the riparian forests along the Santa Cruz River in Southern Arizona reestablishing the functionality and integrity of this river system. By doing so, this project aims to promote carbon sequestration and the maintenance of other societal services provided by the river.

1.3 Report Organization

The "Project Idea Note" (PIN) is presented in section 2 describing potential type and size of an afforestation /reforestation project on riparian areas along Santa Cruz River in Arizona. This PIN is framed in the World Bank's BioCarbon Fund, PIN Template for Land Use, Land Use Change and Forestry (LULUCF) projects, available at: http://wbcarbonfinance.org/Router.cfm?Page=BioCF&FID=9708&ItemID=9708&ft=DocLib&ht=34&dtype=191&dl=0. More relevant information to the development of this project is also reported in section 3 "Additional Information".

2.0 Project Idea Note

Name of Project: Afforestation/restoration of riparian areas along the Santa Cruz River, Arizona USA

Date submitted: *March 2010*

A. Project description, type, location and schedule

General description	
A.1 Project description and proposed activities	Afforestation/ restoration of ~ 2634 acre riparian area along Santa Cruz River, AZ. Project area will be planted with native trees and proper management will assure following vital function of riparian forest: • Carbon sequestration • Maintenance of water quality • Fish and wildlife habitat enhancement • Biodiversity maintenance • Flood and storm water storage • Sediment and nutrient retention
A.2 Technology to be employed (mention if REDD will be undertaken)	• Afforestation & restoration of riparian areas with native tree species
Project proponent submitting the PIN	
A.3 Name	**Winrock International**
A.4 Organizational category *(choose one or more)*	a. Government b. Government agency c. Municipality d. Private company e. **Non Governmental Organization**
A.5 Other function(s) of the project developer in the project *(choose one or more)*	a. Sponsor b. Operational Entity under the CDM c. Intermediary d. **Technical advisor**
A.6 Summary of relevant experience	Winrock International is a 501(c)3 non-profit organization that works with people in the United States and around the world to increase economic opportunity, build local institutional capacity, and sustain natural resources. Winrock has approximately 15 years' experience in the measurement, monitoring and verification (MMV) of forestry carbon projects in the US and internationally. Our peer-reviewed methods for carbon MMV are being used by a broad range of private sector, government and nongovernmental clients on over two million acres around the world. Winrock's carbon project services include project review and carbon benefit assessment, Kyoto Protocol – Clean Development Mechanism (CDM) and Joint Implementation (JI) project development and review, monitoring plan design and implementation, baseline establishment and leakage assessments, design of

	new CDM/JI project methodologies, customized workshops on CDM/JI project development, quality assurance and quality control protocols, spatial prediction of deforestation, workshops on baseline and monitoring plan design and implementation, field training in carbon estimation, aerial geo-referenced imagery for carbon monitoring and other applications, and remote sensing analysis. Winrock has assisted in the design of forestry carbon measurement and monitoring protocols for the USDOE 1605(b) program, the Voluntary Carbon Standard, California Climate Action Registry, Regional Greenhouse Gas Registry, World Bank BioCarbon Fund, UNDP, International Tropical Timber Organization, UNFCCC and others, and is an Authorized Verifier of forestry offset projects for the Chicago Climate Exchange. For publications related to carbon measurement, monitoring and verification, see http://www.winrock.org/ecosystems/publications.asp?BU=9086. Innovative carbon project design and implementation Over the last ten years, Winrock's portfolio has totaled more than $9 million to support carbon supply assessments, development of field carbon measurement methods, development of carbon sequestration and emissions avoidance projects (both terrestrial and clean energy), and transfer of knowledge and build capacity to local governments and organization in developing countries. Winrock has implemented carbon mitigation activities and projects with many partners and from several angles, including: Winrock has been the main carbon sequestration project development and project monitoring partner to the private sector in the U.S. Since the mid-1990s we have worked with more than 30 private companies who heard of us through our involvement in defining measurement criteria and best practices. Among the largest companies are AEP, Entergy and Cinergy/Duke Energy (power) and LaFarge (cement), all of whom have taken major steps to offset their carbon emissions. We have also worked with commercial forest operators in Asia, Africa and Latin America. In part as a result of our continuing efforts to reduce costs while improving measurement and monitoring technologies, Winrock has increasingly been asked by private companies to conduct official verifications for carbon offset registries.
A.7 Address	2121 Crystal Drive, Suite 500 Arlington, VA 22202
A.8 Contact person	Katherine Goslee
A.9 Telephone / fax	703-302-6500
A.10 E-mail and web address	carbonservices@winrock.org http://winrock.org/ecosystems
Project sponsor(s) financing the project *(List and provide the following information for all project sponsors)*	
A.11 Name	TBD
A.12 Organizational category *(choose one or more)*	a. Government b. Government agency c. Municipality d. Private company

e. Non Governmental Organization

TBD

A.13 Address *(include web address)*: TBD

A.14 Main activities: TBA.

A.15 Summary of the financials *(total assets, revenues, profit, etc.)*: This table displays a summary for a project lifetime of 20 years as suggested in C.7

	2011	2012	…	2022	…	2030	2031
Investments	$4,741,200	$447,780	…	$0	…	$0	$0
Total Net Revenues	$0	$0	…	$417,745	…	$233,629	$216,008
(-) Total Costs	$0	$0	…	$25,000	…	$25,000	$25,000
Margin / (EBITDA)	$0	$0	…	$392,745	…	$208,629	$191,008
Net profit	$0	$0	…	$ 392,745	…	$208,629	$191,008
Free Cash Flow	**-$4,741,200**	**-$447,780**	**…**	**$392,745**	**…**	**$208,629**	**$191,008**

Type of project

A.16 Greenhouse gases targeted: CO_2

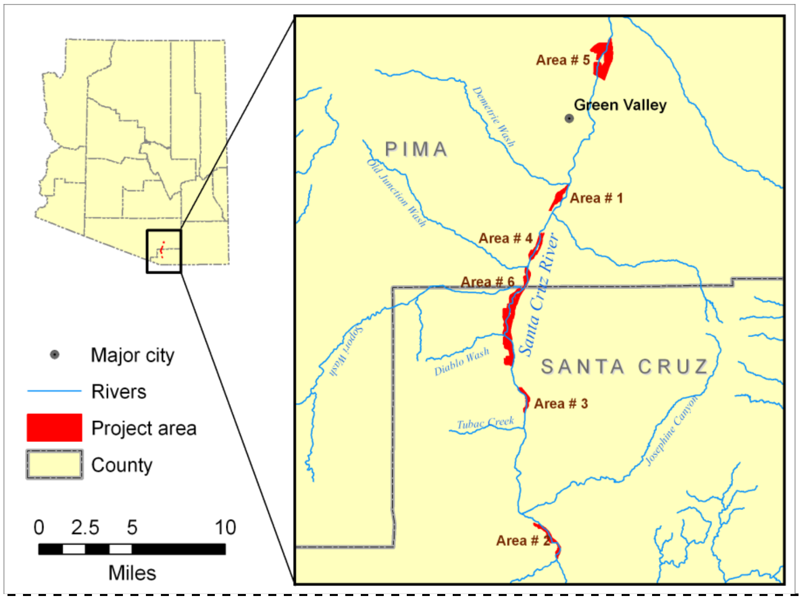
A.17 Type of activities: Sequestration

A.18 Field of activities (*Select code(s) of project category(ies) from the list*): 1a (forest)
Afforestation of riparian areas with native tree species

Location of the project

A.19 Country: USA

A.20 Nearest city and map: Green Valley, AZ
The six (6) project areas are located approximately within 20 miles from Green Valley, AZ



A.21 Precise location	(1) Lat: 31.795 Long -111.010 ; area = 179 acres (2) Lat: 31.530 Long:-111.018 ; area = 230 acres (3) Lat: 31.637 Long:-111.037 ; area = 116 acres (4) Lat: 31.754 Long:-111.032 ; area = 162 acres (5) Lat: 31.908 Long: -110.974 ; area = 835 acres (6) Lat: 31.709 Long: -111.052 ; area = 1,114 acres
Expected schedule	
A.22 Earliest project start date *(Year in which the project will be operational)*	March 2011
A.23 Estimate of time required before becoming operational after approval of the PIN	Time required for financial commitments: 12 months Time required for legal matters: 12 months Time required for negotiations: 12 months Time required for establishment: 12months
A.24 Year of the first expected CER / ERU / RMU / VER delivery	2012
A.25 Project lifetime *(Number of years)*	50 years
A.26 Current status or phase of the project	a. Identification and pre-selection phase b. Opportunity study finished c. Pre-feasibility study finished d. Feasibility study finished e. Negotiations phase f. Contracting phase

B. Expected environmental and social benefits

Environmental benefits	
B.1 Estimate of carbon sequestered or conserved *(in metric tonnes of CO_2 equivalent – t CO_2e. Please attach spreadsheet.)*	Up to and including 2020: 67,897 ±10,544 t CO_2e (mean ± 95% confidence interval) for 10years of expected sequestration Up to and including 2050: 150,010 ± 24,251 t CO_2e (mean ± 95% confidence interval) for 40 years of expected sequestration **Estimated carbon sequestration for riparian areas in Arizona was derived from field measurements along the Lower Colorado River presented in following table.**

Years	Expected Cumulative Sequestration	
	t CO_2e/acre	*95% CI*
0	0	*4.8*
1	2	*4.7*
2	5	*4.5*
3	7.9	*4.4*
4	11	*4.3*
5	14.2	*4.2*
6	17	*4.1*
7	20.3	*4.0*

8	23	*4.0*
9	25.8	*4.0*
10	28	*4.0*
11	30.6	*4.0*
12	33	*4.0*
13	34.9	*4.1*
14	37	*4.1*
15	38.6	*4.2*
16	40	*4.3*
17	41.9	*4.5*
18	43	*4.6*
19	44.6	*4.8*
20	46	*4.9*
21	47.0	*5.1*
22	48	*5.3*
23	49.0	*5.5*
24	50	*5.7*
25	50.7	*5.9*
26	51	*6.1*
27	52.1	*6.3*
28	53	*6.5*
29	53.3	*6.8*
30	54	*7.0*
31	54.4	*7.2*
32	55	*7.5*
33	55.3	*7.7*
34	56	*8.0*
35	56	*8.2*
36	56	*8.5*
37	56.6	*8.7*
38	57	*9.0*
39	57.2	*9.2*
40	57	*9.5*
41	57.6	*9.7*
42	58	*10.0*
43	58	*10.3*
44	58	*10.5*
45	58.3	*10.8*
46	58	*11.0*
47	58.6	*11.3*
48	59	*11.6*
49	58.8	*11.8*
50	59	*12.1*

B.2 Baseline scenario *(What would the future look like without the proposed project? What would the estimated total carbon sequestration / conservation be without the proposed project?)*	Without the project, land remains barren or non-forested composed mostly by grassland and shrubland with few sparse trees. Without the project, no significant changes are expected for total carbon sequestration/ conservation.
B.3 Existing vegetation and land use *(What is the current land cover and land use? Is the tree cover*	The project area is covered predominantly with grassland and shrubland. The tree cover in the project area is less than 10% (Spatial combination of the project area with the 2001 NLCD map and Southwestern GAP 2001 vegetation map indicated that more

more or less than 30%?)	than 90% of the project area is occupied with grassland and/or shrub and scrub land cover and vegetation classes).
B.4 Environmental benefits	• Maintenance of biodiversity by promoting plant and animal genetical fluxes between and within landscapes • Enhancement of plant, fish and wildlife habitat • Improvement and maintenance of water quality • Filtration and retention of upland and upstream sediments and associated nutrients • Regulation of water flow by reducing and storing flood water runoff • Regulation of local microclimate • Improvement of human recreational activities • Improvement of the aesthetics of the landscape

C. *Finance*

Project costs	
C.1 Preparation costs - gathering information on the area and writing PIN	US$ 0.1 million
C.2 Establishment costs - Planting	US$ 4.7 million
C.3 Other costs - Maintenance	US$ 0.4 million Year 1 US$ 0.3 million Year 2
C.4 Total project costs	US$ 5.5 million
C.5 Indicative CER / ERU / RMU / VER price *(subject to negotiation and financial due diligence)*	VERs price estimation: US$ 4.00 US$ 7.00 US$ 15.00
C.6 Emission Reductions Value *(= price per t CO_2e * number of tCO_2e)* Please discriminate VERs from REDD activities.	Price of VER per ton is based on Updegraff et al. (2004) estimations.
Until 2020	67,897 (±10,544) VERs at US$ 4.00 = US$ 271,588 ± 42,156 67,897 (±10,544) VERs at US$ 7.00 = US$ 475,279 ± 73,808 67,897 (±10,544) VERs at US$ 15.00 = US$ 1,018,455 ± 158,160
Until 2050	150,010 (± 24,251) VERs at US$ 4.00 = US$ 600,040 ± 97,004 150,010 (± 24,251) VERs at US$ 7.00 = US$ 1,050,070 ± 169,757 150,010 (± 24,251) VERs at US$ 15.00 = US$ 2,250,150 ± 363,765
C.7 Financial analysis *(If available for the proposed CDM / JI activity, provide the forecast financial internal rate of return (FIRR) for the project with and without the CER / ERU / RMU / VER revenues.)*	FIRR without carbon: This project has no return without the benefits from carbon accounting. FIRR with carbon: In order for this project to achieve balance between all the costs and revenues, the price of the VER needs to be raised to US$ 67.00. In this case, IRR over 20 year would be 0.06%, since the first 5 years would not be crediting period as it

	would pay off emissions caused during establishment of the project.

3.0 Additional Information on Riparian Systems

Riparian ecosystems are the transitional zones characterizing the interface between terrestrial and aquatic environments. Considered ecotones, riparian areas are affected by continuous exchange of energy, nutrients, compounds, and organisms on the landscape at various temporal and spatial scales. These ecosystems are characterized by Naiman et al. (2005) to be among the most diverse, dynamic and complex natural systems. As a result, they encompass a great variety of environmental conditions, ecological patterns and processes, as well as animal and plant communities.

Most definitions of these systems agree upon the uniqueness of riparian forests and their capacity for promoting interactions between and within the landscape (Mitsch and Gosselink, 2000). The interactions across landscapes are defined by exchanges between the uplands and the aquatic ecosystems; whereas the interactions within landscapes are characterized by the exchanges within the different reaches of these aquatic systems. Due to their interconnectivity between and within the landscape, these forests process large fluxes of energy and nutrients, and support significant biotic diversity (Mitsch and Gosselink, 2000) at various scales. As a result of their importance within the landscape mosaic, these systems have been historically linked to society's welfare (Lockaby, 2009), dictating the quality of human life and often improving human wellbeing.

Geomorphologically, riparian forests are complex and dynamic fluvial landforms. The landscape complexity and diversity of these systems are the result of their primary shaping forces, described as the cut-and-fill process (Naiman et. al., 2005). This process depends basically on water mediated erosion in certain areas (cut) followed by transportation and subsequent deposition of this alluvial sediment on the lower reaches of the streams (fill). Therefore, we can infer that this portion of the landscape is continuously eroding in some places while aggrading in others. Generally, the resulting riparian ecosystems may occur as two main types of landforms: (i) narrow strips of streambank, or (ii) broad alluvial valleys. The type of landform which the riparian zone will assume is, however, dependent upon a wide array of factors, including surface and sub-surface geology, slope gradient, and hydrology.

According to Knox (1977), vegetation and forest cover in watersheds and along streams help decrease surface runoff and sediment yield, due to an increase in precipitation interception and soil infiltration capacity. Even though sediment may be considered to be in constant motion over long time scales, most riparian forested areas reveal net aggradation of sediment from two distinct sources: (i) runoff from adjacent lands and (ii) over-bank floods (Hupp, 2000). By trapping sediments, riparian forests also trap nutrients that are either carried by sheetflow or are attached to sediment particles (Hupp, 2000). As a consequence, most riverine forests are known for preserving and maintaining downstream integrity and water quality by retaining nutrients and sediments carried by surface runoff (Hupp, 2000; Cavalcanti and Lockaby, 2005; Jolley et al., 2009). In fact, this process has been identified as a natural function of riparian forests (Mitsch and Gosselink, 2000) and is often taken for granted (Lockaby, 2009).

3.1 Southern Arizona Riparian Forests

In the project area the riparian forest is constituted mostly of Fremont cottonwood (*Populus Fremontii*) and black willow (*Salix nigra*). These native riparian trees are part of nature's healing process for entrenched rivers and streams. The trees slow the flow, help build and hold soils in place, and provide a place for storage and slow release of water, which is an extremely important feature in the dry conditions of the state of Arizona. Riparian vegetation helps regulate flows by making the system "spongy" again. The Increased storage capacity in riparian zones makes available much of the water required for riparian growth.

According to Lomeli (2009, unpublished) earthquakes, climatic changes, historic overgrazing, fuel wood removal, beaver eradication, and altered fire regimes all contributed to river entrenchment between 1890 and 1908. Entrenchment changed many southwestern rivers around the same time period from surficial, sluggish cienega/marsh environments, to faster deeply incised rivers. As nature's response, rapid proliferation of cottonwood-willow riparian forests and increased river sinuosities immediately followed the entrenchment period.

Riparian vegetation increases roughness coefficients in channels and floodplains, slowing down flood flows, causing deposition of soils and debris that build and stabilize banks. Gradually, river beds and banks are stabilized, floodplains are built-up, and perennial river reaches are extended, resulting in a rise of base flow levels and water tables. Good watershed ground cover is essential to infiltrate precipitation and to prevent excessive runoff and erosion. In a floodplain, grasses and shrubs also help the healing process, but during higher flows each year, the larger trees provide better protection and faster aggradation (Lomeli, 2009, unpublished).

Riparian areas act as wildlife corridors between mountains, uplands, and the river by providing habitat continuity for species migrations. Small pools and near-surface water along these washes make excellent habitats. The vegetation provides cover, food, and nesting and roosting areas. Riparian corridors also provide habitat for many insects and reptiles, which in turn serve as a base for a complete food chain.

According to Lomeli (2009, unpublished) the challenge in the Upper Santa Cruz basin is not just one of balancing the water budget. Concentrated groundwater over-drafting between the mountain-front recharge zones and the river can cause loss of base flows in perennial stream reaches, and subsequent loss of riparian habitats. However, working together, impacts can be mitigated with appropriate water management, groundwater recharge, and watershed improvement projects.

4.0 Discussion of Project Feasibility

The VER price estimated in this PIN to break-even between the implementation costs and earned revenues is $67.00 (IRR=0.06%). This price is similar to the credits' costs estimated by Galik et al. (2009) ranging from $30 to $65.00 per ton of CO_2e which varied according to the protocol used (VCS, CCX, etc.). The VER estimated price was high because the project would have to operate for 5 years, out of the 20 years used in the analysis, without crediting, only paying off the emissions caused during the implementation by removing existent vegetation at site preparation for planting.

The feasibility of this project is critically influenced by the area where it is located. The implementation of this project is expensive because of Arizona's natural characteristics. Pearson et al. (2007) showed that 95% of the forests in the state of Arizona are within the six most northerly counties (Apache, Coconino, Gila, Mohave, Navajo and Yavapai). Pima and Santa Cruz counties, where this project takes place are situated in southern Arizona, where conditions for tree growth are poor.

According to the Western Regional Climate Center (WRCC) the state of Arizona has three main topographies that dictate the climate regime: (i) high plateau, (ii) mountainous, and (iii) desert. The proposed project takes place in the desert topographic area, which indicates low precipitation amounts; therefore, forest is not well sustained within this region if not along rivers and wetlands.

The lack of forested landscape in this region creates a lack of professionals who could provide forestry services; which drives the costs of implementation up. Thus, this aforestation/reforestation project becomes expensive in terms of price per area planted.

However, there are Federal incentives to develop such projects. The United States Environmental Protection Agency (US EPA) for instance, provides grants ranging from $5,000 to $20,000 through the Five-Star Restoration grant program.

Considering that the six different areas proposed in this PIN are spatially separated, little decrease in the total budget per acre would be possible due to issues of economies of scale. As a simple exercise to study the feasibility of this proposed project at a different scale, the smallest of the six proposed properties above (property 3 with 116 acres) was used, the cost of implementation proposed by Galik et al. (2009) was applied, and an assumption of an acquisition of a $10,000 US EPA grant was made. Still, the price of VER would need to be at the order of $61.00 for the project to break-even between costs and revenues in 20 years after project establishment. At this VER price, the financial rate of return (FIRR) calculated would be 0.04%. In terms of financial stand-point, the revegetation of riparian forests on all the properties along the Santa Cruz River proposed in this project would only be desirable (IRR>5%) if VER price was raised to $110.00 per t CO_2e.

Although the revegetation of the margins of the Santa Cruz River may generate innumerous environmental and social benefits, this project of revegetation of the riparian forests is ultimately unfeasible if dependent on the benefits produced by carbon offsets alone.

Current carbon credits prices cannot afford the implementation of this project. Furthermore, carbon prices will likely not rise to a level that allows favorable financial returns or even breaking even with costs.

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CHARACTERIZATION OF THE GREENHOUSE GAS EMISSIONS ASSOCIATED WITH CONVERSION OF FOREST TO RESIDENTIAL DEVELOPMENT IN THE PUGET SOUND REGION OF WASHINGTON

Swails, E., TRH. Pearson, M. Netzer, K. Goslee and S. Brown.

Winrock International

DOE Contract No.: DE-FC26-05NT42593
Contract Period: October 1, 2005 - May 11, 2011

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Abstract

The conversion of forest lands to non-forest uses, especially conversion to residential development, is of significant concern to the Washington State Legislature and Washington Department of Natural Resources. As a result of a rapidly growing population, the risk of conversion is especially high in Puget Sound's watersheds. The objective of this study was to develop a regional characterization study for Washington State that defines residential development as it is implemented in the Puget Sound region to estimate the emissions associated with conversion of forested land for residential development. Net emissions in King County ranged from 70 t CO_2-e to 177 t CO_2-e per development. In Pierce County net emissions ranged from 412 t CO_2-e to 1,418 t CO_2-e per development. In Snohomish County development resulted in net emissions for some subdivisions while other subdivisions showed net sequestration (negative net emissions); Net emissions ranged from 12 t CO_2-e to 670 t CO_2-e, and net sequestration ranged from 8 t CO_2-e to 335 t CO_2-e. While original forest cover pre-development varied across the developments, a relationship existed between total area of development and percentage of original forest cover remaining after development. Forest cover cleared during development varied from 57-100% in areas of less than 16 acres but averaged just 35% for development areas that exceed 16 acres. This relationship could form the basis of a future performance standard for development projects such that if a developer exceeded the defined area of forest retained by 10% or more then the carbon stocks of the retained forest would be creditable. For example, the resulting available offsets range from approximately 136 tons for a 10 acre development to almost 3,000 tons for a 60 acre development in an area with forest carbon stocks of 100 t C/ac.

Executive Summary

Introduction

The conversion of forest lands to non-forest uses, especially conversion to residential development, is of significant concern to the Washington State Legislature and Washington Department of Natural Resources.

As a result of a rapidly growing population, the risk of conversion is especially high in Puget Sound's watersheds, where 80% or more of the remaining private forestlands not enrolled in the Designated Forestland Program are at high risk.[1] Although the aim of planning under the Growth Management Act in Washington State is to control population growth in rural areas, growth in unincorporated areas of King, Pierce, and Snohomish Counties has exceeded targets.

In WESTCARB Phase I the baseline for emissions from development in Washington State was estimated (Pearson et al 2007[2]). Over a ten year period from 1987-1997 an estimated 246 thousand acres were deforested for urban development across the state. Forty-two percent of this area was in the King, Pierce and Snohomish counties even though these counties represent just 8% of the State. Pearson et al. (2007) estimated net emissions across the three counties of over 7 million tons of carbon dioxide equivalent per year or 45% of the total from development across the whole state.

The estimates of Pearson et al. (2007) represent a first order approximation based on available data at the time on forest carbon stocks, forest cover change, and approximations of changes in carbon stocks. Furthermore, these results indicate that urban growth around the city of Seattle in King, Pierce and Snohomish counties is an important source of emissions from land use change in Washington State. To improve understanding of this process, Winrock International carried out a study of emissions from conversion of forest to urban area in the Puget Sound region - King, Pierce and Snohomish counties.

Purpose

The objective of this project is to develop a regional characterization study for Washington State that defines residential development as it is implemented in the Puget Sound region to estimate the emissions associated with conversion of forested land for residential development. Although studies of urban forests and ecosystems in the United States and their associated carbon stocks exist,[3] there is little information on carbon stock changes and GHG emissions

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[1] Rogers, L, Cooke, W. 2010. The 2007 Washington State Forestland Database: Final Report. University of Washington – College of Forest Resources.

[2] Pearson, T., S. Brown, N. Martin, S. Martinuzzi, S. Petrova, I. Monroe, S. Grimland, and A. Dushku. 2007. Baseline Greenhouse Gas Emissions and Removals for Forest and Agricultural Lands in Washington State. California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-2007-026.

[3] Alberti et al. 2010. Urban terrestrial carbon stocks. *In review*.: Jo and McPherson. 1995. Carbon Storage and Flux in Urban Residential Greenspace. *Journal of Environmental Management*. 45: 109-133.; Nowack et al. 1996. Measuring and analyzing urban tree cover. *Landscape and Urban Planning*. 36: 49-57. Peper et al.

associated with the conversion process itself. In addition, existing studies of urban forests have focused on average crown cover across urban land, and have not produced a consistent set of definitions of land classes within urban and suburban areas that could be used to estimate carbon storage per unit of land class within settled areas.

The characterization will define residential development in the Puget Sound region in terms of the most common lot size and change in vegetation cover and associated carbon stocks. This regional characterization could be used both for full accounting of greenhouse gas emissions associated with development and also potentially to develop a class of offset projects permitting market pressures and incentives to decrease total net greenhouse gas emissions and retain forests in the Puget Sound region.

Project Results

Hearing Examiner decisions on applications for subdivision of land in rural and urban residential zones from 2000 to 2010 were reviewed to determine the zones where development is most intense in terms of total single-family residential lots created in each county. As most of the lots in the subdivision applications reviewed in Pierce and King Counties were located in zones with minimum lot size 0.25 acres or smaller, we infer that the most common lot size for development of residential subdivisions in unincorporated areas of Pierce and King County is 0.25 acres or smaller. Development in unincorporated areas of these two counties is relatively dense compared to development in unincorporated Snohomish County, where the most common lot size in reviewed subdivision applications was 1 acre.

Parcel boundaries for the subdivision plat were overlaid with a series of orthorectified aerial images from multiple time points to characterize the change in area of forest cover associated with development of the subdivision. The GIS analysis includes roads internal to subdivisions only, although the creation of residential subdivisions may influence the construction of access roads external to the subdivision. There is therefore the necessity for ongoing work to determine the total impact of development incorporating the dedicated roads and emission associated with clearing forest for road construction.

Development in King and Pierce Counties, where the most common lot size was 0.25 acres or less, resulted in clearing of 62% to 98% of forest cover. Development of these small lot sizes resulted in clearing of relatively more forest cover compared to 1 acre lots in zone R-5 in Snohomish County, which resulted in less than 50% clearing of forest cover for all but one of the subdivisions assessed. Proportion of existing forest cover cleared was also related to the total size of the development. Mean total development area in King and Pierce Counties and in zone R-9,600 in Snohomish Counties ranged between 3.3 ac to 9.5 ac with deforestation between 75% and 95%, while in zone R-5 in Snohomish County where the mean total development area was 30 acres only 33% of original forest cover was cleared.

To determine the direct change in carbon stock resulting from development, forest carbon stocks within the boundaries of each subdivision plat were determined by overlaying the parcel

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2001. Equations for predicting diameter, height, crown width, and leaf area of San Joaquin Valley street trees. *Journal of Arboriculture*. 27: 6.

boundaries with the USFS Forest Inventory and Analysis (FIA) biomass stock map.[4] The loss in forest cover through development led to average changes in stock in live trees of 289 t CO_2-e/ac, 1,237 t CO_2-e/ac, and 1,044 t CO_2-e/ac for King, Pierce, and Snohomish Counties respectively.

The average total emissions from forest conversion per subdivision, accounting for the quantity of cleared timber that is converted to harvested wood products resulting in long-term storage of carbon, and assuming that the remainder of cleared vegetation is diverted to energy recovery, was 235 t CO_2-e and 959 t CO_2-e for King and Pierce Counties respectively, and in Snohomish County 1,202 t CO_2-e for development in zone R-5 and 495 t CO_2-e for development in zone R-9,600.

A sample of subdivisions developed in the last ten years in the zones with the highest level of development was selected for field measurements to estimate carbon stock recovery post-development. Total stocks vary from 1.27 tons of carbon in a 0.1 acre lot to more than 39 t C in a 2 acre lot.

Full accounting of development emissions must capture both the emissions from clearing the forest and the sequestration that occurs after development. Net emissions in King County ranged from 70 t CO_2-e to 177 t CO_2-e per development. In Pierce County net emissions ranged from 412 t CO_2-e to 1,418 t CO_2-e per development. In Snohomish County, development resulted in net emissions for some subdivisions while other subdivisions showed net sequestration (negative net emissions). Net emissions ranged from 12 t CO_2-e to 670 t CO_2-e. Net sequestration ranged from 8 t CO_2-e to 335 t CO_2-e.

Net emissions from development was impacted by initial forest cover and by area of forest cleared for development. While the initial forest cover pre-development varied, a relationship existed between total area of development and percentage of original forest cover remaining after development. Forest cover cleared during development varied from 57-100% in areas of less than 16 acres but averaged 35% for development areas that exceed 16 acres.

This relationship could form the basis of a future performance standard for development projects such that if a developer exceeded the defined area of forest retained by 10% or more then the carbon stocks of the retained forest would be creditable. For example, the resulting available offsets range from approximately 136 tons for a 10 acre development to almost 3,000 tons for a 60 acre development in an area with forest carbon stocks of 100 t C/ac.

This study represents an initial analysis of development and associated emissions in three counties of the Puget Sound. The analysis shows the potential value of further examination of this category in the region. Emissions are large and are likely largely unaccounted for in inventories of greenhouse gas emissions. These emissions also present an opportunity for the creation of an offset project category. Where emissions can be reduced without leakage then these emission reductions should be creditable to developers and local authorities.

The limited time and resources for this study meant that only a limited number of development sites could be examined from limited zoning categories. A future study should look more

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[4] http://fsgeodata.fs.fed.us/rastergateway/biomass/

exhaustively at development that has occurred over the last 10 years over a larger sample of counties and zoning areas within the state and should use a similar methodology to calculate forest loss, the emissions resulting from forest loss and post development carbon stock recovery.

1.0 Introduction

1.1. Background and overview

The conversion of forest lands to non-forest uses, especially conversion to residential development, is of significant concern to the Washington State Legislature and Washington Department of Natural Resources.

As a result of a rapidly growing population, the risk of conversion is especially high in Puget Sound's watersheds, where 80% or more of the remaining private forestlands not enrolled in the Designated Forestland Program are at high risk.[5] This study focuses on King, Pierce and Snohomish counties, which are closely associated with the urban growth of the city of Seattle. The forests in these counties are valuable for both timber production and the ecosystem services that they provide including their role as a sink for greenhouse gases. Temperate climate, abundant rainfall, and deep soils make these forests some of the most productive in the nation.[6] Thus the Puget Sound watersheds represent an important area with overlapping competing demands from urban development, timber production and greenhouse gas sequestration.

In WESTCARB Phase I the baseline for emissions from development in Washington State was estimated (Pearson et al 2007[7]). Over a ten year period from 1987-1997 an estimated 246 thousand acres were deforested for urban development across the state. Forty-two percent of this area was in the King, Pierce and Snohomish counties even though these counties represent just 8% of the State. Pearson et al (2007) estimated net emissions across the three counties of over 7 million tons of carbon dioxide equivalent per year or 45% of the total from development across the whole state. The estimates of Pearson et al. (2007) represent a first order approximation based on available data at the time on forest carbon stocks, forest cover change, and estimations of changes in carbon stocks. Furthermore, these results indicate that urban growth around the city of Seattle in King, Pierce and Snohomish counties is an important source of emissions from land use change in Washington State.

The present study was conducted to characterize common practice for conversion of forest land to residential development in three counties of the Puget Sound region to estimate immediate emissions and baseline carbon stocks in converted lands. Estimation of baseline carbon stocks could be used to create a performance standard above which developers would receive credit for retaining forest cover on land converted for residential use. The characterization will cover minimum lot sizes and site clearing that are implemented according to local zoning standards

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[5] Rogers, L, Cooke, W. 2010. The 2007 Washington State Forestland Database: Final Report. University of Washington – College of Forest Resources.

[6] WA DNR. 2009. Future of Washington Forests: Washington's Forests, Timber Supply, and Forest-Related Industries.

[7] Pearson, T., S. Brown, N. Martin, S. Martinuzzi, S. Petrova, I. Monroe, S. Grimland, and A. Dushku. 2007. Baseline Greenhouse Gas Emissions and Removals for Forest and Agricultural Lands in Washington State. California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-2007-026.

and common practice as well as landscaping and disposal of removed vegetation. The characterization will also include an analysis of the carbon stocks in existing vegetation on forested land pre- and post-conversion.

1.2. Administration of development in the Puget Sound region

Various development regulations and official controls are applied in Washington State at different levels to ensure that development occurs in a coordinated manner that meets the needs of an expanding population while conserving the natural resource base of the State. Different mechanisms are in place in the three counties to concentrate development in urban areas and ensure appropriate development in rural areas.

1.2.1. The Growth Management Act

The Washington State Growth Management Act (GMA) requires the fastest growing counties and cities in the State to plan goals for sprawl reduction, concentrated urban growth, preservation of open space and areas for recreation, environmental protection, and promoting natural resource industries. Each of the three counties in the study has prepared a "unified development code" that includes regulations controlling how land is subdivided, used, and developed.

1.2.2 The development process

The development of large residential subdivisions for single-family detached housing begins when a parcel of land that is zoned for residential development is subdivided into smaller lots. This process is regulated by two categories of development controls: zoning and subdivision development provisions.

Zoning

Zoning defines the permitted uses of property, density coverage, setbacks, and landscaping levels for a given area. Zoning effectively controls what kind of development is allowed to occur in any given area. For example, zoning prevents commercial development in residential districts. Likewise, zoning can be used to prevent dense residential development in traditionally rural areas.

Subdivision

Subdivision is the re-division of land into five or more lots, tracts, parcels, sites, or divisions for sale, lease, or transfer of ownership[8]. The subdivision development process begins when a preliminary map or "plat" delineating small divisions within a larger parcel is submitted to county authorities. The preliminary plat is subject to a public hearing before a planning commission or hearing examiner. Once a preliminary plat is conditionally approved, the applicant has 5 years to file the final plat.

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[8] Washington State Subdivision Act of 1969

Development

Depending on the initial development site conditions, clearing of existing vegetation and some excavation may be required to prepare parcels for construction. At a minimum, trees and stumps must be removed from the building site and wherever excavation may be required for such things as basements, septic systems, wells, or utilities. However, the impacts of conventional development can be significant, including complete clearing of existing vegetation, leveling and grading topography, and compacting of soils. Various county ordinances regulate the removal of trees and soil disturbance for site preparation in the Puget Sound region. Figure 1 shows pre- and post-construction lots in the same subdivision in Snohomish County.

Figure 1 Examples of 1 acre residential lots in Snohomish County immediately following site clearing and post-construction

1.2.3 Density incentive provisions

Cluster development in rural areas allows for the preservation of open space while continuing to provide at least the same number of lots for residential development. This is accomplished through density incentives that are applied to reduce the minimum allowable lot size. For example, developers may receive on-site density incentives for maintaining a minimum proportion of a development site in open space.

1.3. Project objectives

The objective of this project is to develop a regional characterization study for three counties of Washington State that defines residential development as it is implemented in the Puget Sound region to estimate the emissions associated with conversion of forested land for residential development. Although studies of urban forests and ecosystems in the United States and their associated carbon stocks exist,[9] there is little information on carbon stock changes and GHG

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emissions associated with the conversion process itself. In addition, existing studies of urban forests have focused on average crown cover across urban land, and have not produced a consistent set of definitions of land classes within urban and suburban areas that could be used to estimate carbon storage per unit of land class within settled areas.

The characterization will define residential development in the Puget Sound region in terms of the most common lot size and change in vegetation cover and associated carbon stocks. This regional characterization could be used both for full accounting of greenhouse gas emissions associated with development and also potentially to develop a class of offset projects permitting market pressures and incentives to decrease total net greenhouse gas emissions and retain forests in the Puget Sound region.

1.4. Report organization

The introduction to this report is followed by a description of the methods used to achieve the project objectives. Methods used to define common practice, including spatial analysis and field measurements, are explained in this section. Following the methods section, the results of the study are presented in terms of the most common lot size for residential development in the three counties, zones with most extensive and/or intense development, associated land cover change determined from spatial analysis, and estimation of carbon stock recovery in the baseline determined with field measurements of biomass stocks in residential areas. The discussion of the results is followed by conclusions and suggestions for the development of a performance standard. Detailed information on county development standards and field measurement methods are included in the appendices.

2001. Equations for predicting diameter, height, crown width, and leaf area of San Joaquin Valley street trees. *Journal of Arboriculture*. 27: 6.

2.0 Analysis of Zoning and Deforestation

2.1. Background on zoning in forest areas

The rural and urban residential zones in Pierce, King and Snohomish were examined and characterized by minimum lot size.

> The King County Code Development Standards[10] divide residential zones into three categories: rural, urban reserve, and urban residential.
>
> The Pierce County Code Development Regulations[11] defines residential zones under urban and rural classifications.
>
> The Snohomish County Unified Development Code[12] defines urban residential and rural zones. The purpose of urban residential zoning in Snohomish County is to provide for predominantly single family residential development with minimum density of 4 dwelling units per acre.

Rural residential zoning in the three counties is generally applied to lands that are not designated as agricultural or forest lands of long-term commercial significance. Minimum lot size in these urban and rural residential zones in the three counties ranges from 0.02[13] acre to 40 acres.

2.2. Analysis methods

Hearing Examiner decisions on applications for subdivision of land in rural and urban residential zones from 2000 to 2010 were reviewed to determine the zones where development is most intense in terms of total single-family residential lots created in each county. Samples of approved applications for subdivision to create lots for single family residential units in each county were randomly selected for review. The following criteria were assessed for each subdivision application:

- number of lots created,
- zoning designation,
- subdivision design (cluster or non-cluster), and
- forest cover.

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[10] K.C.C. Chapter 21A.12

[11] P.C.C. Title 18A

[12] S.C.C. Title 30

[13] In King County, base density for urban residential zone R-48 is defined as 48 dwelling units per acre while minimum lot size in rural residential zone R-40 in Pierce County is 40 acres.

Forest cover was assessed by inputing the location information from the hearing examiner decisions into Google Earth.

2.3. Residential zones with highest levels of development

2.3.1. King County

Six zoning codes were evaluated in King County based on eligibility for single family dwellings. The six codes ranged in density requirements from a maximum density of 0.2 to 8 dwellings per acre (Table 1).

Table 1 Zoning categories and maximum development density for King County

Zoning Category	Zoning Code	Definition	Maximum Density
Rural Area	RA5	Rural area – 5 acre	0.2 dwellings/acre
Urban Residential	R1	Residential – 1 dwelling/acre	1 dwelling/acre
	R4	Residential – 4 dwellings/acre	4 dwellings/acre
	R6	Residential – 6 dwellings/acre	6 dwellings/acre
	R8	Residential – 8 dwellings/acre	8 dwellings/acre

In King County the majority of lots created through the subdivision applications assessed were made for parcels in zone R-4, R-6, and R-8 (Figure 2). Cluster development is not permitted in these three zones in King County.

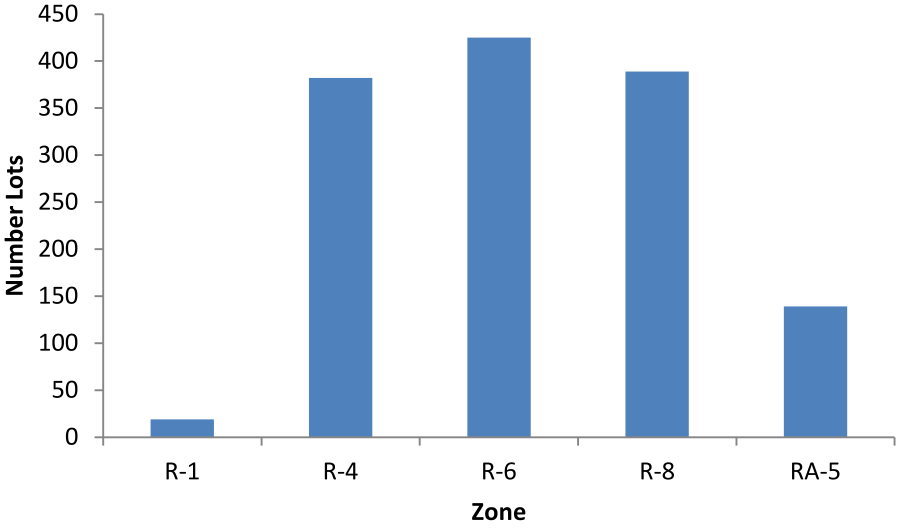


Figure 2 Number of lots for single family residential units created per zone from sample of 50 applications for subdivision in King County from 2000 to 2010.

Only 22 subdivision applications were assessed for land cover prior to development. The majority of the subdivisions (81%) in King County were developed on land with at least partial forest cover (Figure 3).

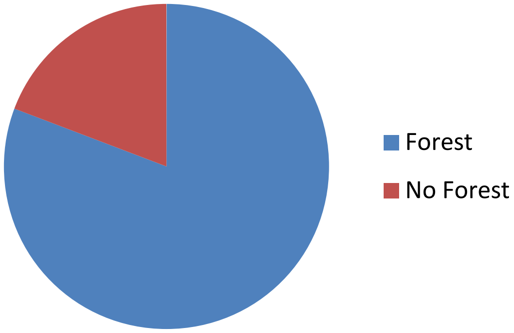


Figure 3 Subdivisions developed on land with forest cover in King County

2.3.2. Pierce County

Five zoning codes were evaluated in Pierce County based on eligibility for single family dwellings. The five codes ranged in density requirements from a maximum density of 1 to 25 dwellings per acre (Table 2).

Table 2 Zoning categories and maximum development density for Pierce County

Zoning Category	Zoning Code	Definition	Maximum Density
Urban Centers	CC	Community Center	25 dwellings/acre
Urban Residential	MHR	Moderate High Density - Residential	25 dwellings/acre
	MSF	Moderate Density Single-Family	6 dwellings/acre
	SF	Single Family	4 dwellings/acre
Rural Residential	Rsv5	Rural Residential, Resource Lands and Other Zones Reserve 5	1 dwelling/acre

In Pierce County, the largest proportion (40%) of the subdivisions applications assessed were made for parcels in the Moderate Density Single-Family zone (MSF), accounting for the majority of lots created for single family residential units (Figure 4). None of the applications reviewed indicated that cluster design was used.

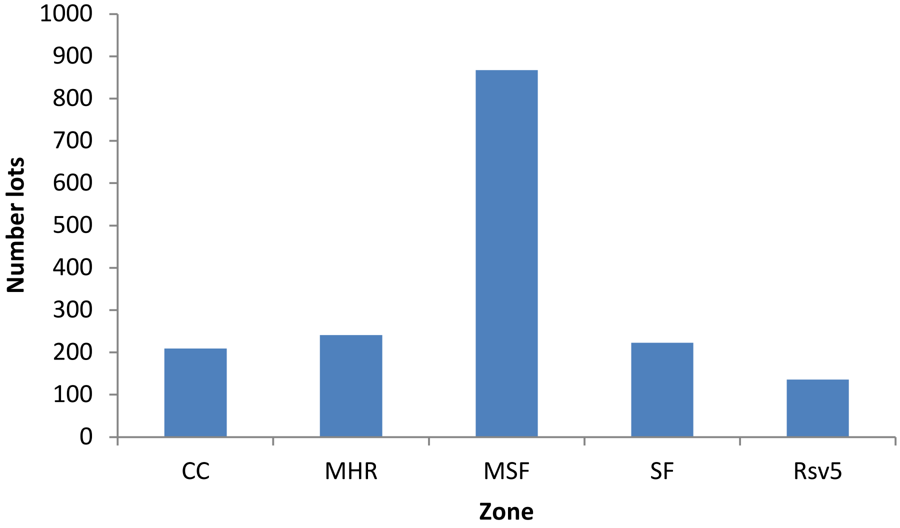


Figure 4 Number of lots for single family residential units created per zone from sample of 49 applications for subdivision in Pierce County from 2000 to 2010.

Slightly more of these subdivision projects in Pierce County included in the sample (55%) occurred on parcels with at least partial forest cover than on parcels with no forest cover (Figure 5).

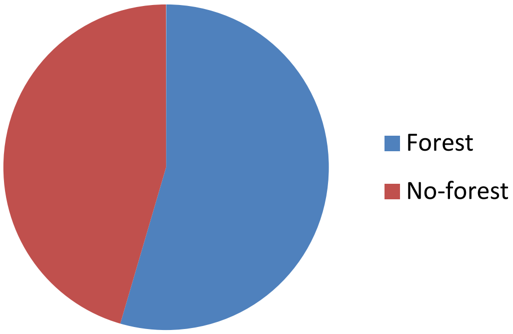


Figure 5 Development projects occurring on parcels with forest cover and with no forest cover per zone from sample of approved applications for subdivision in Pierce County from 2000 to 2010.

2.3.3. Snohomish County

Four zoning codes were evaluated in Snohomish County based on eligibility for single family dwellings. The five codes ranged in density requirements from a maximum density of 0.1 to 6 dwellings per acre (Table 3).

Table 3 Zoning categories and maximum development density for Snohomish County

Zoning Category	Zoning Code	Definition	Maximum Density
Urban Residential	R-7,200	Residential – 7,200 square feet	6 dwellings/acre
	R-9,600	Residential – 9,600 square feet	4.5 dwellings/acre
Rural	R-5	Rural – 5 acre	0.2 dwellings/acre
	RRT-10	Rural Resource Transition – 10 acre	0.1 dwelling/acre

In Snohomish County the majority of the subdivisions applications assessed were made for parcels in zone R-5, accounting for the majority of lots created for single family residential units (Figure 6). All of the applications for subdivision in zone R-5 were cluster subdivision with 1 acre lots. Cluster design is not allowed in zone R-9,600 or zone R-7,200.

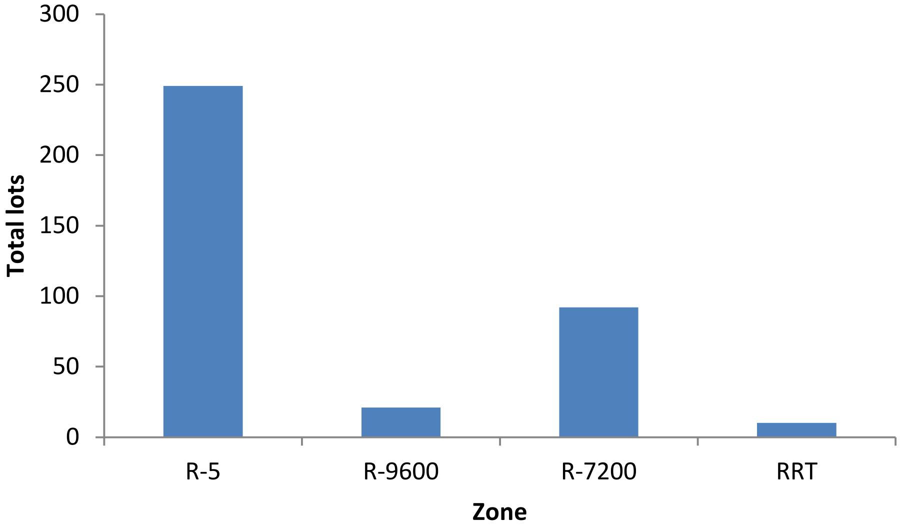


Figure 6 Number of lots for single family residential units created per zone from sample of 25 applications for subdivision in Snohomish County from 2000 to 2010.

The majority (84%) of the subdivision projects assessed occurred on parcels with at least partial forest cover (Figure 7).

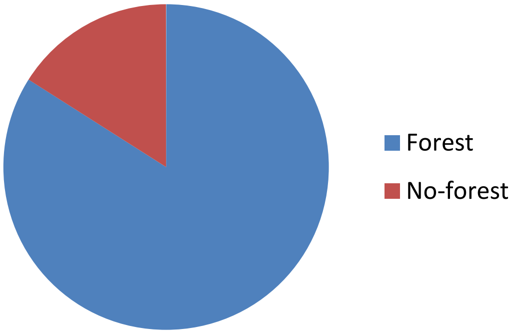


Figure 7 Development projects occurring on parcels with forest cover and on parcels with no forest cover per zone from sample of approved applications for subdivision in Snohomish County from 2000 to 2010.

2.4. Zoning summary

As most of the lots in the subdivision applications reviewed in Pierce and King counties were located in zones with minimum lot size 0.25 acres or smaller, we infer that the most common lot size for development of residential subdivisions in unincorporated areas of Pierce and King County was 0.25 acres or smaller. Development in unincorporated areas of these two counties is relatively dense compared to development in unincorporated Snohomish County, where the most common lot size in reviewed subdivision applications was 1 acre. Although the most common lot size in King and Pierce County might result in less area of forest conversion per lot developed compared to development in Snohomish County, the impact of residential development on forest in King and Pierce counties could be significant because the majority of subdivisions evaluated in these counties occurred on land with forest cover.

The majority of lots in unincorporated Snohomish County were located in cluster developments in zone R-5. Because the minimum allowed lot size without density incentives in Snohomish County in zone R-5 was 5 acres, the majority of residential subdivisions in Snohomish County occurred in rural areas in zones where large lot subdivisions would likely not be common practice without cluster development.

This study focuses from this point onwards on those zones where single family residential development is a primary use and large residential subdivision developments are a common practice. In each county, residential development standards are defined for rural and urban residential zones. In urban residential zones, dimensional standards ranged from very dense development with very small lot sizes (as high as 48 units per acre in King County) to moderate density development with an average of 4 units per acre with a minimum lot size of approximately 0.25 acre. In rural residential areas, development is typically less dense. It is reasonable to assume that the proportion of the area cleared of vegetation for each lot developed in rural zones with very large minimal lot size is small compared to zones with smaller lot sizes. Furthermore, large residential subdivisions are not a common practice in these zones. On the other hand, zones with very dense development likely result in 100% clearing of vegetation and more impervious surface areas as a proportion of total lot area. Therefore, the greatest opportunity for changing common practice to mitigate emissions may be expected in the zones listed in Table 4, taking into account the zones with the highest levels of development in the three counties.

Table 4 Medium density residential zones in King, Pierce, and Snohomish Counties

County	Zone	Category	Minimum Lot Size (ac)
King	R-4	Urban Residential	0.25
Pierce	MSF	Urban Residential	0.17
Snohomish	R-5	Rural Residential	0.40* / 5
	R-9,600	Urban Residential	0.22

**Minimum area achieved through application of density incentives*

3.0 Analysis of Deforestation with Development

3.1. Methods for spatial analysis of deforestation

The steps used to define common practice for forest clearance and associated emissions in the three counties are described in Figure 8.

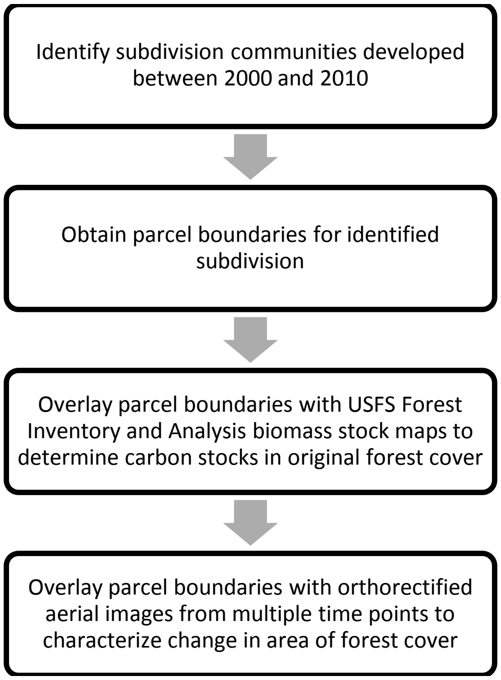


Figure 8 Flow chart of steps used for defining common practice for site preparation

To identify new home communities developed in the last ten years (2000-2010), archived Hearing Examiner decisions for each county were reviewed to identify approved applications for preliminary subdivision plats in the zones with the highest level of development and the greatest opportunity for changing common practice listed in Table 5. Google Earth was used to locate these subdivisions to verify that they had actually been developed and to visually assess land cover before and after development to select subdivisions developed on land with at least partial forest cover. The visual assessment was based on a time series of aerial images in Google Earth.

Parcel boundaries for the subdivision plat were overlaid with a series of orthorectified aerial images from multiple time points to characterize the change in area of forest cover associated with development of the subdivision. An example of aerial images overlaid with parcel boundaries is shown in Figure 9.

Figure 9 Aerial images overlaid with parcel boundaries used to estimate change in forest cover and carbon stocks associated with development for a Snohomish County R-9600 subdivision Copper Creek

Images were processed to identify forest and non-forest land cover classes to quantify the area of deforestation associated with the land use change.

The GIS analysis includes roads internal to subdivisions only, although the creation of residential subdivisions may influence the construction of access roads external to the subdivion. For some subdivisions, external access roads may already exist, while in other cases the creation of subdivisions may influence the construction of these roads. There is therefore the necessity for ongoing work to determine the total impact of development incorporating the dedicated roads and emission associated with clearing forest for road construction.

3.2. Results for spatial analysis of deforestation

The spatial analysis identified the area of cleared forest per development and per parcel for King, Pierce and Snohomish Counties.

3.2.1. King County

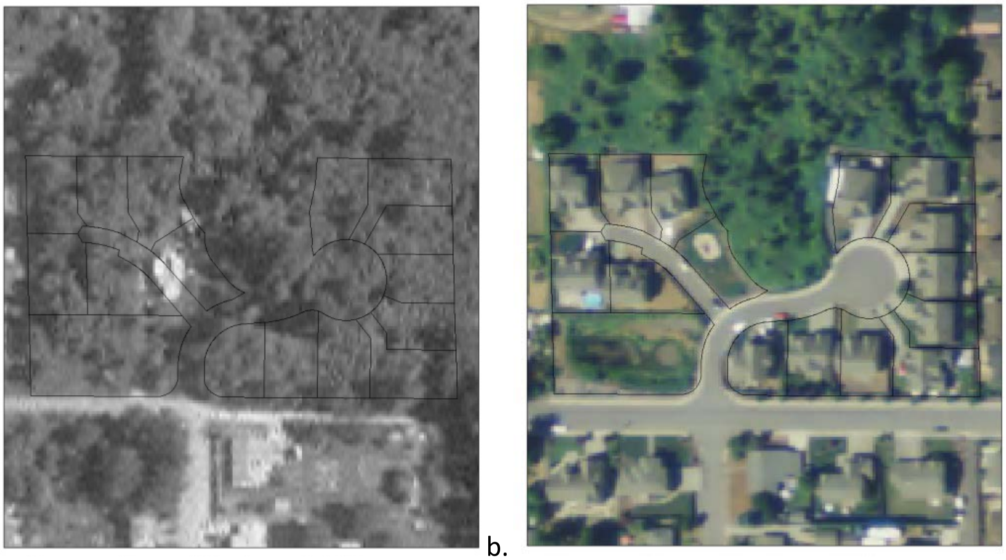
In King County five developments were examined as part of the spatial analysis with a total area of 16.6 acres and an average area of 3.3 acres per development. Prior to development the areas were on average 76% forested with a range between 59% and 95%. All five developments were in zone R-4.

Five subdivisions in zone R-4 were included in the spatial analysis for King County. Percent change in forest cover associated with development of these subdivisions ranged from 62% to 88% (Table 5).

Table 5 Results from spatial analysis of forest area (acres) pre- and post-development in zone R-4 in King County

Subdivision name	Total subdivision area	Forest area before development		Forest area after development		Deforestation	
		Area	% total area	Area	% total area	Area	%
Canterberry Crossing	3.2	2.6	81%	0.3	9%	2.3	88%
Edenwood	3.1	2.9	95%	0.4	13%	2.5	86%
Evetts Park	4.1	2.4	59%	0.7	17%	1.7	71%
Hidden Tree	3.2	2.2	69%	0.4	12%	1.8	82%
Norway Knoll	3.0	2.4	79%	0.9	30%	1.5	62%

Figure 11 shows an example of forest clearing for development in zone R-4 of King County. Of existing forest cover pre-development, 86% was cleared.



a. b.

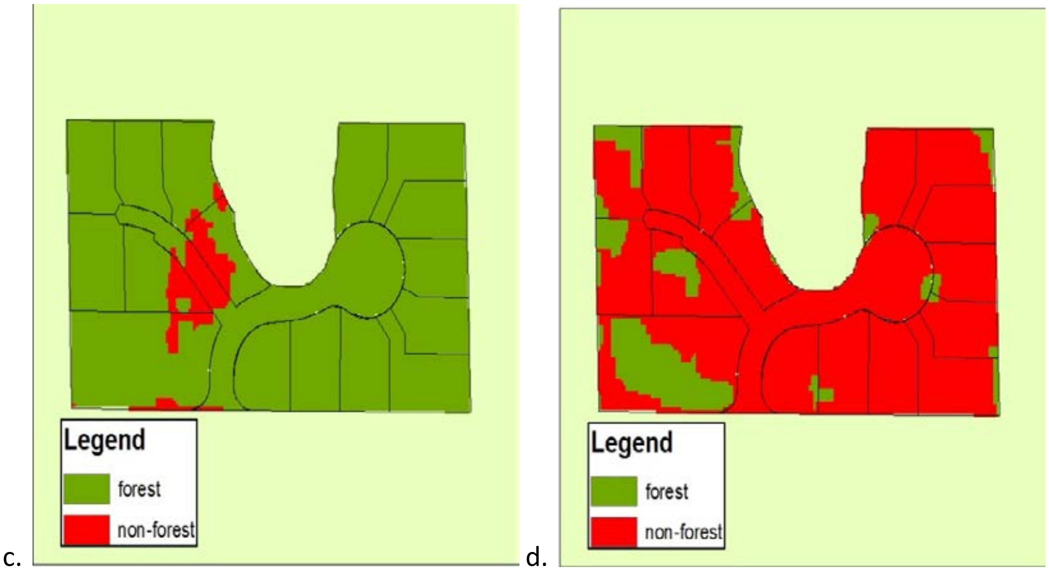


Figure 10 Edenwood development in King County: (a) imagery before development (image circa 1990), and (b) after development 2009, and (c) classification of forest and non forest before development and (d) classification after development.

3.2.2. Pierce County

In Pierce County four developments were examined as part of the spatial analysis with a total area of 28.3 acres and an average area of 7.1 acres per development. Prior to development the areas were on average 88% forested with a range between 81% and 95%. All four developments were in zone MSF.

Table 6 shows results of the analysis of deforestation in four subdivision developments in zone MSF in Pierce County. Most of the existing forest cover was cleared for development in all four subdivisions (92 – 98%).

Table 6 Results from spatial analysis of forest area (acres) pre- and post-development in zone MSF in Pierce County

Subdivision name	Total development area	Forest area before development		Forest area after development		Deforestation	
		Area	% total area	Area	% total area	Area	%
Pierce-MSF-1	8.5	6.9	81%	0.3	4%	6.6	96%
Pierce-MSF-2	8.2	7.6	92%	0.6	8%	7.0	92%
Pierce-MSF-4	7.1	5.9	83%	0.2	3%	5.7	97%
Pierce-MSF-5	4.5	4.3	95%	0.1	2%	4.2	98%

Almost complete clearing of forest area for development of MSF subdivisions are shown in Figures 12 and 13. Figure 12 shows clearing of 97% of forest cover in subdivision MSF-4.

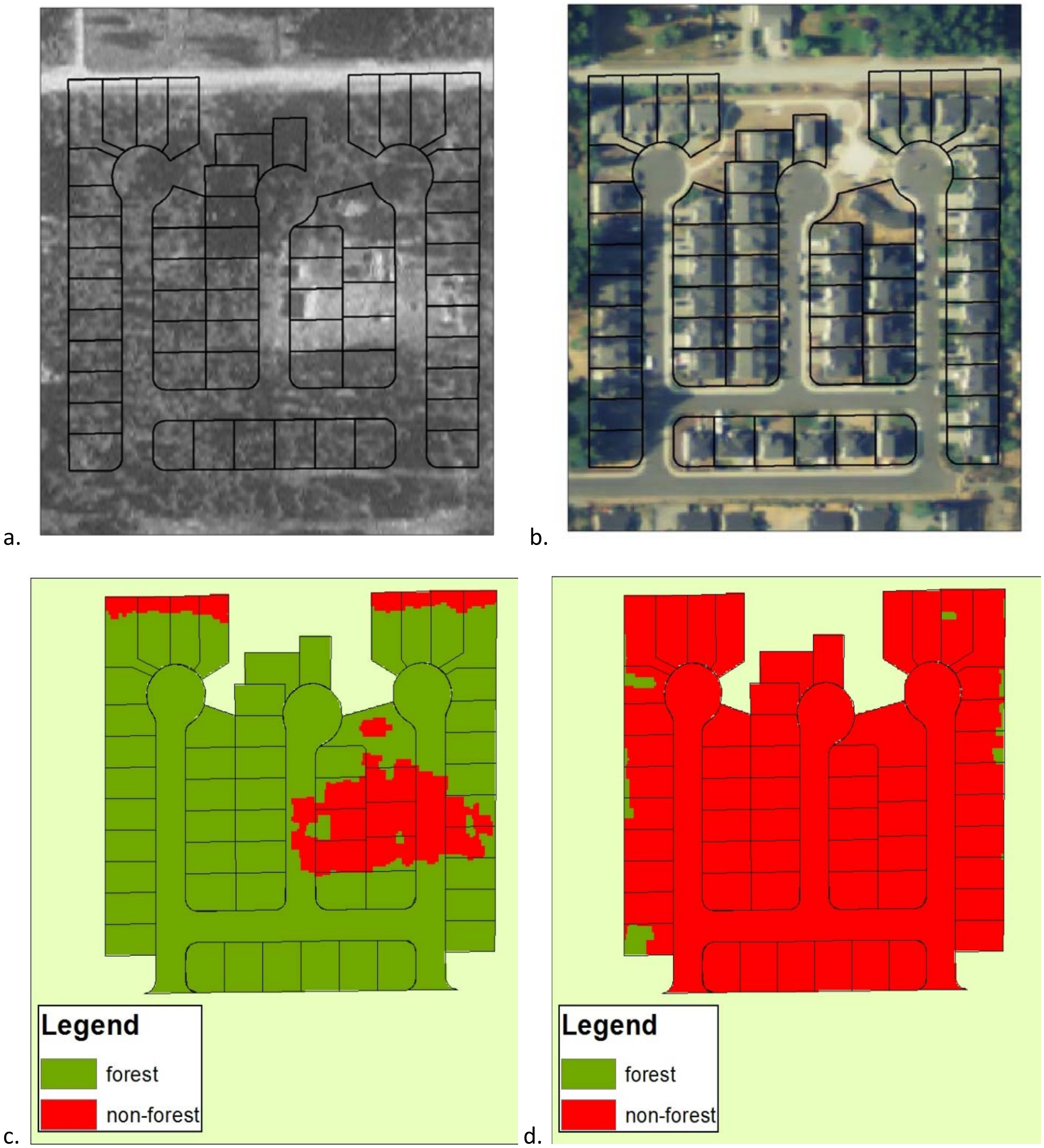


Figure 11 MSF-4 development in Pierce County: (a) imagery before development (image circa 1990), and (b) after development 2009, and (c) classification of forest and non-forest before development and (d) classification after development

Figure 13 shows 96% clearing in subdivision MSF-1.

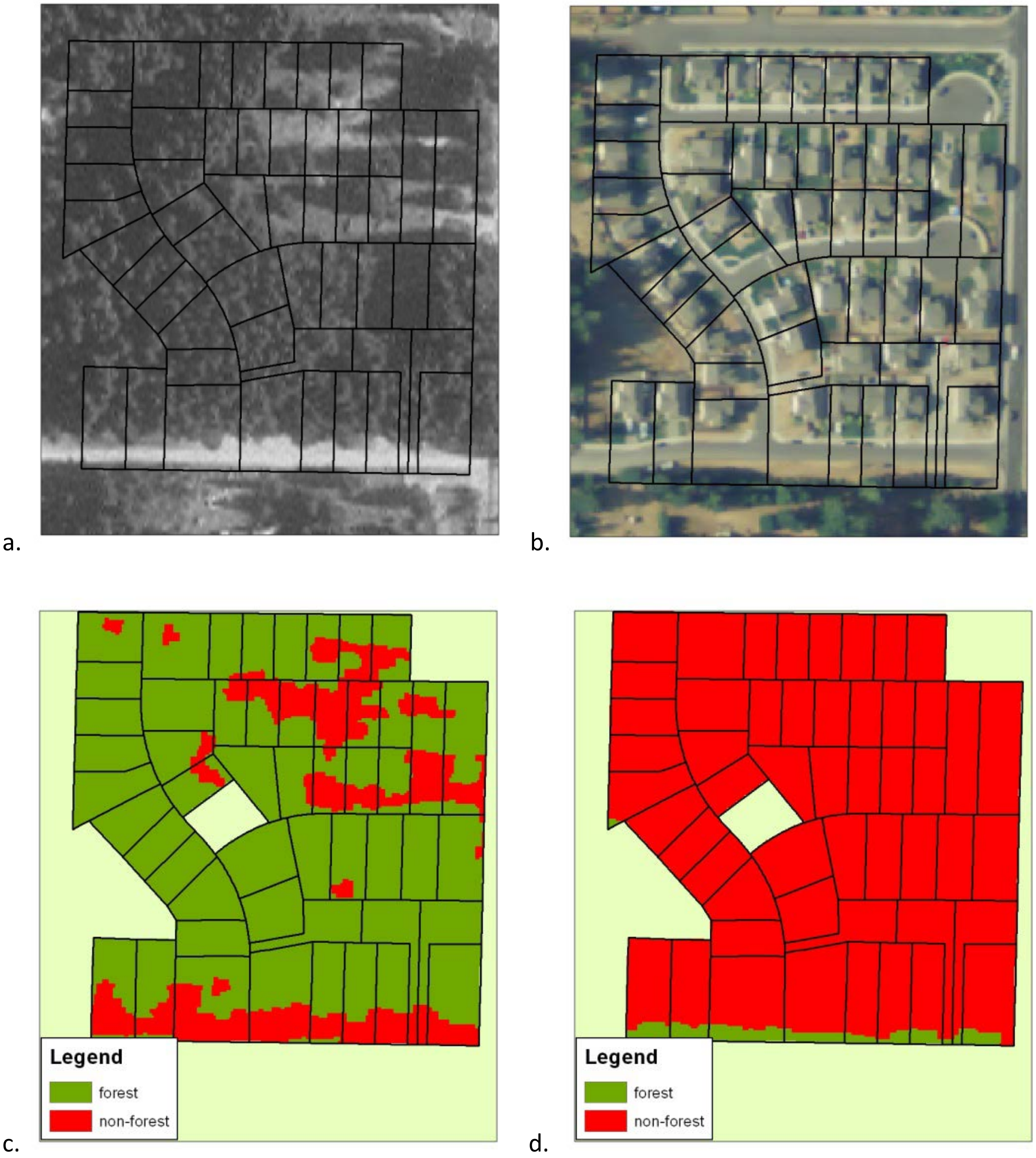


Figure 12 MSF-1 development in Pierce County: (a) imagery before development (image circa 1990) and (b) after development 2009, and (c) classification of forest and non forest before development and (d) classification after development

3.2.3. Snohomish County

In Snohomish County sixteen developments were spatially analyzedwith a total area of 316.1 acres and an average area of 19.8 acres per development. Prior to development the areas were on average 73% forested with a range between 21% and 99%. Eight of the developments were in zone R-5 and eight were in zone R-9,600.

Zone R-5 developments had an average of 91% forest cover before development, and 61% after development, showing an average decrease in forest cover of 33%. In zone R-9,600 (minimum lot size 0.22 acres) there was an average of 56% forest cover before development and 16% after, showing an average decrease in forest cover of 75%. While developed areas in R-5 (minimum lot size 5 acres) had more forest cover prior to development than R-9,600 (average - 83%), on average only 33% of forest area was cleared in R-5 subdivisions while on average 75% of forest area was cleared for development in R-9,600 subdivisions (Table 7).

Table 7 Results of spatial analysis of forest area (acres) pre- and post-development in zones R5 and R-9,600 in Snohomish County

Subdivision name	Total development area	Forest area before development		Forest area after development		Deforestation	
		Area	% total area	Area	% total area	Area	%
Zone R-5							
Blacktail Forest	67.3	42.3	63%	23.3	35%	19.0	45%
Cascade Peaks	30.5	29.2	96%	17.7	58%	11.5	39%
Echo Ridge	21.9	21.8	99%	17.5	80%	4.3	20%
Kenrose Heights	19.1	19.0	99%	13.8	72%	5.2	27%
Quail Ridge	19.9	17.7	89%	15.7	79%	2.0	11%
Ridgewood Estates	57.5	47.4	82%	29.4	51%	18.0	38%
Snowbird	16.1	15.9	99%	12.8	80%	3.1	19%
Wardrum Woods	7.6	7.4	97%	2.6	34%	4.8	65%
Zone R-9,600							
Cedarwood Estates	3.5	1.5	43%	0.4	11%	1.1	74%
Copper Creek	14.2	10.9	77%	3.8	27%	7.1	65%
Creekwood	7.7	2.2	29%	0.4	5%	1.8	82%
Holly Hill Estates	3.7	3.5	95%	1.5	41%	2.0	57%
Lake View Park	2.6	0.6	21%	0.1	4%	0.5	82%
Margate	16.9	10.3	61%	2.2	13%	8.1	79%
Summerset	12.2	6.1	50%	0.0	0%	6.1	100%
The Park at Creekside	15.5	11.1	72%	4.5	29%	6.6	59%

Figure 13 shows a R-5 cluster subdivision in Snohomish County before and after development. The significant majority of the forest area remains following development (80%).

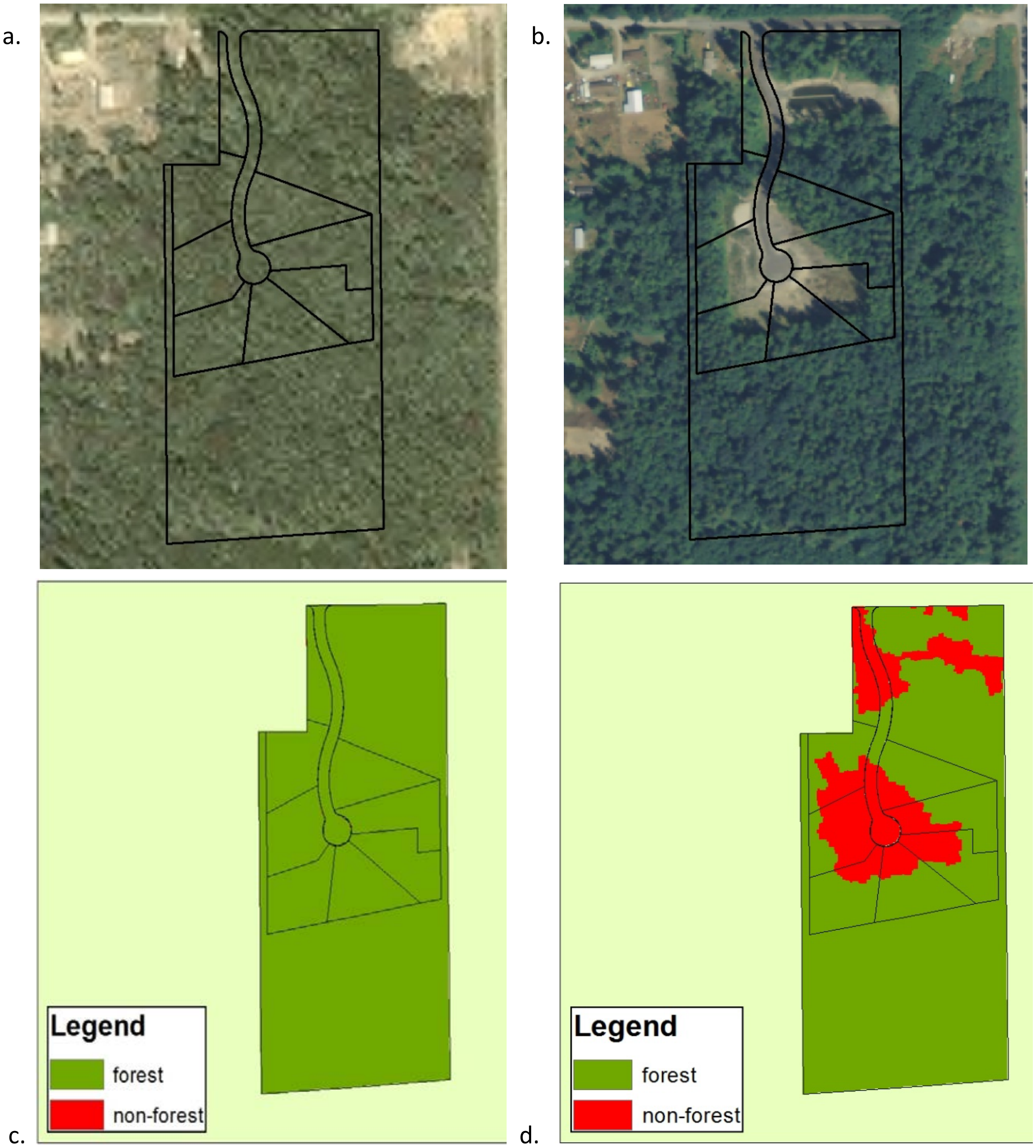


Figure 13 The R-5 Echo Ridge Development parcel boundaries overlaid with aerial imagery (a) from 2004 (before the development) and (b) 2009 (after the development) and (c) classification of forest before development and (d) classification of forest and non forest after development.

In contrast, R-9,600 subdivisions had less forest cover before development and a greater proportion of existing forest was cleared during development. For example in Figure 14, 51% the development was already cleared for farmland before development and during development almost all the remaining trees were cleared.

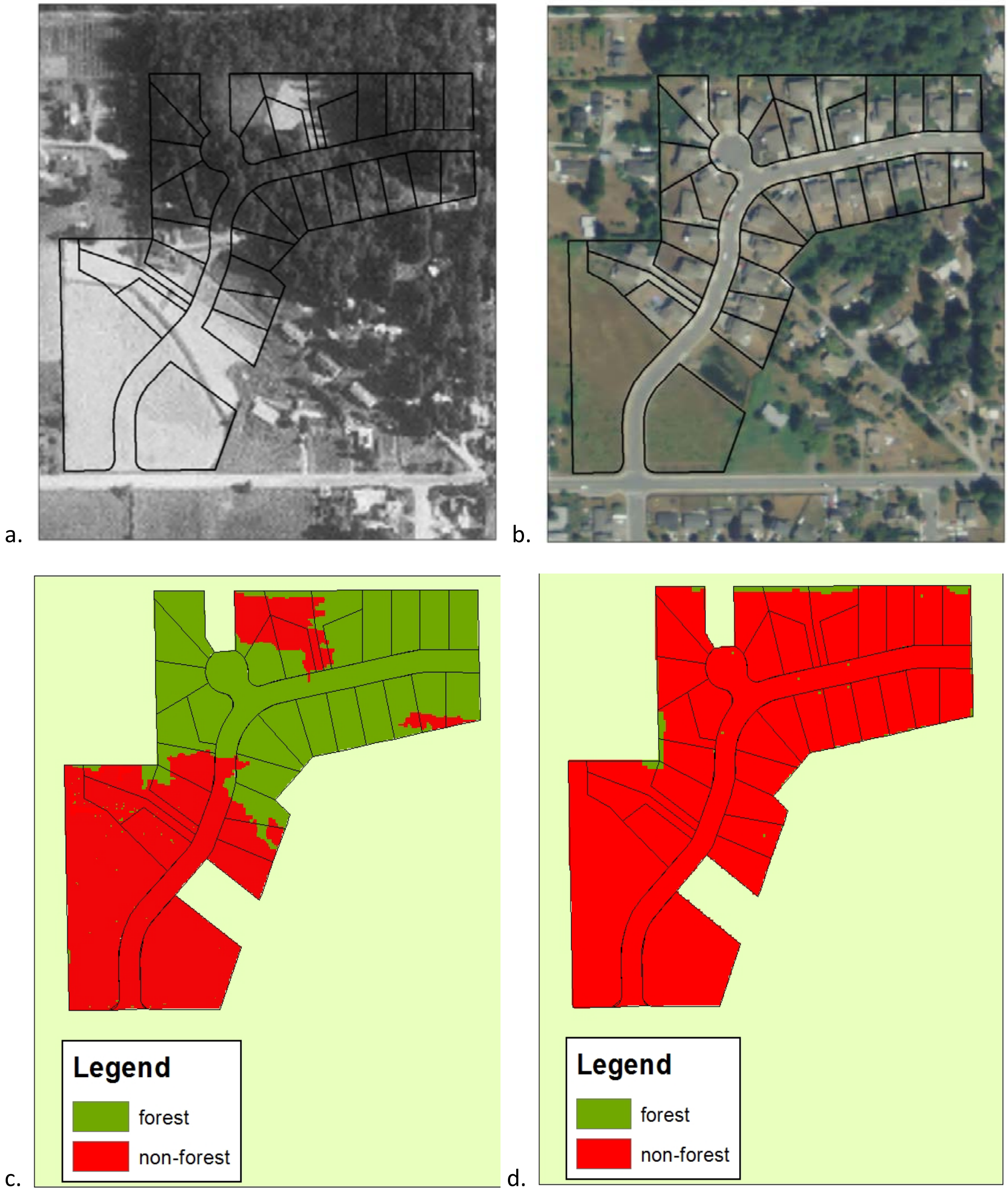


Figure 14 The R-9,600 Summerset Development: parcel boundaries overlaid with (a) aerial imagery from circa 1990 (before the development) and (b) 2009 (after the development) and (c) classification of forest and non forest before the development and (d) classification after the development.

3.3. Deforestation with development summary

The most common lot size in King and Pierce Counties was 0.25 acres or less and resulted in clearing of 62% to 98% of forest cover. Development of these small lot sizes resulted in clearing of relatively more forest cover compared to 1 acre lots in Snohomish County, which resulted in less than 50% clearing of forest cover for all but one of the subdivisions assessed (Table 8). Proportion of existing forest cover cleared seems to be in part a function of lot size, because subdivision developments with smaller lot sizes in zone R-9,600 in Snohomish County had similar levels of clearing compared to development of lots in King and Pierce Counties. Impervious surfaces in smaller lots (primarily the house and driveway) are a greater proportion of the total area of the lot compared to larger lots, as measured in the field (see Section 4.3.2), leaving less area available for vegetation cover. As well, it is likely that more extensive clearing facilitates construction activities in a relatively smaller area. In the 1 acre lots in Snohomish County remaining forest cover on residential lots was generally found on the back of the lot, where most likely it does not present an impediment to construction activities. However, part of the difference in forest cover between the large 1 acre lots in Snohomish County and relatively smaller lots in all three counties can be explained by the use of cluster development in the 1 acre lot subdivisions, where the developer is obligated to leave part of the development project area as green space. Cluster development was not used in the R-9,600 zone in Snohomish County or in any of the subdivision developments in King or Pierce Counties.

Proportion of existing forest cover cleared was also related to the total size of the development. Mean total development area in King and Pierce Counties and in zone R-9,600 in Snohomish Counties ranged between 3.3 ac to 9.5 ac with deforestation between 75% and 95%, while in zone R-5 in Snohomish County where the mean total development area was 30 acres only 33% of original forest cover was cleared (Table 8). In the relatively larger, less dense developments there is greater opportunity to retain existing forest cover.

Table 8 Summary of the results from the spatial analysis showing lot sizes, % cover before development and the % forest cover lost during development

County	Zone	Minimum Lot Size *(ac)*	Mean Total Development Area *(ac)*	Initial Forest Cover *(%)*	Deforestation *(%)*
King	R-4	0.25	3.3	76%	78%
Pierce	MSF	0.17	7.1	88%	95%
Snohomish	R-9600	0.22	9.5	56%	75%
Snohomish	R-5	1.00*	30.0	83%	33%

**with clustering*

4.0 Greenhouse Gas Emissions Associated with Development

To assess the greenhouse gas emissions associated with conversion the specific subdivisions spatially analyzed in Section 3 were further studied to estimate the greenhouse gas emissions that resulted from the development of each residential lot.

4.1. Change in stocks associated with measured area of deforestation

To determine the direct change in carbon stock resulting from development, forest carbon stocks within the boundaries of each subdivision plat were determined by overlaying the parcel boundaries with the USFS Forest Inventory and Analysis (FIA) biomass stock map.[14] Biomass was converted to carbon by applying the commonly used conversion factor of 0.5 t C/t biomass, and then converted to CO_2-e by applying the conversion factor of 3.67 t CO_2-e/t C. The most common forest type in the three counties was Douglas fir, with a minority of sites dominated by Red Alder forest.

4.1.1. King County

In King County the five development sites had carbon stocks of between 38 and 43 t C/ac. The loss in forest cover through development led to changes in stocks in live trees equivalent to between 230 and 351 t CO_2-e with an average of 289 t CO_2-e or 89 t CO_2-e per acre of the total area of development (Table 9).

Table 9 Predevelopment carbon stocks and decrease in stocks as a result of forest conversion (acres) from development in zone R-4 in King County

Subdivision name	Forest carbon stocks *(t C/ac)*	Total development *(Area)*	Deforestation *(Area)*	Deforestation *%*	Decrease in forest carbon stocks *(t C)*	Equivalent carbon dioxide emission *(t CO_2-e)*
Canterberry Crossing	42	3.2	2.3	88%	95	350
Edenwood	38	3.1	2.5	86%	96	351
Evetts Park	39	4.2	1.7	71%	67	245
Hidden Tree	41	3.2	1.8	82%	74	271
Norway Knoll	43	3.0	1.5	62%	63	230

4.1.2. Pierce County

In Pierce County the four development sites had carbon stocks of between 42 and 87 t C/ac. The loss in forest cover through development led to changes in stock in live trees equal to between

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[14] http://fsgeodata.fs.fed.us/rastergateway/biomass/

631 and 2,216 t CO_2-e with an average of 1,237 t CO_2-e or 170 t CO_2-e per acre of the total area of the development (Table 10).

Table 10 Predevelopment carbon stocks and decrease in stocks as a result of forest conversion (acres) from development in zone MSF of Pierce County

Subdivision names	Forest carbon stocks *(t C/ac)*	Total development *(Area)*	Deforestation *(Area)*	*%*	Decrease in forest carbon stocks *(t C)*	Equivalent carbon dioxide emission *(t CO_2-e)*
Pierce-MSF-1	46	8.5	6.6	96%	304	1,113
Pierce-MSF-2	87	8.2	7.0	92%	604	2,216
Pierce-MSF-4	48	7.1	5.7	97%	269	988
Pierce-MSF-5	42	4.5	4.2	98%	172	631

4.1.3. Snohomish County

In Snohomish County the sixteen development sites had carbon stocks of between 32 and 68 t C/ac. The average carbon stock for the R-5 development sites was 44 t C/ac and the average for the R-9,600 sites was 37 t C/ac. The loss in forest cover through development led to changes in stock in live trees equal to between 59 and 4,737 t CO_2-e with an average of 1,044 t CO_2-e or 51 t CO_2-e per acre of the total area of the development. Looking at the development zones separately the mean emission from the R-5 development sites was 1,489 t CO_2-e and for the R-9,600 sites 598 t CO_2-e (Table 11).

Table 11 Predevelopment carbon stocks and decrease in stocks as a result of forest conversion (acres) from development in zone R-5 and R-9,600 in Snohomish County

Subdivision names	Forest carbon stocks *(t C/ac)*	Total development *(Area)*	Deforestation *(Area)*	*%*	Decrease in forest carbon tocks *(t C)*	Equivalent carbon dioxide emission *(t CO_2-e)*
Zone R-5						
Blacktail Forest	68	67.3	19.0	45%	1,292	4,737
Cascade Peaks	41	30.5	11.5	39%	472	1,729
Echo Ridge	48	21.9	4.3	20%	205	750
Kensrose Heights	35	19.1	5.2	27%	182	667
Quail Ridge	41	19.9	2.0	11%	82	300
Ridgewood Estates	39	57.5	18.0	38%	693	2,541
Snowbird	38	16.1	3.1	19%	118	432
Wardrum Woods	43	20.7	4.8	65%	206	757
Zone - 9,600						
Cedarwood Estates	36	3.5	1.1	74%	40	147
Copper Creek	39	14.2	7.1	65%	276	1,014

Creekwood	32	7.7	1.8	82%	58	213
Holly Hill Estates	33	3.7	2.0	57%	66	242
Lake View Park	35	2.6	0.5	82%	16	59
Margate	46	16.9	8.1	79%	372	1,366
Summerset	35	12.2	6.1	100%	213	780
The Park at Creekside	40	15.5	6.6	59%	263	965

4.2. Estimation of timber transferred to harvested wood product pool and immediate emissions from forest conversion

To estimate emissions from forest clearing, knowledge about the fate of the cleared biomass is needed. Interviews with county planners and property developers revealed that merchantable timber is sold when land with forest cover is cleared for development. This information was used to determine carbon stocks transferred to harvested wood products and long-term emissions from this pool. We assumed that the proportion of cleared forest vegetation that is merchantable timber is transferred to harvested wood products.

The simplifying assumption is made that any products projected to still be in use or stored in landfills 100 years after harvest are a permanent sequestration with the remaining proportion considered immediately emitted.

The relative amount of the initial stock that would have been extracted for wood product production and the proportions in use or in landfills after 100-years is derived from US Forest Service data and analyses (Table 12)[15]. Forest type was determined from the USFS FIA carbon stock maps and the Pacific Northwest-West region was used to determine the fractions of softwood and hardwood growing stocks, and sawtimber volumes.

Table 12 Average disposition patterns of carbon as fractions in industrial roundwood in the Pacific Northwest, West 100 years following harvest[16]

Year after production	Hardwood				Softwood			
	In use	Landfill	Energy	Emitted w/o energy	In use	Landfill	Energy	Emitted w/o energy
100	0.030	0.177	0.448	0.345	0.130	0.279	0.242	0.349

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[15] Smith, J.E., Heath, L.S., Skog, K.E. and Birdsey, R.A. 2006. Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-243. Newtown Sq, PA. USDA.

[16] Smith, J.E., Heath, L.S., Skog, K.E. and Birdsey, R.A. 2006. Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-243. Newtown Sq, PA. USDA.

A permanent ban on land-clearing burning in Snohomish, King, and Pierce Counties was adopted by the Puget Sound Clean Air Agency (PSCAA), and went into effect July 1, 2008.[17] Other means that may be used to dispose of vegetation from land clearing include chipping, energy recovery or incineration at appropriate facilities, or landfill.[18] For example, a strong business infrastructure has developed in Pierce County diverting landclearing debris to recycling, landscape mulch, or for energy as hog fuel.[19]The simplifying assumption is made that this material is diverted to incineration facility with direct conversion of biomass to CO_2 with minimal emission of non-CO_2 gases. Any avoided emission from substitution of hog fuel for fossil fuels is not included here at this time.

4.2.1. King County

In King County the total emissions from forest conversion incorporating the impact of harvested wood products and energy recovery ranged from 186 t CO_2-e to 279 t CO_2-e with an average of 235 t CO_2-e (Table 13).

Table 13 Emissions from conversion of forest to urban area in zone R-4 in King County

Subdivision name	Forest carbon stock change (t CO_2-e)	HWP emissions (t CO_2-e)	Energy recovery emissions (t CO_2-e)	Total emissions (t CO_2-e)
Canterberry Crossing	350	105	173	278
Edenwood	351	103	176	279
Evetts Park	245	72	122	194
Hidden Tree	271	67	171	238
Norway Knoll	230	71	115	186

4.2.2. Pierce County

In Pierce County the total emissions from forest conversion incorporating the impact of harvested wood products and energy recovery ranged from 508 t CO_2-e to 1,664 t CO_2-e with an average of 959 t CO_2-e (Table 14).

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[17] http://www1.co.snohomish.wa.us/Departments/PDS/Divisions/Fire_Marshal/Burninfo.htm

[18] WAC 173-425-040

[19] Pierce County Department of Public Works and Utilities. 2008. Stepping up to the Challenge. Supplement to the Tacoma-Pierce County Solid Waste Management Plan.

Table 14 Emissions from conversion of forest to urban area in zone MSF in Pierce County

Subdivision	Forest carbon stock change (t CO_2-e)	HWP Emissions (t CO_2-e)	Energy Recovery Emissions (t CO_2-e)	Total Emissions (t CO_2-e)
Pierce-MSF-1	1,113	342	538	880
Pierce-MSF-2	2,216	817	847	1,664
Pierce-MSF-4	988	307	476	783
Pierce-MSF-5	631	192	316	508

4.2.3. Snohomish County

In Snohomish County the total emissions from forest conversion incorporating the impact of harvested wood products and energy recovery ranged from 374 t CO_2-e to 3,642 t CO_2-e in zone R5 with an average of 1,202 t CO_2-e. In zone R-9,600 emissions ranged from 52 t CO_2-e to 1,080 t CO_2-e with an average of 495 t CO_2-e (Table 15).

Table 15 Emissions from conversion of forest to urban area in zones R-5 and R-9,600 in Snohomish County

Subdivision name	Forest carbon stock change (t CO_2-e)	HWP Emissions (t CO_2-e)	Energy Recovery Emissions (t CO_2-e)	Total Emissions (t CO_2-e)
Zone R-5				
Blacktail Forest	4,737	1,608	2,034	3,642
Ridgewood Estates	1,729	555	936	1,491
Wardrum Woods	750	247	396	643
Cascade Peaks	667	208	371	579
Echo Ridge	300	95	161	256
Kenrose Heights	2,541	750	1,279	2,029
Quail Ridge	432	137	237	374
Snowbird	757	229	372	601
Zone R-9,600				
Cedarwood Estates	147	45	80	125
Creekwood	1,014	301	510	811
Summerset	213	63	118	181
The Park at Creekside	242	69	126	195
Copper Creek	59	19	33	52
Holly Hill Estates	1,366	420	660	1,080
Lake View Park	780	244	435	679
Margate	965	309	526	835

4.3. Post-development carbon sequestration

To develop an estimate of carbon sequestration post-development, it is necessary to correlate lot size and:

a. Impervious area (i.e. the footprint of buildings plus patios, decks, paths and driveways) – the area unavailable for biomass accumulation

b. Biomass of grass and other non-herbaceous vegetation

c. Biomass of shrubs

d. Biomass of trees

A sample of subdivisions developed in the last 10 years in the zones with the highest level of development was selected for field measurements and property owners were contacted to obtain permission to access properties for field work. The objective of field measurements was to gather data to estimate post-deforestation carbon stocks on forested land that is converted to moderate density residential subdivision development in King, Pierce, and Snohomish Counties. The assessment considered the conversion of forest to the following land covers: landscaping vegetation, street trees, open spaces, and impervious surfaces.

4.3.1. Field measurements of existing biomass in developed residential areas

The field sites were defined using parcel data to determine the boundaries of residential subdivisions and individual lots. Initially the study area included 8 moderate density residential subdivisions from the three counties comprising 174 residential lots. Due to low response rate (<10%) to requests to access properties for measurements, additional subdivisions were added to the study area. Where required, permission to access lots was requested in the field from property owners so that additional lots could be included in the sample. Biomass measurements were collected from a total of 97 properties in subdivisions ranging in age from recently developed to those developed several decades previously. Landscaping vegetation within the boundaries of residential lots was measured, including isolated trees, shrubs, grass, and other herbaceous vegetation.

For each property measured, a complete inventory of vegetation and impervious surfaces was conducted. More detail on field methods may be found in the field measurement plan included in Annex 2.

4.3.2. Calculation of carbon stocks

The carbon stocks in trees, shrubs, and herbaceous vegetation cover was estimated for each property included in measurements. For trees and shrubs, allometric equations were applied to estimate biomass using appropriate correction factors as needed. For shrubs, an allometric equation developed for shrubs in Shasta County, California was used[20]. For trees, we used allometric equations developed from a compilation of equations from the literature predicting the biomass of trees from diameter measures for species in the United States. Carbon stocks in grass and other herbaceous vegetation were estimated using conversion factors from Jo and McPherson 1995.[21]

Relatively high variation was recorded for all categories arising from the variability in land management associated with the individual preferences and interests of the home owners. In particular, trees and shrubs can be planted at any point in time so that some present after 30 years for example will have been planted immediately after development but others would have been planted at any point in the intervening years.

Impervious area

In the 174 lots measured in the Puget Sound area the impervious area was recorded. The relationship between lot size and impervious area is displayed in Figure 15. Impervious area approaches 100% in very small lots but drops to below 20% in lots of more than 1.5 acres.

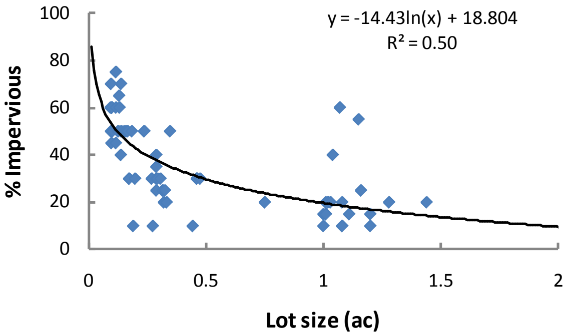

Figure 15 Relationship between lot size and impervious area

Biomass of grass and other herbaceous vegetation

Grass cover varies from almost zero in very small lots to approximately 50% in 1.5 acre lots (Figure 16). Non-grass herbaceous vegetation has very low coverage in all instances (2-3%). There was no strong relationship between non-herbaceous grass cover and lot size.

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[20] Goslee, K., T. Pearson, S. Brown, B. Rynearson, L. Bryan, S. Petrova, and S. Grimland. 2010. WESTCARB Afforestation Pilot Projects in Shasta County, California. California Energy Commission, PIER. CEC-500-2010-XXX.

[21] Jo, H, McPherson, G. 1995. Carbon storage and flux in urban residential greenspace. *Journal of Environmental Management* 45 (109-133).

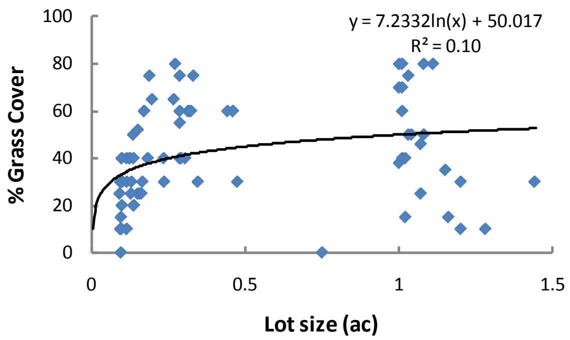

Figure 16 Relationship between lot size and area of grass

Biomass of shrubs

The relationship between lot size and number of shrubs and between mean shrub biomass and years since development are shown in Figure 17. The number of shrubs increases slightly with lot size, varying between approximately 10 shrubs in very small lots to 30 shrubs in 1.5 acre lots. Mean biomass of planted shrubs increases with time, reaching approximately 0.3 t C / shrub at 25 years post-development. Here we make the assumption that the long term average stock can be approximated by the predicted biomass of individual shrubs after 20 years of growth multiplied by the number of shrubs per lot.

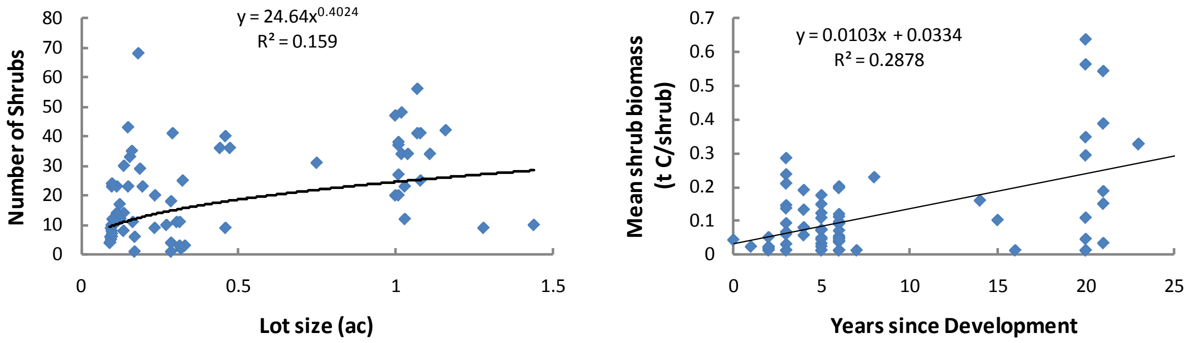

Figure 17 Relationship between lot size and number of shrubs and relationship between years since development and mean shrub biomass

Biomass of trees

For trees the area available for planting was defined by the area not covered by an impervious surface. A relationship between the non-impervious area and the total number of trees per lot was developed (Figure 18). Due to the fact that trees can be planted at any point in time the maximum diameter at breast height (DBH) of trees measured in the developed lots was used in the analysis with the assumption that these trees would have been planted shortly after initial development. It was assumed that trees with DBH greater than this maximum had not been felled during development and were excluded. The relationship between the number of years since development and maximum DBH of trees is shown in Figure 19(b). The species that can be planted and therefore the ultimate biomass of planted trees varies with plot size. Based on the collected data and expert opinion the average DBH once the developed yards have reached maturity are estimated to be:

For yards ≤ 0.15 acres	15 cm
For yards 0.16 – 0.49 acres	30 cm
For yards ≥ 0.5 acres	50 cm

Using allometric equations[22] the mean stock per tree was calculated for the assumed mature post-development tree (15 cm DBH – 0.07 t; 30 cm DBH – 0.39 t; 50 cm DBH – 1.33 t). This mean stock was then applied to the projected relationship between number of trees per lot and non-impervious area.

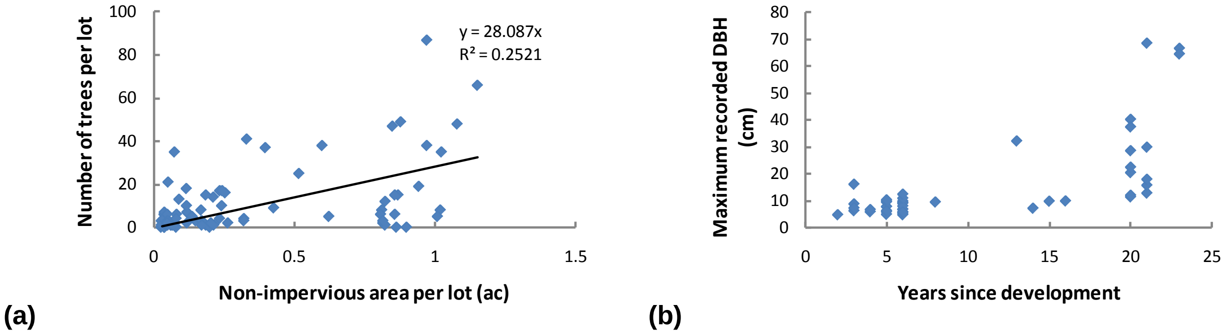

Figure 18 Relationship between number trees in a developed lot and the total non-impervious area in each lot and relationship between the number of years since development and the maximum recorded breast height diameter (DBH)

Total Stocks

The post-development carbon stock for areas deforested during development will be equal to the sum of stocks in trees, shrubs and herbaceous vegetation. In Figure 19 and Table 16 the estimated stocks are shown by lot size. Total stocks vary from 1.27 tons of carbon in a 0.1 acre lot to more than 39 t C in a 2 acre lot.

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[22] Jenkins, J.C.; Chojnacky, D.C.; Heath, L.S.; Birdsey, R.A. 2003. National scale biomass estimators for United States tree species. Forest Science. 49: 12-35.

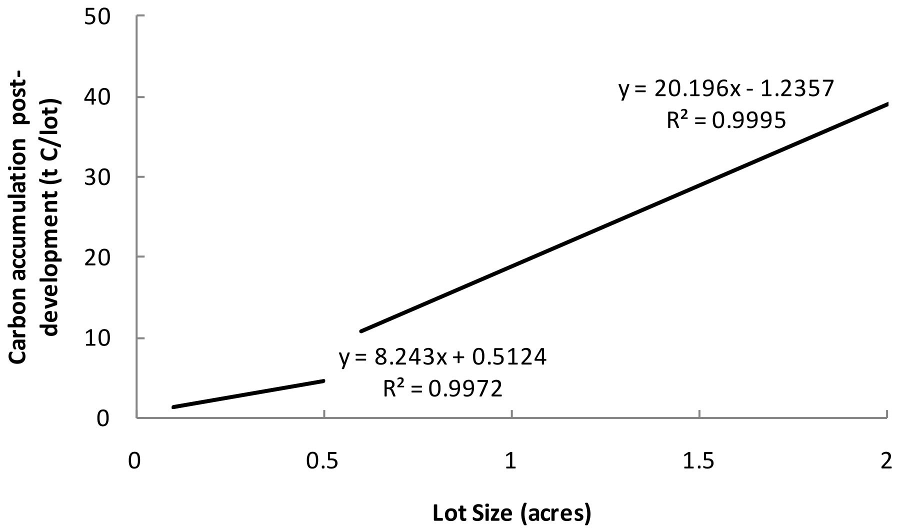

Figure 19 Relationship between lot size and carbon accumulation in all vegetation types post-development

Table 16 Estimated carbon stocks in herbaceous vegetation, shrubs and trees by lot size. Also displayed are the estimated % of the lot that is impervious, % covered by grass plus the estimated ultimate number of shrubs and trees.

Lot Size ac	Impervious %	Grass %	Number of trees	Total tree biomass t C	Total grass biomass t C	Total non-grass herbaceous biomass t C	Number of shrubs	Total shrub biomass t C	Total biomass t C
0.1	52	33	1	0.0	0.03	0.00	10	1.20	1.27
0.2	42	38	3	0.6	0.07	0.01	13	1.56	2.21
0.3	36	41	5	1.0	0.12	0.01	16	1.92	3.01
0.4	32	43	8	1.6	0.16	0.01	18	2.15	3.88
0.5	29	45	10	1.9	0.21	0.01	20	2.39	4.56
0.6	26	46	12	8.0	0.26	0.01	21	2.51	10.76
0.7	24	47	15	10.0	0.31	0.02	23	2.75	13.04
0.8	22	48	18	12.0	0.36	0.02	24	2.87	15.21
0.9	20	49	20	13.3	0.41	0.02	25	2.99	16.71
1	19	50	23	15.3	0.47	0.02	27	3.23	19.00
1.1	17	51	26	17.3	0.52	0.02	28	3.35	21.17
1.2	16	51	28	18.6	0.57	0.03	29	3.47	22.67
1.3	15	52	31	20.6	0.63	0.03	30	3.59	24.84
1.4	14	52	34	22.6	0.68	0.03	31	3.71	27.01
1.5	13	53	37	24.6	0.74	0.03	32	3.83	29.18
1.6	12	53	40	26.6	0.80	0.03	33	3.95	31.35
1.7	11	54	42	27.9	0.85	0.03	34	4.07	32.86
1.8	10	54	45	29.9	0.91	0.03	35	4.19	35.03
1.9	10	55	48	31.9	0.97	0.04	36	4.31	37.20
2	9	55	51	33.9	1.02	0.04	36	4.31	39.25

4.4. Full Accounting of Development Emissions

Full accounting of development emissions must capture both the emissions from clearing the forest and the sequestration that occurs after development. Here the total net emissions are estimated for the 25 analyzed development sites across King, Pierce and Snohomish Counties.

This study did not include soil emissions, though site preparation could cause significant emissions from soil disturbance. Following site preparation, landscaping restores soil carbon while impervious surfaces completely stop emissions. Small lots result in a relatively large proportion of impervious surface to total lot area, possibly resulting in zero net change in soil carbon stocks. Further investigation is needed to characterize soil carbon emissions resulting from conversions of forest to suburban area.

4.4.1. King County

In King County development resulted in net emissions for all subdivisions included in the analysis, as shown in Table 17. Net emissions ranged from 70 t CO_2-e to 177 t CO_2-e.

Table 17 The net greenhouse gas emission/sequestration from urban development (acres) at five sites in Zone R-4 in King County

Subdivision names	Total development area	Number of built lots	Average size of built lots	Built lots as a proportion of total area	Development emission t CO_2-e	Carbon stock recovery t CO_2-e	Net emission t CO_2-e
Canterberry Crossing	3.2	20	0.12	75%	278	110	168
Edenwood	3.1	15	0.16	80%	279	102	177
Evetts Park	4.1	10	0.35	85%	194	124	70
Hidden Tree	3.2	19	0.12	71%	238	105	133
Norway Knoll	3.0	20	0.12	78%	186	109	77

4.4.2. *Pierce County*

In Pierce County development resulted in net emissions for all subdivisions included in the analysis, as shown in Table 18. Net emissions ranged from 412 t CO_2-e to 1,418 t CO_2-e.

Table 18 The net greenhouse gas emission/sequestration from urban development (acres) at four sites in Zone MSF in Pierce County

Subdivision names	Total development area	Number of built lots	Average size of built lots	Built lots as a proportion of total area	Development emission t CO_2-e	Carbon stock recovery t CO_2-e	Net emission t CO_2-e
Pierce-MSF-1	8.5	51	0.17	100%	880	353	527
Pierce-MSF-2	8.2	25	0.26	80%	1664	246	1,418
Pierce-MSF-4	7.1	59	0.11	92%	783	308	475
Pierce-MSF-5	4.5	15	0.15	50%	508	96	412

4.4.3. *Snohomish County*

In Snohomish County development resulted in net emissions for some subdivisions while other subdivisions showed net sequestration (negative net emissions) as shown in Table 19. Net emissions ranged from 12 t CO_2-e to 670 t CO_2-e. Net sequestration ranged from 8 t CO_2-e to 335 t CO_2-e. Net sequestration can result when the emissions from forest clearance are low and the pre-development carbon stocks on developed land are low. Low emissions from forest clearance can be a result of low initial forest cover or high forest cover retention. Low carbon stocks on land prior to development can result from low initial forest cover on developed land or direction of development away from forested areas.

Table 19 The net greenhouse gas emission/sequestration from urban development (acres) at 15 sites in zone R-5 and R-9,600 in Snohomish County

Subdivision name	Total development area	No. of built lots	Average size of built lots	Built lots as a proportion of total area	Development emission t CO_2-e	Carbon stock recovery t CO_2-e	Net emission t CO_2-e
Zone R-5							
Blacktail Forest	67.3	51	1.07	81%	3642	3815	-173
Cascade Peaks	30.5	14	1.09	50%	1491	1070	421
Echo Ridge	21.9	7	1.03	33%	643	501	142
Kenrose Heights	19.1	9	1.01	47%	579	630	-51
Quail Ridge	19.9	9	0.46	21%	256	142	114
Ridgewood Estates	57.5	25	1.10	48%	2029	1925	104
Snowbird	16.1	5	1.04	32%	374	361	13

Wardrum Woods	7.6	12	1.11	176%	601	936	-335
Zone R-9,600							
Cedarwood Estates	3.5	25	0.11	81%	125	133	-8
Copper Creek	14.2	53	0.11	42%	811	281	530
Creekwood	7.7	30	0.12	48%	181	169	12
	3.7	15	0.17	69%	195	105	90
Lake View Park	2.6	13	0.17	85%	52	92	-40
Margate	16.8	61	0.16	58%	1080	410	670
Summerset	12.2	32	0.23	61%	679	284	395
The Park at Creekside	15.5	68	0.10	43%	835	327	508

5.0 Forest Conversion and Carbon Projects

The opportunity to provide economic incentives for preventing the conversion of forest land to other uses through a carbon credit trading system has been explored by the Washington State Government. The following issues were identified in Washington State's Department of Natural Resources Future of Washington Forests Report as challenges to creating a carbon credit system that would bring financial benefits to forest land owners:

1. Establishing carbon ownership rights;
2. Determining the source of carbon credit generation and compensation;
3. Estimating baseline carbon stocks above which carbon credits can be traded;
4. Accounting for long term storage of carbon in wood products;
5. Addressing leakage caused by the displacement of conversion to alternative locations;
6. Ensuring permanence of credits generated by preventing conversion of forest land to other uses.

These same issues apply to the development of a financial mechanism to provide an economic incentive for reducing emissions from conversion of forest land to residential development. In regards to Point 3 above, the Forest Sector Workgroup of the 2008 Washington State Climate Action Team identified the baseline for avoided forestland conversion as "the carbon storage in trees left, if any, following development clearing according to current legal provisions." However, no estimation of this baseline exists.

Deforestation events for development are poorly accounted for under current greenhouse gas emission monitoring systems. If such knowledge was available it becomes possible to consider the costs and benefits of different forms of development and to make policy decisions to influence the magnitude of emissions associated with development. One mechanism that could be used is the crediting of development projects that improve upon the business-as-usual scenario in terms of emissions associated with deforestation for development.

Carbon projects are formulated based on the difference in carbon emissions or sequestration between a baseline, or business-as-usual scenario, and project case. For avoided emissions projects, carbon credits are calculated as the difference in carbon emissions between a baseline case, such as complete or partial deforestation of a tract of land for development, and the project case.

5.1. Issues for avoided conversion projects

Population growth and the expansion of urban area drive competition between incompatible land uses.

This raises several issues:

- With any avoided conversion project, there is always the risk of "leakage." Leakage refers to emissions that occur outside of the project boundary as a result of project activities. In the case of avoided forest conversion for development, there is the risk that development will be displaced from the project area to another forested location due to market demand, resulting in emissions associated with forest clearing at the other location. To prevent leakage, the Forest Sector Workgroup recommended that market demand for development be met with a smaller development footprint either through clustering or transfer into urban areas, avoiding displacement of development to other forested locations.
- Emission reduction credits awarded for avoided conversion should be "permanent," therefore forested tracts not developed as a result of clustering or other mechanisms should be permanently protected with a forest conservation easement or other legal instrument with similar third party enforceability and durability.
- Some of the timber removed during site preparation for development may be transferred to the Harvested Wood Products (HWP) pool or land-filled. This should be accounted for as a part of the estimation of emissions associated with forest conversion for development.
- Transaction costs to project developers are likely too high to provide an incentive for the crediting of emission reductions on a project-by-project basis. A performance standard approach, as detailed in the following section, would encourage broad participation while generating real and credible emission reductions.

5.2. Performance Standards

The purpose of carbon projects is to produce credits that are considered real and equal to emissions occurring from industry, transport, residences, agriculture and other emission sectors. For credits to be real they must lead to carbon benefits beyond the business-as-usual scenario or baseline. There are two approaches to assessing business-as-usual:

- Project-specific baselines

- Performance standard

Performance standards (also known as benchmarks) are one approach for defining the baseline and proving additionality for carbon offset projects. Well designed performance standards ensure, across a portfolio of projects, that the average project is providing additional carbon credits above the baseline due to a balancing of projects that will be overcredited with those that will be undercredited. Where a balance is not achieved and a standard leads to more overcrediting than undercrediting then so-called "hot air" is created. Credits are issued for emission reductions that are not really reductions and these are then traded allowing others to increase their own emissions leading to a net increase in the concentration of atmospheric greenhouse gases.

Performance standards are best applied when emissions or sequestration can be defined relative to a unit of production and where little variability in emissions or sequestration occurs from one location to another.

Performance standards function accurately only across a portfolio of similar project types. A proportion will be overcredited relative to the actual project-specific baseline and at least a balancing proportion should be undercredited.

5.3. Challenges to developing a mechanism to generate offsets from residential development

Various mechanisms could be considered for generating offsets from residential development. Mechanisms that create incentives for developers to mitigate emissions from site preparation by leaving trees standing on forest converted to residential subdivisions likely presents the greatest opportunity for developing such a mechanism. However, challenges exist.

5.3.1. Leakage

In terms of residential subdivision development, preventing residential development in areas with forest cover could lead to leakage because high demand for real estate produces likely would shift to another area. In another example, a subdivision project may reduce emissions from deforestation by creating less residential lots and designating part of the project area as greenspace, but result in conversion of forest elsewhere by another development project to fill the deficit in available housing units.

A clustered approach to development could present an option for mitigating leakage if the number of lots created by a given development is maintained by reducing the minimum allowable lot size. However, reducing the minimum allowable lot size through clustering could create an incentive for the development of large residential subdivisions in areas where they are not usually a common practice. For example, in Snohomish County, it is not likely that large lot residential subdivisions development would be a common practice in zone R-5 if it were not possible to reduce the minimum lot size to 1 acre through cluster development. As a result of density incentives, zone R-5 had the highest level of development of all residential zones assessed in applications to the Snohomish County Hearing Examiner for subdivision.

5.3.2. Additionality

In order for an offset project to generate a real positive impact on the atmosphere in terms of reduced GHG emissions, the project must be additional. This is to say that the project must prove that the offsets are generated as a direct result of the economic incentive of carbon financing. For project developers, the burden of proving the additionality of individual projects could be a barrier to participation in carbon markets

5.3.3. Carbon credit ownership

Various actors participate in the development process. While the developer might be responsible for site plans and site preparation for construction, the homeowner's association could be responsible for landscaping the developed properties. In order for a project to be able to sell the carbon credits, it must be able to prove that it has the rights to them. In the case of avoided emissions from forest conversion for residential development, the entity responsible for making decisions regarding the removal or retention of vegetation as a part of preparing sites for construction would be the owner of offsets.

5.4. A potential approach for creating a development offset category in the Puget Sound region

As described above an offset project that merely halts development in a forested area would be subject to great leakage risk. It is possible that as many or more emissions would result at the alternative site or sites to which the development was displaced. Instead, net emission reductions can result where the course of development is altered without changing the number or category of developed properties. Ultimately the area of forest retained within the full boundary of the development must be increased relative to the proportion that would remain under business-as-usual.

The relationship between the total area of a development parcel and percentage of original forest cover remaining after conversion to urban area, as determined by the spatial analysis conducted here (see Section 4), is shown in Figure 20. Forest cover cleared during conversion varied from 50-100% in areas of less than 16 acres but averaged 35% for development areas that exceed 16 acres (Figure 21).

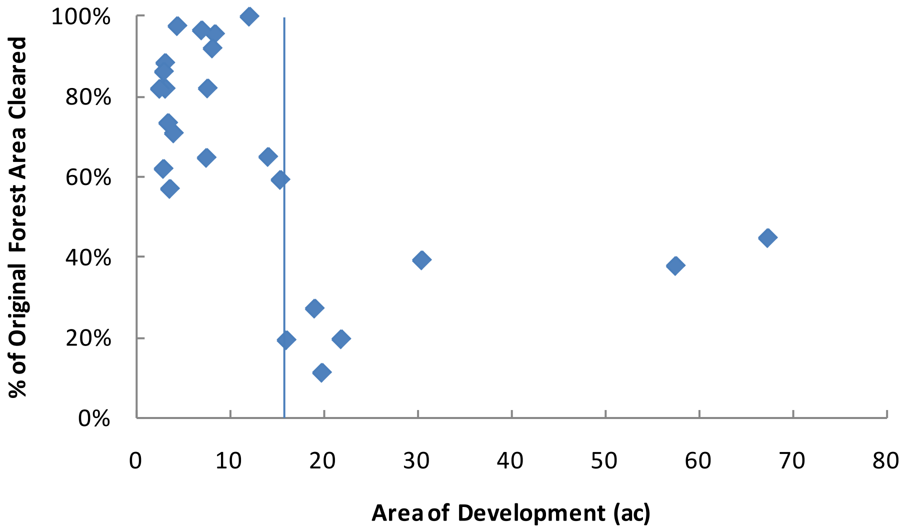

Figure 20. Relationship between total area of a development parcel and area of original forest cover remaining after conversion to urban area

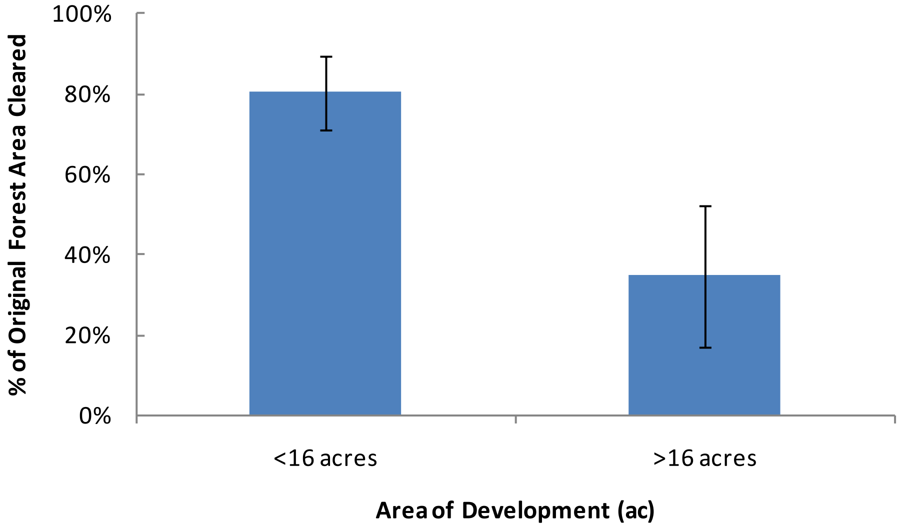

Figure 21 The percentage of original forest cover that is cleared in relation to total development size. Error bars represent 95% CI.

This relationship could form the basis of a future performance standard for development projects such that if a developer exceeded the defined area of forest retained by 10% or more then the carbon stocks of the retained forest would be creditable.

This is illustrated below in Table 20 in which areas of forest are planned for development. Here the baseline forest retention is calculated from the proportions in Figure 21 and the performance standard is this area inflated by 10%. The calculated offsets are equal to the emissions under the performance standard minus the emissions in the project case. The resulting available offsets range from 136 tons for a 10 acre development to almost 3,000 tons for a 60 acre development.

This emission reduction can also be calculated per unit developed (Table 21). In this case the baseline (which could be further developed into a performance standard) would be an emission of 55 t CO_2-e/unit for a 10 acre development with 0.20 acre lots up to 440 t CO_2-e/unit for a 60 acre development with 5 acre lots. In the project case the hypothetical emissions per unit are lower (due to the increased forest retention) leading to net emission reductions, which could be sold by the developer as offsets.

Table 20 Hypothetical example showing the emissions and emission reductions from increasing the area of forest retained across developments of different sizes. The forest carbon stocks in this example are 100 t C/ac

	Baseline Case				Project Case						
Area of Development *(Acres)*	Forest Retention *(Acres)*	# lots	Lot size *(Acres)*	Performance Standard Forest Retention *(Acres)*	Forest Retention *(Acres)*	# lots	Lot size *(Acres)*	Equivalent stocks *(t C)*	Incorporating Wood Products *(t C)*	Incorporating post-development sequestration *(t C)*	Offsets *(t CO2-e)*
10	2.0	35	0.20	2.2	2.4	35	0.18	71	61	37	136
20	13.0	42	0.35	14.3	15.6	42	0.25	473	402	287	1,053
30	19.5	40	0.50	21.5	23.4	40	0.35	709	603	444	1,627
40	26.1	25	1.00	28.7	31.2	25	0.50	946	804	659	2,417
50	32.6	17	2.00	35.8	39.0	17	1.00	1,182	1,005	586	2,150
60	39.1	8	5.00	43.0	46.9	12	2.00	1,419	1,206	816	2,991

Table 21 Estimated emission reductions for hypothetical developments in the Puget Sound region with calculations on a per unit developed basis

BASELINE CASE:

Area of Development *(Acres)*	Forest Retention *(Acres)*	# lots	Lot size *(Acres)*	Baseline Emission *(t C)*	Incorporating Wood Products *(t C)*	Incorporating post-development sequestration *(t C)*	Per unit *(t CO_2-e)*
10	2.0	40	0.20	804	683	597	54.70
20	13.0	42	0.35	697	593	450	39.29
30	19.5	40	0.50	1046	889	704	64.51
40	26.1	20	1.00	1395	1,185	757	138.75
50	32.6	17	2.00	1743	1,482	774	166.97
60	39.1	8	5.00	2092	1,778	960	440.21

PROJECT CASE:

Area of Development *(Acres)*	Forest Retention *(Acres)*	# lots	Lot size *(Acres)*	Project Emission *(t C)*	Incorporating Wood Products *(t C)*	Incorporating post-development sequestration *(t C)*	Per unit *(t CO_2-e)*	Emission Reduction *(t CO_2-e /unit)*
10	2.4	40	0.18	765	650	570	52.26	2.44
20	15.6	42	0.25	438	372	264	23.07	16.21
30	23.4	40	0.35	657	559	423	38.74	25.76
40	31.2	20	0.50	876	745	652	119.55	19.20
50	39.0	17	1.00	1095	931	567	122.21	44.76
60	46.9	12	2.00	1314	1,117	618	188.71	251.50

6.0 Conclusions

Site preparation for medium density residential development in the Puget Sound region results in a significant change in forest carbon stocks relative to initial forest cover and is likely an important source of emissions from the land use sector in Washington State. If options to create the same number of lots on a given parcel of land while maintaining forest cover by reducing the minimum allowable lot size through "cluster development" were more widely and strictly applied, it could be possible to mitigate emissions from forest conversion while avoiding leakage. Cluster development represents an available option to reduce emissions for development while preventing leakage – however, it is important to ensure that cluster development, by reducing the minimum lot size, does not result in an increased conversion of forest in rural areas where medium to high-density urban development would normally not occur.

Crediting developers for avoiding immediate emissions from site preparation through a performance standard likely offers a good opportunity for mitigating emissions from forest conversion to residential development. However, common practice for vegetation removal and disposal would need to be further explored in order to establish a performance standard to credit developers for exceeding common practice for site preparation. Likewise, a region-wide performance standard would need to be designed in a way to account for lot size and original vegetation cover as the most common lot size differed between counties and subdivision, and are developed on land with varying proportion of initial forest cover.

Finally, retaining forest cover and trees on residential properties does not guarantee that this vegetation will be retained over time by property owners in the absence of regulations such as tree ordinances. The carbon stocks on urban and suburban lands will always be less than carbon stocks on forest lands. County governments could also take actions to mitigate emissions from development by directed development to open lands as opposed to land with forest cover.

This study represents an initial analysis of the impact of development and associated forest conversion and emissions in the Puget Sound. The analysis shows the potential value of further examination of this category in the region. Emissions occurring are large and are likely largely unaccounted in inventories of greenhouse gas emissions. These emissions also present an opportunity for development of an offset project category. Where emissions can be reduced without leakage, as in cluster development, then these emission reductions should be creditable to developers and local authorities.

This study was limited to a sample of development sites from limited zoning categories. A future study should look more exhaustively at development that has occurred over the last 10 years and should use a similar methodology to calculate forest loss, the emissions resulting from forest loss and post development carbon stock recovery.

Emissions associated with urban development are not limited to those associated with the loss of forest. Greenhouse gas emission consequences are also associated with the materials used in construction (e.g. wood versus concrete and steel) and in the siting of development units with regard to the future commuting distance of future residents. An entire life cycle study would be immensely valuable for understanding the total greenhouse gas consequences of development decisions.

Annex 1: Complete Urban Residential and Rural Zone Listings included in Study for Pierce, Snohomish, and King Counties

Zone	Purpose and Intent	Code
Pierce County		
Community Center	Commercial focus with some moderate to high density residential developments	CC
Moderate-High Density Residential	Areas that are composed of moderate and high density single-, two-, and multi-family housing and compatible civic uses	MHR
Moderate-Density Single Family	Moderate density single- and two-family residential activities and and compatible civic uses in areas with a mixed residential pattern	MSF
Single Family	Low and moderate density single- and two-family residential activities and compatible civic uses in areas with a predominantly detached single-family development pattern	SF
Reserve-5	Intended to provide for rural uses at a rural density and includes lands between the Rural 10 classification and the Rural 40 or Forest Lands classifications	Rsv-5
Snohomish County		
Residential-7,200	Provide for predominantly single family residential development that achieves a minimum net density of four dwelling units per acre.	R-7,200
Residential-9,600	Provide for predominantly single family residential development that achieves a minimum net density of four dwelling units per acre.	R-9,600
Rural Resource Transition - 10 Acre	Implement the rural residential-10 (resource transition) designation and policies in the comprehensive plan, which identify and designate rural lands with forestry resource values as a transition between designated forest lands and rural lands	RRT-10
Rural-5 Acre	Maintain rural character in areas that lack urban services	R-5
King County		
Residential-1	Predominantly single detached dwelling units and other development types with a variety of densities and sizes in locations appropriate for urban densities	R-1
Residential-4		R-4
Residential-6		R-6
Residential-8		R-8
Rural Area-2.5	Rural areas where the predominant lot pattern is below five acres in size for lots established prior to the adoption of the 1994 Comprehenisve Plan	RA-2.5
Rural Area-5	Rural areas where the predominant lot pattern is five acres or greater but less than ten acres in size and the area is generally environmentally unconstrained	RA-5

Annex 2: Field methods

WESTCARB Regional Characterization – Field Measurement Plan

The objective of field measurements described in this plan is to gather data to estimate post-deforestation carbon stocks on forested land that is converted to moderate density residential subdivision development in Snohomish, King, and Pierce Counties. The assessment will consider the conversion of forest cover to the following landcover: landscaping vegetation, street trees, open spaces, and impervious surfaces.

Definition of study area boundaries

The study area boundaries will be defined using parcel data to determine the boundaries of residential subdivisions and individual lots. The study area will include 8 medium density residential subdivisions from the three counties comprising 174 residential lots. For this study, moderate density residential development includes subdivisions with minimum lot size between 0.25 and 1 acre. The developed subdivision selected for field measurements are listed in Table 1.

Table 22. Medium density residential subdivisions selected for field measurements

County	Town	Subdivision	No. Lots
Pierce	Spanaway	Pierce-1	51
	Bonney Lake	Pierce-2	25
	South Hill	Pierce-3	23
	South Hill	Pierce-4	59
	Tacoma	Pierce-5	15
	Puyallup	Pierce-6	40
Snohomish	Snohomish	Wardrum Woods	12
	Monroe	Ridgewood Estates	25
	Arlington	Quail Ridge	9
	Stanwood	Blacktail Forest	49
	Stanwood	Cascade Peaks	13
	Arlington	Kenrose Heights	9
	Arlington	Echo Ridge	7
King	Renton	Cavanaugh	37
	Fall City	Evetts Park	9
	Bothell	Norway Knoll	15
	Federal Way	Creekside Lane	53
	Auburn	Adlers Cove	94
	Auburn	Hidden Tree	19

The vegetation in the study area will be divided into three preliminary strata.

Preliminary Strata

Baseline strata and existing land cover:

No.	Name	Description
1	Low vegetation	Landscaping vegetation within residential lot boundaries including isolated trees,

		shrubs, grass, other herbaceous vegetation and impervious surfaces (driveways and buildings)
2	Rights of way	Isolated trees or "street trees" located along rights of way within the boundaries of the residential development and impervious surfaces
3	Open space	Vegetation within the boundaries of land dedicated to public use in the residential subdivision. Open space may include public forests, parks, etc. with trees, shrubs, grass, and other herbaceous vegetation

Delineate Strata in GIS

Strata will be delineated based on existing aerial imagery and property boundary shapefiles.

Field Verify Strata

The accuracy of the GIS data layers used to define project boundaries and project strata must be assessed. GIS data used to define the boundaries of the project lands may not accurately portray what is found on the ground. For example, the GIS layer may be shifted slightly, or the accuracy may be lower than what would be appropriate for the project. Therefore, field verification of such features will take place.

A selection of carbon pools in each stratum will be included in measurements to estimate existing carbon stocks and GHG removals in the baseline.

The carbon pools measured for each stratum are listed in a separate table. In the low vegetation stratum, pools for which destructive sampling is required for direct measurement will be estimated using default values instead. This is because destructive sampling in residential lots will not be feasible.

The following staff will be included on the field measurement team that will be responsible for collecting the field measurements: Erin Swails, Sean Grimland, Felipe Casarim, Alex Grais, and Zack Smith. The field measurements will be collected between 19 - 23 July 2010. A brief field measurement training will be conducted on 19 July prior to commencing field measurements.

The approach to measurement of each stratum is as follows: low vegetation and impervious surfaces will be measured in the developed residential lots. For each residential lot included in measurements, a complete inventory of vegetation and impervious surfaces will be conducted. Street trees will also be inventoried. For open space with forest cover, sample plots will be used. For open spaces without forest cover, an inventory method will be used as for residential lots.

Sample size

For low vegetation, the sample size will depend on the response rate to the requests for permission to access private property. If necessary, permission to access lots will be requested in the field by knocking on property owners' doors so that additional lots can be included in the sample. For rights of way, the entire street tree population will be inventoried in each neighborhood where measurements are collected. In open space and undeveloped parcels with forest cover, 10% of the area of the parcel will be measured with sample plots.

Plot design

For the low vegetation strata and open spaces without forest cover, an inventory of above ground tree and non-tree woody biomass, herbaceous vegetation cover and impervious surfaces will be conducted in each residential lot selected for sampling. The plot will include the entire residential lot. For open space with forest cover, the plot design described in "Winrock – Terrestrial Carbon Measurement – SOP Manual" will be used.

Distribution of plots in project area

Plot locations will depend on the response rate to the requests for permission to access private property. Each property for which permission is granted will be measured. If additional lots must be selected in the field, every lot where permission to access the lot is granted will be measured.

Measurement Procedures

The same measurement procedures will be used for aboveground tree biomass in low vegetation, rights of way, and open space.

Above-ground tree biomass

DBH and height of each tree will be measured and recorded following the guidance in SOP: "SOP Measurement of Trees" and "SOP Measurement of Tree Height" in "Winrock – Terrestrial Carbon Measurement – SOP Manual." The species of each tree will also be recorded.

Shrubs

For isolated shrubs, the height and two diameters for each shrub will be measured and recorded following guidance in SOP: "SOP Measurement of Shrubs." For hedgerows, the length, width, and height of the hedgerow will be measured. The species of each shrub or hedgerow will be recorded.

Herbaceous vegetation and impervious surfaces

The percentage of each ground cover type in residential subdivisions and any open space without forest cover will be estimated to the nearest 5%:

- Herbaceous ground cover, other than grass
- Grass
- Impervious surfaces: buildings, driveways, etc.

Annex 3: Subdivisions included in field measurements

County	Zone	Subdivision	Town
King	R-4	Norway Knoll	Bothell
King	R-4	Cavanaugh	Renton
King	R-4	Creekside	Federal Way
Pierce	MSF	MSF-1	Spanaway
Pierce	MSF	MSF-3	South Hill
Pierce	MSF	MSF-4	South Hill
Pierce	MSF	MSF-5	Puyallup
Pierce	MSF	MSF-7	Bonney Lake
Snohomish	R-5	Blacktail Forest	Stanwood
Snohomish	R-5	Wardrum Wood	Snohomish
Snohomish	R-5	Kensrose Heights	Arlington
Snohomish	R-5	Ridgewood Estates	Monroe
Snohomish	R-5	Quail Ridge	Arlington

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COMMUNITY PERCEPTIONS OF CARBON SEQUESTRATION: INSIGHTS FROM CALIFORNIA

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DOE Contract No.: DE-FC26-05NT42593

Contract Period: October 1, 2005 - May 11, 2011

IOP Publishing — Environmental Research Letters

Environ. Res. Lett. **4** (2009) 034002 (8pp) doi:10.1088/1748-9326/4/3/034002

Community perceptions of carbon sequestration: insights from California

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Received 13 January 2009
Accepted for publication 16 July 2009
Published 24 July 2009
Online at stacks.iop.org/ERL/4/034002

Abstract
Over the last decade, many energy experts have supported carbon sequestration as a viable technological response to climate change. Given the potential importance of sequestration in US energy policy, what might explain the views of communities that may be directly impacted by the siting of this technology? To answer this question, we conducted focus groups in two communities who were potentially pilot project sites for California's DOE-funded West Coast Regional Partnership (WESTCARB). We find that communities want a voice in defining the risks to be mitigated as well as the justice of the procedures by which the technology is implemented. We argue that a community's sense of empowerment is key to understanding its range of carbon sequestration opinions, where 'empowerment' includes the ability to mitigate community-defined risks of the technology. This sense of empowerment protects the community against the downside risk of government or corporate neglect, a risk that is rarely identified in risk assessments but that should be factored into assessment and communication strategies.

Keywords: public perceptions, carbon sequestration, community

1. Introduction

Burning fossil fuels is the largest source of energy for electricity generation in the US, and is projected to remain so until at least 2030 (EIA 2008). However, this large-scale combustion of fossil fuels presents a large-scale problem for global climate change mitigation. The US electricity sector contributes nearly one-quarter of all greenhouse gas emissions (EIA 2009). Given the growing political and social impetus for US action on climate change (NETL 2006, WESTCARB 2008), how does the US deal with the environmental challenge of fossil fuels, and in particular with coal?

The answer put forth by many policymakers, both in the USA and internationally, is 'clean coal technologies' (e.g., Parson and Keith 1998, IPCC 2005, DOE 2008b). These technologies, which include integrated gasification combined cycle, circulating fluidized bed coal combustors, and carbon sequestration, are being promoted as 'one of the most promising ways for reducing the buildup of greenhouse gases in the atmosphere' (DOE 2008a). Since 2000, the US DOE has invested heavily in the research and development of these and other energy-related technologies. As part of this effort, DOE developed seven regional research partnerships to develop technology, infrastructure, and regulations through pilot tests, including community outreach and education efforts, to implement large-scale carbon sequestration projects in different regions and geologies in the US (DOE 2006, 2007a, 2007b, 2008c).

The successful deployment of carbon sequestration will be a major endeavor that requires technical know-how, innovative regulations, financial incentives, and public acceptance. Many professionals argue that public acceptance remains one of the most challenging barriers to this technology, at least in the US (e.g. Parfomak 2008). Research shows that public opinion so far varies from slightly in favor of CCS to opposition to it, and that carbon sequestration is sometimes seen as a stalling tactic compared to addressing the 'real' issue of fossil fuel use (Palmgren *et al* 2004).

It can be argued that public opinions, and eventually acceptance, matter for two reasons. First, public acceptance of large-scale infrastructures, and their attendant costs, benefits and risks, could be considered intrinsically important in a democratic nation. Second, public acceptance could be of instrumental importance in that organized protests could slow down, increase the transactions costs of, or even block, sequestration projects. The latter is a real possibility; past projects with potentially negative environmental impacts, such as hazardous waste disposal facilities, have faced social resistance and public protest (Beierle 1999, Shively 2007, Endres 2009). Thus far, most of the research on public perceptions of carbon sequestration has focused on how the general public views the risks of this technology and on how to garner acceptance of it (de Coninck *et al* 2008, Ha-Duong *et al* 2007, Huijts *et al* 2007, Miller *et al* 2007, Palmgren *et al* 2004, Shackley *et al* 2004, Sharp 2000). However, actual deployment of carbon sequestration will directly impact not 'the public' but specific communities.

How host communities themselves understand and define the risks of being host sites remains an understudied question. Host community opinions may differ from those of the public at large because their perceptions are based on the concrete rather than the abstract, particularly when the benefits of hosting are widespread but the risks are locally concentrated. If carbon sequestration needs public acceptance, the directly impacted public is arguably the most important segment to understand and accommodate[1]. This paper asks: what do communities located near actual or potential sequestration sites view as the risks of carbon sequestration? What factors explain community perceptions of the risks of carbon sequestration?

To answer these questions, we conducted focus groups and interviews in two communities that could have been pilot project sites for California's DOE-funded West Coast Regional Partnership (WESTCARB). Pilot projects are by definition not 'real' projects, but they reveal a number of challenges and possibilities, both technological and social, that scaled-up implementation could face[2]. We chose a low-income largely Hispanic community as our first study site and compared its responses to those of a relatively well-off mainly Caucasian community.

Our research finds that communities want a voice in defining the specific risks to be mitigated as well as the justice of the procedures by which the technology is implemented. Consistent with existing work on individual risk perceptions of large-scale technologies, we found that the community-defined risks of sequestration are as much social in nature as they are technological (EPA 2008, Fischoff *et al* 1978, Freudenburg and Pastor 1992, Morgan *et al* 1992, Slovic 1987). In this literature, the social risks of technologies such as sequestration have been related, for example, to how the community is perceived by outsiders (will it be stigmatized?) or to political structures (is the risk voluntary or involuntary, and who is imposing a risk on whom?). Another risk factor cited is the 'trustworthiness' of the project information provider—people sometimes distrust safety information provided by government or companies (Rousseau *et al* 1998, Siegrist and Cvetovich 2000). Our findings extend this important work to include the risk of government and corporate neglect, meaning the risk of no compensation or damage mitigation, should the technology not perform as expected. We argue that this risk should be included in assessing the overall set of risks faced by a community when hosting any large-scale infrastructure, including carbon sequestration.

We find that while both communities were reluctant to host CCS sites a community's sense of empowerment is key to understanding its range of carbon sequestration opinions. 'Empowerment' includes (i) the ability to mitigate community-defined risks of the technology, and (ii) the ability to ensure that just procedures would be followed in implementing the technology. We argue that a community's sense of empowerment is rooted in its history and its material and social asset base. This sense of empowerment allows its members to exercise 'voice' (Hirschman 1970) and to seek redress if they think they are being harmed; it thus gives the community some protection against the downside risk of government or corporate neglect. It is the perception of this risk, more than that of technology failure associated with carbon sequestration, and that is rarely discussed in the sequestration literature, that distinguished our two study communities from each other.

In the rest of the letter, we first recount the data collection methods followed for this research. We then report and interpret our findings on each of our two questions: how communities view the risks of hosting carbon sequestration sites and what factors might explain the range of these perceptions. We highlight in particular a community's history with local industries and its experience of past environmental harm and its mitigation. Finally, we conclude with some thoughts on the implications of our findings for CCS-related risk identification and risk communication.

2. Study sites and methods

Underlying the Sacramento Basin, which spans over 60 miles from the Coast Ranges to the Sierra Nevada, and 140 miles from south of Stockton to just north of Black Butte, are the largest deposits of natural gas west of the Rocky Mountains. Although some deposits are still extractable, and a few new sites are found every year, most are depleted. Such are the formations that underlie Rio Vista and Thornton (figure 1). It is in these depleted gas fields, among other geologic formations such as deep saline aquifers and depleted oil fields, where WESTCARB planned to test carbon sequestration. WESTCARB originally selected the Thornton gas field as an appropriate test location. Before any outreach effort had begun, while WESTCARB was still in the process of negotiating with the owners of the land overlying the proposed site, an article about the Thornton site appeared in the *Los Angeles Times* (Wilson 2006). To mitigate any community concerns, WESTCARB decided to hold a town hall meeting to present the details of carbon sequestration and of the test

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[1] This would hold true whether public opinions were valued for intrinsic or for instrumental reasons.

[2] It is widely accepted that pilots are necessary as trial runs for the implementation of new technologies or infrastructure. But they also offer the opportunity to test social responses to such projects. Of course, pilots cannot perfectly predict the social or the technological impacts of projects at scale.

Figure 1. Map of the locations of the two study communities, Thornton, CA and Rio Vista, CA. Thornton is located 30 miles south-east of Sacramento, California's state capital. Rio Vista is located 13 miles from Thornton. (Map of Northern California is from google.maps.com and the pictures were taken by Gabrielle Wong-Parodi in February 2007.)

project. Despite their efforts, WESTCARB could not reach an agreement with the landowners, and its cost-share partner pulled out of the project. Thornton was therefore a potential, but is not as of now an actual, project site.

We conducted three focus groups in Thornton in the spring of 2007. Thornton is an unincorporated, 'tree-lined woodsy'[3] farming community of about 1500, and is located 30 miles south-east of Sacramento, the state capital. The community is largely Latino and has low socio-economic status, where fewer than half of all adults hold a high school diploma and the median household income is \$30 469 yr^{-1} (\$1999) (The comparable median household income for all of California is \$47 493.) According to our interviewees, Thornton's legal US residents have been leaving due to a sagging local economy, while its undocumented population has been increasing with the demand for (cheap) labor in the agricultural sector. A much-cited outcome of the economic downturn is the recent closure of Thornton High School. Students now commute some 8 miles away to a high school in the larger community of Galt.

To compare Thornton's concerns with those that might be voiced by a better-off population, we also conducted two focus groups and sixteen one-on-one interviews[4] in a nearby town, Rio Vista. Rio Vista is a small tight-knit rural community of 4500. Unlike Thornton, the community is largely white, with an educated population and a median household income of \$44 534 yr^{-1} (\$1999). Also unlike Thornton, the community has experienced a period of rapid population growth: 'I think a lot of people are moving here to get away from the smog and all that hustle and bustle and stuff like that in the city' (Interview; business owner). Only 13 miles from Thornton and geologically very similar, Rio Vista had also been considered as a sequestration host site. The complicated negotiations that its numerous landowners would have required WESTCARB to go through removed it as an actual site early in the process.

In our Thornton focus groups we informed the community that they were under consideration as a pilot site, which they then were, but that no final decision had been reached. We found that, other than some of our Chamber of Commerce participants, no one knew this: our focus group members, at least, had not read the earlier *Los Angeles Times* article. In Rio Vista we informed the community that their gas fields were viable sites for geologic sequestration, and that the DOE had seriously considered them as CCS pilots. We asked our participants in both communities to imagine that they had actually been selected as a host. In both cases we made clear the small and experimental nature of WESTCARB's test injections.

Our sampling method was purposive so that the first focus group in each town comprised people of local standing, such as the Fire Chief and Chamber of Commerce members. We

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[3] This was the description offered by one of the participants in our study.

[4] We did not conduct one-on-one interviews in Thornton, which, at the time of our research, was under consideration as a CCS test site. The DOE approved our focus group protocol, but did not permit individual interviews. Rio Vista had already been discounted as a CCS site; therefore no restrictions on our research activities were in effect.

wanted to ensure that these groups would welcome us, and our research agenda, in their towns. Some of these early individuals continued to act as key informants for our study. Other participants were recruited through snowball sampling—a non-probabilistic sampling method in which participants already in the study recommend other persons to be invited to participate. Considerable effort was made, through flyers and radio messages, to ensure that participants for the focus groups and interviews were demographically representative of their communities. To ensure that all participants would be comfortable in sharing their views, we kept the focus groups internally homogeneous (by standard socio-economic measures such as household income, level of education and primary language) but heterogeneous across groups (Bryman 2008)[5].

We chose focus groups as our main data collection method for two reasons. Investigating host community opinions of carbon sequestration is a relatively new area of research, and focus groups allow multiple dimensions important to participants to emerge through discussion. Because focus group participants are self-selected, their views may not represent those of the larger community and should not be treated as doing so. Rather, a series of focus group discussions reveal and clarify the range of perspectives held in the community on the focal theme; for emergent research areas this is especially valuable. Second, focus groups are an excellent way to pilot and refine surveys for any subsequent larger-scale studies (Richards and Morse 2007); we plan to conduct these in several sequestration sites in the future.

Our focus group materials were developed and piloted during the summer of 2006 in collaboration with the education and outreach teams from the Southwest Regional Partnership and the Midwest Regional Carbon Sequestration Partnership. After half of the focus groups had been conducted, we used the results from the group discussions to develop a one-on-one interview protocol. We conducted interviews so that additional views could be solicited, and to test the focus group responses for robustness[6]. The focus group instrument covered four areas: (a) community concerns overall; (b) climate change (c) carbon sequestration; and (d) alternatives to carbon sequestration. Our main interest was sequestration, but in order to help respondents to understand why sequestration was an issue at all, we embedded the sequestration questions within the context of climate change as well as other energy policy options. The interview protocol covered similar themes. Examples of questions we asked are ‘Where do you think these [carbon sequestration] projects will be sited?’ and ‘In California we live with risk (e.g. earthquakes and flooding). Given the scale of these risks, how much does the additional risk of CCS (carbon sequestration) matter?’ Each focus group comprised 6–8 participants and ran up to 3 h in length. The individual interviews ranged from 25 to 60 min depending on the time constraints of the participant. At the end of the data collection period, we organized a Town Hall style meeting in each community and shared our main observations with interested residents.

3. What do host communities view as the risks of carbon sequestration?

In this section we report the range of risks with respect to hosting a CCS site that our participants expressed in the course of our discussions. As with most small-*n* qualitative studies, we use quotes from our participants to illustrate our findings. We mainly report quotes that were reflective of opinions commonly expressed during our focus groups and interviews. Across focus groups within each community (including our interview results in Rio Vista) our results were remarkably similar.

In common with several studies on the siting of infrastructure projects (Kearney and Smith 1994, Lober and Green 1994), both communities in our study were overall negatively disposed towards hosting a CCS site. This reluctance was, as we show below, partly but not wholly a result of the NIMBY[7] phenomenon (Heiman 1990, Piller 1991, Takahashi 1998). Also in common with studies cited above we found that the community-defined risks of hosting a sequestration site were both technological and social in nature. In our study, the social risks appeared to be of greater concern; indeed, the risks of the technology and the risks of being a host site appear to be quite distinct issues. The expressed risks were related to technical problems that might arise with the sequestration process as well as to procedures to be followed during project implementation.

Both communities defined technological risks as actual physical harm and linked it to their suspicion of deficiencies in the quality of expert knowledge: ‘We are concerned. If we bubble up this CO_2, we cannot live in it, we cannot breathe it. What could you do? . . . You (experts) do not know, we do not know’ (Thornton). Participants’ concern about unknown technical problems led some to fear that injection of CO_2 could result in a catastrophic leak or induced seismicity, which then could result in injury to people or things. For example, one Thornton resident said, ‘It would kill people . . . it is a silent gas. That is pretty scary’. Both communities also expressed doubts about either the government or companies as trustworthy sources of information, and preferred to receive information from multiple sources. Neither community felt differently about hosting a large and permanent injection project as compared to a small and temporary one; their view was that they would have ‘more of a problem with it if it lasted five years. They did (DOE) go through all the disruption to get it started and it would be short term’ (Rio Vista).

On the social front, participants were concerned that the (actual or imagined) technological risks of a carbon sequestration project would change the nature of the town: ‘We

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[5] Rio Vista’s two focus groups comprised influential members of the town and lay community members respectively. The final town hall meeting was attended primarily by the second group. Thornton’s three focus groups were composed of the influential, teachers and educators, and lay community members (documented and otherwise) who mainly spoke Spanish. The final town hall style meeting attracted a mix of the first two.

[6] Interviews were performed to assess the opinions of community members who did not choose to participate in the focus groups. These were used to validate the opinions expressed during the focus groups as being reflective of the community at large. As explained earlier, we conducted individual interviews in Rio Vista only.

[7] ‘Not in my back yard’. This is sometimes modified to NUMBY (‘not under my back yard’) for CCS (Huijts *et al* 2007).

would have to be forever vigilant' (Rio Vista). Some believed that the quality of life in the community would be adversely impacted, for example through increased traffic or reduced property values for their homes. The property value concern was especially strong in Thornton, a town that has experienced economic stress and de-population.

Participants in each community were equally interested in the procedures of sequestration site selection, deployment and redress in case of damages. During site selection, participants would want to know 'what advantages there were for (them)' (Thornton, Rio Vista). Sequestering carbon is a global public good, and most respondents argued that some local benefits such as better school buildings or new jobs were due to them if they were to serve as host sites. During and after project deployment, our respondents wanted transparency and participation: 'Thornton wants to see (what) their reports are of gas leaking, or whatever'. It was clear that information posted on the DOE website was not what the communities wanted; they wanted consultation and information at regular intervals. Finally, if something should go wrong with the project, residents wanted to know: 'is not there some law or something that says they have to explain or inform . . . (and) is there something that we can respond to?' (Thornton).

Although just implementation procedures such as the granting of local benefits and transparency were important to both communities, our interviews revealed that residents of Thornton did not expect to have voice or redress during the lifetime of a project, while most Rio Vista residents did. Although both communities had similar concerns about the technological risks of carbon sequestration, they did not have similar perceptions of the social risks of hosting a site. Thornton residents displayed resignation and powerlessness: 'Because they say right here that they are going to test, right? They are going to do it. So you do not think that regardless of what we say it is going to happen? It is going to happen' (Thornton). This community, whose material and social assets were relatively low, was convinced that it would be unable to exercise voice or have recourse to mitigation in case of future harms. They somewhat feared the risks of sequestration per se, but feared even more the risk of being neglected or ignored if the sequestration project turned out to be more harmful than currently expected.

In contrast, Rio Vista residents believed in their power of voice and redress. For example, one resident said '(if carbon sequestration proponents) were to come to Rio Vista and *shove* their way in here, we would shove them right back out'. Another person, during the final town hall meeting, told us: 'we will keep watching. We know what to do if we do not like what's going on; there are people of influence here in this room'.

Thus we found Thornton to be more concerned than the relatively well-endowed Rio Vista when it came to hosting the technology. Many residents were strongly opposed to it; during one discussion, a teacher's aide was particularly angry about the (then-planned) Thornton project and about everything else that gets 'pulled over' poor people. Another participant noted that most of the pilot projects were taking place in rural but populated locations: 'Why are not they doing this in the desert where they cannot hurt nobody. Why is it here?'[8] Another chimed in saying that these projects were likely to be placed in mostly poor and Latino communities. Overall, there was considerable anger at being close to selection as a sequestration site without any degree of consultation, and at what was seen as yet another marker of their low status.

Although hardly enthusiastic about hosting a project, the residents of Rio Vista were more mixed in their responses. Every participant was unwilling to see his or her town as a host site but few were as hostile as their Thornton counterparts. The community's confidence that it would be able to arrange some local benefits and maintain some oversight made at least some members more open to the idea. One retiree said, 'If I am assured that this is a safe technology then I do not have a problem with it'. Others cited possible benefits such as job creation and 'royalties to the City from mineral deeds'. Rio Vista citizens were generally more aware of climate change than Thornton citizens, and were also aware that some action to halt climate change was necessary. This knowledge had little impact on their willingness to host; they would only consider hosting a site if their local economy saw direct benefits (e.g. royalties) and the local community could exercise some control ('we will keep watching'). No such expectations were raised in Thornton, where residents are pre-occupied with life's basic necessities: 'I think survival is most important. Yeah, absolutely, I think trying to survive on a day-to-day basis'.

Our research suggests that the degree to which being a host community is considered risky is significantly influenced by a community's sense of *empowerment*, or the degree to which a host community believes that it has the power to control its own future. Empowerment partly stems from the community's ability to exercise voice and have recourse to compensation or damage mitigation, as well as its belief in that ability. In this study this sense of empowerment was correlated with a community's affluence, education, connections to the outside world and cohesion as a community. The perceived risk of being a host site is also, as we found, a function of previous histories of environmental damage, its mitigation or lack thereof, and the role of industries in the community. These histories are themselves partly determined by a community's capital endowments. In section 4, we present three examples of our study communities' experiences with industrial harm, environmental harm, and the natural gas industry. These experiences, which were recounted in detail, with mention of specific dates and specific episodes, reinforced a community's sense of empowerment or disempowerment.

4. What factors explain community perceptions of carbon sequestration risks?

4.1. Experience with industrial harm

In general, Thornton's experience with industry-caused environmental damage has been negative. One example of

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[8] As one of our anonymous reviewers pointed out, this is an excellent question. In California, depleted oil and gas reservoirs or deep saline aquifers are considered appropriate sites for carbon sequestration. Many of these reservoirs are close to human populations. Why WESTCARB chose or did not choose a particular site was, however, not a focus of our research.

this is water contamination by the (now defunct) Tri-Valley Growers cannery. For a number of years, many residents had suspected that the cannery was polluting their drinking water; these fears were confirmed when tests by the Regional Water Quality Control Board showed that dangerous levels of lead had seeped into the groundwater via the cannery's underground storage units. But before the community could demand abatement or reparations, the company filed for bankruptcy. Today, poor water quality still plagues the community. Many residents cited this and similar examples to explain why a carbon sequestration project, whatever the community felt about it, would go ahead anyway. They all seemed sure that if something were to go wrong during deployment, any demands for recourse would go unheard.

Rio Vista, too, has had negative experiences with industry. However, the community has also had some successes that have bolstered its sense of empowerment. In 1975 DOW Chemical started to build a $500 million petrochemical complex along the Sacramento River near the town, but later dropped the project. Members of the community attributed the failed attempt by DOW Chemical to their protests at not being sufficiently involved, and not to the political 'red tape' cited by DOW (Stammer 1977). Whatever the actual sequence of events, Rio Vista residents felt that they had collectively exercised their voice and that it had been heard. With respect to hosting a sequestration project, a significant segment, while somewhat resistant, nevertheless possessed the confidence that, if necessary, they could act collectively again.

4.2. Experience with environmental harm

Thornton's most pressing environmental problem in the eyes of the community was its poor water quality. The drinking water was allegedly so poor that you could not only taste it, you could also see it: 'If you live over here in the housing where the water drips, it stains the sink brown. Yeah, just yesterday it was coming out brown'. Many in the community were unhappy with their water, and wanted to see improvements. However, the community felt that their voice was not heard nor their fears understood, and therefore insufficient or inappropriate solutions were offered:

> 'I have gone to some of the town meetings where they have (discussions) about this water thing that they say they come out and clean it out every so often. But, I do not think they do . . . I do not think they do it as often as they should . . . A lot of people cannot afford to buy (water treatment) equipment for their house' (Thornton).

The community's failure to get its water cleaned up, even after repeated efforts, clearly contributed to the overall sense of disempowerment. As their experience with the cannery had also shown, they could not trust their local governments or any other entity to help with damage mitigation.

Neighboring Rio Vista also suffered in the recent past from water contamination; their effort for remediation, however, has largely been successful and their water quality has improved. For example, in response to the community's ongoing concern about poor water quality, the city of Rio Vista is planning on developing its own hazardous waste program to identify sources of contamination and possible solutions. Our discussions showed that Rio Vista residents could call upon their collective social and economic capital to organize against perceived environmental harms and to ensure a degree of redress and accountability from the relevant authorities. They did not share Thornton's feeling of powerlessness, and so did not share Thornton's perceived risk of official neglect should 'the gas project leak or something'.

4.3. Experience with the natural gas industry

Both Thornton and Rio Vista were built up on natural gas fields. Thornton's view of the natural gas industry can best be described as one of indifference. Not many people in the community directly benefited from the gas industry; only a few people hold mineral rights and most of those no longer live in the community. Furthermore, because Thornton is unincorporated, any tax revenues generated from gas extraction royalties went to San Joaquin County and not to the community itself. To many in Thornton, the benefits from a carbon sequestration project were tied to those few who owned mineral rights or land. Hosting the technology was seen as imposing a burden on, but not benefiting, the community as a whole.

Rio Vista had a markedly different relationship with the natural gas industry. Natural gas production was one of the largest sources of town revenue, and several hundred people in town owned land or mineral rights. The discovery of gas deposits and milestones in gas production are prominently featured in the tiny, well-maintained Rio Vista Museum. The industry has had a tremendous influence on the social and cultural makeup of the community (e.g. '. . . most people here get mineral income, which justifies a lot of things'). To many residents of Rio Vista, hosting a carbon sequestration project was seen as imposing a modest burden, but also as a potential financial opportunity for the whole town. Our interviewees admitted that some in the community had benefited enormously from the natural gas industry, but felt that the broader community had shared in those benefits. In short, 'We know them here. We trust them. Let them put the carbon dioxide in the ground. That's a good thing, is not it? I mean, it's not a bad thing, is it?'

5. Discussion

Consistent with previous research on risk perceptions, we found community-defined risks could be both technological and social in nature. Both communities were concerned that inadequate knowledge of carbon sequestration could lead to mistakes during the injection of CO_2. Most of these technology related concerns echoed those reported by other studies on sequestration and the public (e.g. Palmgren *et al* 2004, Sharp 2000). Both communities feared that neither the government nor companies could be trusted as the sole source of safety-related information (e.g. Siegrist and Cvetovich 2000).

Social risks centered on the implications of hosting the technology and the procedures to be followed during project implementation. Common concerns were how the presence of the technology would affect the character of the community and property values. Just procedures were important to both communities and included local benefits such as jobs or compensation, upgrading school buildings, and a measure of transparency and community participation. But our focus groups revealed that residents of Thornton did not expect to have voice or redress during the lifetime of a project, while Rio Vista residents did. This difference—the downside risk of government or corporate neglect should something go wrong with the technology deployment—is what distinguished the two communities from each other. It can plausibly be argued that softer responses are to be expected when the project in question is hypothetical (Rio Vista) rather than imminent (Thornton). But our research reveals that this risk is related not just to the likelihood of a project in a community's backyard, but to the community's social and material assets, its history and its ensuing sense of empowerment.

The risk of neglect should something go wrong, and the correlation of this risk with a community's past history and experiences with industry, has not been adequately addressed in the literatures on the risks of sequestration or risk communication. But this finding is consistent with Bradbury *et al* (1994) who concluded that individuals evaluate the risks of a technology not with respect to the specific technology but in light of their life histories; and it is consistent with sociological studies arguing that risk perceptions are as tied to broader worldviews and beliefs as they are to actual risks (Freudenburg and Pastor 1992). It also supports arguments in the procedural justice literature that the fairness of the process is central to the legitimacy of the outcome (e.g. Thibaut and Walker 1975, Lind and Tyler 1988, Senier *et al* 2008).

We argue that a community's sense of empowerment, defined as its ability to exercise voice and to seek redress, acts as protection against the downside risk of neglect. To the extent that our communities are representative of other possible sequestration sites, our research suggests that communities that already feel disempowered are likely to resist hosting a site in part because they fear neglect ('. . . they say they come out and clean it out . . . but I do not think they do') and they fear that having a site thrust upon them only cements their low social standing ('why is it here?'). Yet Thornton also knew that any resistance to a potential site would not be effective, that they would have to accept it if they were chosen ('. . . you do not think that regardless of what we say it is going to happen?'). What then, are the implications of our findings for gaining community acceptance of carbon sequestration?

If policy experts assume, as they still often do, that technical risks and inadequate risk communication are the main barriers to public acceptance, they could find themselves reassuring communities on the wrong front entirely. If policy implementers consult only landowners or office bearers in a community—as was the case when Thornton was under consideration as a sequestration site—the broader community and its set of concerns will remain invisible. Such an approach loses the opportunity to make the terms of technology deployment more inclusive. This acceptance this approach leads to can best be described as passive, mainly reflecting the lack of community information, engagement or organized protest. This is the sort of acceptance that the residents of Thornton were ready to bestow on a CCS site.

An alternative approach would be to seek a more active form of acceptance: to consult a range of local stakeholders throughout the site selection process, so that a grounded understanding of risks, concerns and mitigation options can emerge. However, while lauded in theory (Beierle 1999, Chess and Purcell 1999) and in official policy documents (Bradbury *et al* 1994, National Academies Press 2008), this approach is often avoided because it carries the risk of prolonged negotiation or outright rejection of the proposed technology. Of course, the timing and level of community engagement are always open to debate. It is unclear which forms of participation work best, there are no guarantees of acceptance even with early consultation (e.g. Chess and Purcell 1999), and consultation is more expensive than hierarchical decision-making. Nevertheless our research supports Morgan *et al* (1992) in suggesting that open-ended engagement remains the best way to identify the diverse concerns of the intended hosts.

Our conclusions from this research are preliminary; while they do provide insights into community perceptions of the risks of sequestration, they are best viewed as guides to better research on risk perceptions with respect to the siting of any energy (or other large-scale) infrastructures. We believe that they can usefully inform future efforts at risk identification and communication, which previous studies have highlighted as critical to acceptance: we have to understand what each community views as its greatest risks before we know which ones to allay or communicate about.

Our particular findings relate the social risks of hosting climate change mitigation technologies to perceived levels of community empowerment and to the history of community–industry relations. Before attempts are made at public outreach and education in the service of carbon sequestration, it is crucial to understand that there are several 'publics', and that their risk perceptions are specific to their histories and their sense of empowerment. A risk assessment grounded in community perceptions could identify factors (such as the sense of empowerment) that are not identified in conventional risk assessments but should be included in risk assessment, communication and mitigation strategies.

Acknowledgments

We thank Sarah Wade, Judith Bradbury, Eric Biber and two anonymous referees at this journal for their helpful comments. We also thank Larry Myers for his insights into WESTCARB's process. This material is based upon work supported by the US Department of Energy (Award no MR-06-031). Any opinions, findings, and conclusions expressed in this material are those of the authors and do not necessarily reflect the views of these organizations. This paper is dedicated to the memory of our colleague, the late Professor Alex Farrell.

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WEST COAST REGIONAL CARBON SEQUESTRATION PARTNERSHIP

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ENVIRONMENTAL NON-GOVERNMENT ORGANIZATIONS' PERCEPTIONS OF GEOLOGIC SEQUESTRATION

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DOE Contract No.: DE-FC26-05NT42593

Contract Period: October 1, 2005 - May 11, 2011

Environ. Res. Lett. **3** (April-June 2008) 024007
doi:10.1088/1748-9326/3/2/024007

Environmental non-government organizations' perceptions of geologic sequestration

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Received 23 November 2007
Accepted 29 May 2008
Published 6 June 2008

Abstract. Environmental non-governmental organizations (NGOs) have been influential in shaping public perceptions of environmental problems, their causes and potential solutions. Over the last decade, carbon capture and storage (CCS) has emerged as a potentially important technological response to climate change. In this paper we investigate how leading US NGOs perceive geologic sequestration, a potentially controversial part of CCS. We examine how and why their perceptions and strategies might differ, and if and how they plan to shape public perceptions of geologic sequestration. We approach these questions through semi-structured interviews with representatives from a range of NGOs, supplemented by content analysis of their documents. We find that while all the NGOs are committed to combating climate change, their views on CCS as a mitigation strategy vary considerably. We find that these views are correlated with NGOs' histories of activism and advocacy, as well as with their sources of funding. Overall, most of these NGOs accept the necessity of geologic sequestration, while only a small fraction do not.

Keywords: Environmental NGOs, carbon capture and storage, geologic sequestration, perceptions

Contents

1. Introduction

Non-governmental organizations (NGOs) have historically been influential in shaping public perceptions of environmental problems, their causes and their potential solutions. They are therefore an important part of the political process of creating and enforcing environmental laws (**Cohen 1995**, **Jepson 2005**). This paper investigates the current and future roles of NGOs in the US in shaping public perceptions of geologic sequestration of carbon dioxide (CO_2), a technology that is being widely discussed as a storage method for mitigating climate change.

Geologic sequestration is one of a set of storage technologies (e.g., terrestrial sequestration, ocean storage, and chemical mineralization) that are part of an overall climate change mitigation solution called carbon capture and storage (CCS)[Note1]. CCS involves capturing CO_2 from fossil fuel combustion exhaust or from the air, and then storing it safely away from the atmosphere, for example in porous rock deep underground. While the capture of the CO_2 is expensive, it is a common and uncontroversial industrial process. CCS for mitigation purposes, on the other hand, is a new and incompletely understood technology that will require government approval, and that may be visible to the public, especially at the sites where the CO_2 is injected (**IPCC 2005**). Moreover, CCS is part of a larger debate about the future of fossil fuels versus other sources of energy such as nuclear power or renewables. This paper begins to explore the political strategies that US environmental NGOs may pursue with respect to this technology.

Over the last decade, many in the expert and advocacy communities have begun to think that CCS (and therefore geologic sequestration) may be a viable and important technological response to climate change (**Parson and Keith 1998**, **IPCC 2005**). In recent years, US political leaders have begun to talk about geologic sequestration as well. Little research has been done, however, to understand what NGOs' views are of these technologies, or if and how they plan to share them with the public. In this paper we ask, how do leading environmental NGOs active in the US perceive geologic sequestration? What might explain variations among NGO positions on this topic? And, how do they plan to share their views with the public, and otherwise engage in the politics of geologic sequestration and climate change?

The political impetus for geologic sequestration as part of US energy policy is growing (**Princen and Finger 1994**). An example of this at the federal level is the investment in a series of 25 pilot-projects by the Office of Fossil Energy at the US Department of Energy (DOE) (**Princen and Finger 1994**, **Carbon Sequestration Home Page 2008**). At the state level, in 2006 Texas lawmakers passed House Bill 149 which provides liability protection to fossil-fuel-based power providers who sequester CO_2 by transferring the ownership of the CO_2 to the state (**McDonald 2007**). Additionally, in California assembly member Huffman authored Assembly Bill 705 that mandates the California Environmental Protection Agency to develop regulations and standards for geologic sequestration as a climate change mitigation strategy[Note2]. Increasingly, political leaders and advocates speak as if geologic sequestration were a well-understood, reliable technology, ready to be used in large scale in conjunction with continued fossil fuel use.

Over the past few decades, however, conflicts over unpopular energy policies such as nuclear power have demonstrated the importance of societal acceptance for the successful implementation of new technologies (**Johnson 1987**, **Rowe and Frewer 2000**). Evidence suggests that the lay public tends to trust information presented on energy technologies by NGOs, and environmental public-interest groups in particular (**Jepson 2005**), more than similar information presented by corporations or even government agencies.

The confluence of these environmental, political, and social factors suggests that NGOs' view of geologic sequestration may play an important role in shaping future energy policy. NGOs represent, and in a sense `speak for', the public, especially the part of the public that constitutes their support and donor base. In this paper we investigate how environmental NGOs perceive geologic sequestration, how and why their perceptions and strategies might differ, and how they plan to share their views with the public. Our analysis will be accomplished through the results of one-on-one interviews with representatives from selected NGOs, as well as a review of NGO histories of activism and sources of funding.

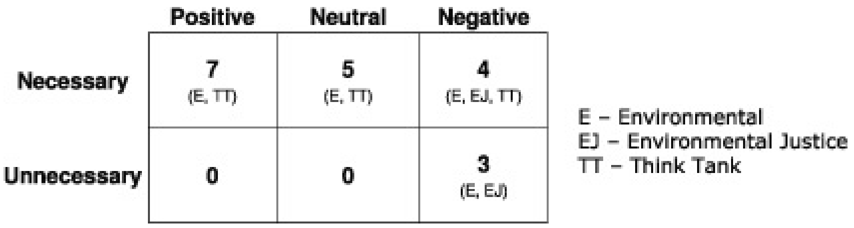
2. Methods

Climate change experts were interviewed from nineteen NGOs specializing in the environment and environmental justice[Note3]. We focused on traditional public-interest environmental groups and think-tanks, and not on industry-supported `NGOs' and think-tanks, although these are, of course, also interested in influencing the public. The NGOs were purposively selected such that their spheres of influence ranged from international policy circles to the local grassroots levels. Expert interviewees were identified through a search of NGO websites and snowball[Note4] recruiting methods. Our study covered most of the NGOs with a strong US presence that are actively working on climate change mitigation, and more specifically on mitigation technologies including, but not restricted to, CCS. In general, we sought views that were representative of the organization, but individual opinions were also stated in the course of our discussions.

Our primary method of information gathering was the semi-structured interview. We developed an open-ended interview guide in which the eventual outcome of the interview process is understood to be shaped by the interaction between interviewer and interviewee (**Mishler 1986**). The strength of this method is that it is more likely than a conventional survey to allow interviewees to respond in their own terms, using their own language, and also to provide unexpected arguments and descriptions (**Bewley 2002**).

The open-ended interview covered four topics: (a) the work done by the interviewee and organization; (b) the organization's view of geologic sequestration as a way to mitigate climate change; (c) education of the public on this technology; and (d) the public's potential reaction to this technology. The interviews ranged from 15 to 45 min in length depending on the time constraints of the interviewee.

Based upon a content analysis of the interviews and climate change related documents, if any, we developed a typology of NGO views of geologic sequestration. The first of the two axes is the NGO's opinion of geologic sequestration (positive, neutral or negative) and the second is of its perceived necessity (necessary or unnecessary) as part of a mitigation solution (see figure **1**).



	Positive	Neutral	Negative
Necessary	7 (E, TT)	5 (E, TT)	4 (E, EJ, TT)
Unnecessary	0	0	3 (E, EJ)

E – Environmental
EJ – Environmental Justice
TT – Think Tank

Figure 1. Positive, neutral, and negative versus necessary and unnecessary.

For the first axis, we split the NGOs into three groups with respect to geologic sequestration: positive, neutral, or negative[Note5]. Positively inclined NGO interviewees described geologic sequestration with language such as `enthusiastic' or `favorable towards'[Note6]. Negatively inclined interviewees described it as `terrible' or `not a good thing'. Organizations were classified as neutral if no explicit positive or negative language was used to describe the technology, e.g.: `it is not a question of whether I like it or do not like it, but that we need it'.

Further examination of the data revealed the second axis of the typology—necessary and unnecessary. Throughout the interviews, the interviewees expressed whether they believed geologic sequestration were necessary and why they believed so. For example, one respondent viewed geologic sequestration positively and thought it to be necessary: `we see carbon sequestration as an important technology that should be developed further, and further utilized'.

From our typology in figure 1, we classified the NGOs into four categories: the *Enthusiasts*, the *Prudents*, the *Reluctants*, and the*Opponents*. Interviewees from NGOs who viewed geologic sequestration positively and necessary are the *Enthusiasts*. Interviewees who were neutral towards the technology but considered it necessary are the *Prudents*. The development of the typology yielded an interesting category, the *Reluctants*, who viewed the technology negatively but suggested that it was necessary. For example, one of these respondents stated, `I have a slogan that I repeat to anyone who asks me, which is, it is a terrible idea that we desperately need'. Other mitigation solutions such as renewable energy or energy efficiency, however, should be given more emphasis than sequestration. The fourth group comprised the *Opponents* who viewed geologic sequestration negatively and thought it was unnecessary. Two of the cells in figure 1 are empty; no one interviewed viewed the technology positively or neutrally *and* thought it unnecessary.

It is, of course, possible that the positions of the organizations whose representatives we interviewed will change as geologic sequestration policy unfolds in the US. It is also the case that NGOs are not monoliths and that multiple viewpoints exist within them. This is especially likely to be the case for geologic sequestration, on which people's positions have yet to solidify. Internal differences notwithstanding, NGOs frequently take public positions *as organizations* on several environmental issues. Our interviewees themselves regularly used `we' rather than `I' when responding to questions. Table 1 provides an overview of the category under which each NGO currently falls, based on our interviews and on our analysis of its documented positions (if any) on climate change mitigation.

Table 1. Summary of organizational positions on geologic sequestration. (Note: it is possible that the positions of the organizations whose representatives we

interviewed will change as geologic sequestration policy unfolds in the US It is also the case that NGOs are not monoliths, and that multiple viewpoints exist within them. Table 1 represents our assessment of each NGO's overall position in 2007.)

	Organization	Type
Enthusiasts	Climate Registry (CR)	Environment
	Environmental Defense-TX (ED)	Environment
	Natural Resources Defense Council-CA (NRDC)	Environment
	Natural Resources Defense Council-DC	Environment
	World Resources Institute (WRI)	Think Tank
	National Council on Energy Policy (NCEP)	Think Tank
	Pew Center for Global Climate Change (Pew)	Environment
Prudents	Environmental Defense-NY	Environment
	The Nature Conservancy (TNC)	Environment
	Stockholm Environmental Institute (SEI)	Think Tank
	Union of Concerned Scientists (UCS)	Environment
	US Climate Action Network (USCAN)	Environment

	Organization	Type
Reluctants	EcoEquity (EE)	Environmental Justice
	Environment California	Environment
	World Wildlife Fund (WWF)	Environment
	Redefining Progress (RP)	Environmental Justice
Opponents	Sierra Club (SC)	Environment
	Greenpeace	Environment
	Communities for a Better Environment (CBE)	Environmental Justice

3. Findings

In this section we report our respondents' opinions on the necessity of geologic sequestration, on what the risks are of this technology, and on whether and how their NGOs planned to shape public opinion on this topic. We present their views as they expressed them, without comment on the extent to which they agree or disagree with mainstream scientific opinions on specific topics. For every theme discussed below, we present only those views that were representative of at least two-thirds of each subgroup (Enthusiast, Prudent, Reluctant, and Opponents).

3.1. Views on climate change

Our findings confirm that climate change is a top environmental concern for the NGOs, a typical example being an interviewee who `realized the huge impact that climate change has on our mission'. These NGOs are actively seeking climate change mitigation solutions. For some, the most feasible mitigation solution is CCS. An Enthusiast respondent argued that `in the past five years CCS has suddenly become so mainstream (amongst NGOs); almost partly because of the fact nothing else seems to have been able to address the problem (of climate change)'.

3.2. Necessity of geologic sequestration

All the interviewees from Enthusiast, Prudent and Reluctant NGOs viewed CCS as a necessary mitigation solution. The primary reason was the global reliance on fossil-fuel-based sources of power, especially coal, which they expected would continue. The dominant view was that the development and implementation of this technology should be the responsibility of developed countries such as the US. Although climate change would have adverse impacts in developing countries (**IPCC 2007**), these interviewees argued that the probability of independent mitigation by these countries was low because of immediate and pressing concerns such as healthcare or education. They also expressed concern that weak research and institutional capacities in these countries would hinder the successful implementation of geologic sequestration. In addition, they argued that the favorable political environment for geologic sequestration in the US made it a feasible mitigation solution. Examples were given of recent legislative activity on it by some states (i.e. Texas HB 149) and an increased interest in energy independence (reduction of fossil fuel imports) within the US. On the whole, Prudents were more insistent than Enthusiast NGOs that other solutions, such as renewable energy or energy efficiency, deserve the same amount of attention as geologic sequestration. Reluctant NGO interviewees, however, expressed reservations even while accepting the (temporary) necessity of the technology: `CCS... is about winning time... it is about mitigating climate change but it is not something that is sustainable for the long-term'.

Interviewees from Opponent NGOs disagreed with the others and did not accept CCS as a mitigation solution because they favored solutions such as renewable energy and increased energy efficiency. These interviewees were wary of the long history between the fossil fuel industry and geologic sequestration, given that it was originally developed for enhanced oil recovery (EOR) operations (**Bondor 1992**). They expressed concern that the fossil fuel industry may use geologic sequestration to continue with EOR, thereby allowing the continued use of an unsustainable energy infrastructure. Finally, they argued that the technology is itself unsustainable because the space in which to put CO_2 may eventually run out.

3.3. Risks of geologic sequestration

In the opinion of all the NGO interviewees, a major obstacle to the development and implementation of geologic sequestration was economic uncertainty. They suggested that there were unanswered questions about the capital and maintenance costs of large-scale geologic sequestration, as well as a `yawning set of unanswered questions in the regulatory and institutional framework that would govern how the technology entered the market'. These questions about costs and regulation could make investment in geologic sequestration unattractive for private firms[Note7]. Another obstacle facing geologic sequestration was technological uncertainty. Technological concerns included whether enough was known about the hydro-geologic characteristics of potential sequestration sites to ensure its safety and success. Everyone also agreed that `rigorous studies and examples' were needed to understand monitoring and verification techniques as well as site characteristics. A third obstacle was uncertainty with respect to social equity. Many argued that land use would be a major issue with the public and could prevent the implementation of geologic sequestration. Opponent interviewees in particular suggested that the technology would likely be located in poor areas: `many low-income communities of color do not have that kind of clout (economic or political); they are much more vulnerable to being the home for the sequestered CO_2 '.

3.4. Policy framework for geologic sequestration

Opinions differed on what policy framework would be the most effective for the development and implementation of geologic sequestration. The Enthusiast and Prudent interviewees viewed a cap-and-trade system as the most efficient and effective policy structure. The Reluctant and Opponent interviewees favored a mandatory cap on GHG because it would be difficult to develop a cap-and-trade system that `is not full of holes'. They expressed concern that a cap-and-trade system would allow `polluters to continue to pollute' and would not provide incentives to shift away from fossil-based forms of energy. Although there is no national US regulatory framework for geologic sequestration, all of the interviewees agreed that it should be federally regulated. They suggested, albeit with some reservations, that the Environmental Protection Agency should regulate it because `it has the legislative history, the authority, and the expertise to do it'.

3.5. Paying for geologic sequestration

Most interviewees agreed that the research, development, and implementation of geologic sequestration should be paid for through a federal tax. Opponent interviewees argued that since the mitigation of climate change was a public good the costs should be borne widely, whereas the Reluctants argued that a carbon tax on industry might be more appropriate. Most conceded, however, that the consumer would end up paying for geologic sequestration: `although the polluters should pay in practice, I think we all know they essentially pass on all of those costs and it is essentially passed onto the consumer prices'. Reluctant interviewees also argued that US consumers would bear the costs of the technology in the developing world: `basically, you know Americans and Europeans are going to pay to bury carbon in China and India and everywhere else'.

3.6. Public perceptions

All of the NGO interviewees viewed positive perceptions of geologic sequestration by the public as important to its success, because `as we have seen, (negative perceptions) can be enough to kill' a technology. Most interviewees suggested that the public's knowledge of the technology was low or non-existent. With greater awareness, however, people could be worried about impacts on human health: `they will be worried about their kids playing in some abandoned lot that is suddenly flooded with CO_2 '. They could oppose the technology `for the same reasons that people have been opposed to nuclear for years', because of its similarities to large-scale technologies such as nuclear power; or, since geologic sequestration could take place at fossil fuel burning sources, especially coal, people may be concerned with the environmental impacts of coal mining. Finally, echoing the NGOs' own concerns, a segment of the public may be concerned with social equity issues arising from the location of potential sites.

3.7. Public education

All the interviewees argued that educational efforts should be carried out by NGOs rather than by organizations they feel are deemed not `credible' in the eyes of the public. As stated by an Enthusiast interviewee: `it would be the big NGO community and the research community with the most standing in the public's eyes, you know, accurate and objective information'. In this view, `the public does not really trust the government even, I mean clearly they would not trust big coal companies or oil companies'. Each NGO category expressed different opinions of when the educational effort should begin and how it should be structured (see table 2). Only the Enthusiasts planned to present CCS as a climate change mitigation solution to the public in the near-term, where it would be part of the `whole toolbox that we present to combat global warming'.

Table 2. Summary of views on geologic sequestration education efforts for the public.

	Example of views on public education	How?	When?	Desired outcome
Enthusiast	`The most important element in the success of this technology is a huge education effort with everybody, the public, the media, academia'	Reports, public venues, websites, press, curricula in schools, public in scientific journal	Now or near-term	Immediate acceptance
Prudent	`There does need to be a political discussion that involves the public and brings in the stakeholders'	Reports, public venues, websites, press, public in scientific journals	Long-term	Increased dialog on all fronts possibly with acceptance
Reluctant	`(CCS) is something like disaster relief, you cannot win hearts and minds with CCS, you can only appeal to some rational acceptance'	Reports, public venues, websites, press, publish in scientific journals	No plans	Multi-pronged strategy with equal or more emphasis on other methods but including acceptance
Opponent	`If we ever reach out to our membership it is to tell them to contact policymakers to tell them not to do this'	Reports, public venues, websites, press, publish in scientific journals	No plans	Rejection

3.8. Industry perspective

The Enthusiast, Reluctant, and Opponent NGO interviewees suggested that the fossil fuel industry would look upon geologic sequestration favorably, perhaps as an offset (compensating for emissions in one location by reducing or capturing emissions elsewhere) or under an emissions cap. Some interviewees argued that oil companies might actually gain from geologic sequestration. Industries with large stationary sources of emissions would likely pay for geologic storage, creating business opportunities that the oil industry is very well positioned to take advantage of. Finally, the Enthusiast interviewees suggested that the development of the technology may foster competition between companies: `you are going to have pulverized coal technology fighting with the gasification technology manufacturers about who can do it (geologic sequestration)'. This type of competition could fuel innovation and eventually lower the costs of the technology.

4. Interpretation of findings

In order to understand why particular NGOs occupied particular cells in our typology (see figure **1**), we classified the NGOs along two dimensions—their histories of activism and their sources of funding. Our research results, while they cannot establish causation, do suggest a correlation between an NGO's position and strategies regarding geologic sequestration, and its history of activism and sources of funding.

Histories of activism can broadly be distinguished by two strategies: cooperative bargaining or contentious politics (**Conca 2007**). Cooperative bargaining means a strategy in which the NGO negotiates with other actors such as government and private firms to reach consensus on how to manage an environmental problem. An example of an NGO that uses predominantly cooperative bargaining is the NRDC, which worked with California businesses and state government officials to reach an agreement on the text of Assembly Bill 32 in 2006 (the Global Warming Solutions Act of 2006). Contentious politics can be defined by outside-the-institution strategies, which may include direct action or even disruptive techniques such as public demonstrations or civil disobedience to make a political point or to change environmental policy (**Conca 2007**). An NGO that uses contentious politics is Greenpeace, whose strategy in their historic anti-nuclear campaign of 1971 was to sail a group of protesters to a nuclear testing facility at Amchitka, off the coast of west Alaska.

NGOs receive funding from four main sources: governments (national, international or multilateral), private firms, foundations and private individuals. Through a review of publicly available tax forms (Form 990), NGO publications such as Annual Reports, and our interviews, we determined each NGO's most significant sources of funding, as defined by its top ten donors. For example, in response to questions about funding, the SEI representative said `funders range from government institutions, like the US EPA, US DOE, other governments like the Dutch government, Swedish government, multilateral organizations like UN Environment Program, UN Development Program, (and the) World Bank'. The correlation between funding source and NGO advocacy strategies is likely to be one of feedback rather than of simple causation—NGOs' strategies may be influenced by, and may themselves influence, the sources of funding that they receive (**Fisher 1997**, **Fox and Brown 2000**). By tracing NGO histories of activism and sources of funding, we now explain why some NGOs favor geologic sequestration while others do not.

4.1. Enthusiasts

The Enthusiast NGO history of activism reveals a dominant strategy of cooperative bargaining with businesses, policymakers, and other stakeholders on environmental problems. A review of 990 tax forms and NGO Annual Report publications shows that most of their top ten donors are foundations and private firms, including in some cases the fossil fuel and utilities industry. These characteristics enable the Enthusiasts to work collaboratively with a range of actors on climate change, the outcome of which is the endorsement of climate change mitigation solutions that all involved can accept (in this case, CCS with geologic sequestration).

4.2. Prudents

The Prudent NGO history of activism shows that their strategies on environmental problems are also those of cooperative bargaining. In addition, several of these interviewees presented their organizations' primary role as that of the objective scientist for whom multistakeholder dialog was essential. The Prudents actively participate in the same forums as do the Enthusiasts, and provide their information directly to their funders and collaborators rather than to the public. The Prudents receive a significant portion of their funding through governments and the multilaterals, but also foundations and private firms. These characteristics enable Prudent NGOs to investigate and propose a number of different solutions to mitigate climate change, only one of those being geologic sequestration.

4.3. Reluctants

The Reluctant NGO history of activism shows that their strategies include cooperative bargaining as well as contentious politics. For instance, WWF's strategies include organizing community groups among others to manage environmental problems (as in the debt-for-nature swap program in Ecuador). In the past, WWF has also used contentious politics to champion the rights of indigenous peoples in struggles over land management (e.g., in the Amazon). The Reluctant NGOs receive a significant portion of their funding from foundations and governments, but not from corporations.

4.4. Opponents

The Opponent NGO history of activism reveals a dominant strategy of extra-institutional and contentious politics on environmental problems. As described above, NGOs such as Greenpeace define their advocacy strategy as `non-violent direct action'. The Opponents are mainly membership-based, with a significant portion, if not all, of their funding coming from foundations and private individuals. All of these characteristics leave Opponent NGOs free to reject consensus mitigation solutions such as CCS in favor of fossil-free alternatives such as energy efficiency or renewables. For example, the Sierra Club interviewee said, `right now we have the choice between the clean stuff and the dirty stuff'. It seems likely that the Opponents will always choose the `clean stuff'.

In 1982, Douglas and Wildavsky proposed a sociocultural analysis of environmental organizations in which they classified the social structure of NGOs as either hierarchical or sectarian. They argued that hierarchical NGOs, by which they meant centrally-organized groups with clear chains of authority, would generally value social stability, and would collaborate with mainstream social and political institutions to mitigate environmental harms. Sectarian organizations, which are more flexibly organized and significantly volunteer-dependent, typically stand at the `border' (Douglas and Wildavsky 1982: p 174) of mainstream society. They would generally have less faith in established institutions, and so would favor extra-institutional strategies such as direct action in order to rescue the environment. Despite the many limitations of their analysis of the environmental movement (**Winner 1982**, **Abel 1985**, **Tulloch and Lupton 2003**), Douglas and Wildavsky's sociocultural perspective remains influential (see e.g., **Rayner 1992**, **Thompson *et al* 1999**). In our sample of 19 NGOs, we do find the correlation between NGO social structure and strategy to be loosely corroborated. Some of the NGOs are more hybrid in structure than the overly rigid hierarchical-versus-sectarian would imply. Overall, however, Enthusiast and Prudent NGOs do tend to be more centrally organized while Reluctants and Opponents are more loosely structured, often with semi-autonomous local chapters.

5. Conclusions and preliminary hypotheses

Our interview findings show that, in the US, three NGO categories favor acceptance of geologic sequestration: immediate acceptance (Enthusiasts), increased dialog on all fronts possibly with acceptance (Prudents), equal or more emphasis on other methods but including acceptance of geologic sequestration (Reluctants). Only the Opponent group favors rejection. Existing research on public perceptions of geologic sequestration shows that the public is largely unaware of the technology, and, when made aware of it, is neutral to negative about it (**Sharp 2000**, **Curry 2004**, **Uno *et al* 2004**, **Palmgren *et al* 2004**).

Our findings do not indicate whether any NGOs will eventually have much impact on the public's view of geologic sequestration, but we suspect that their effectiveness may be limited. Despite the universal agreement that the public should be educated about geologic sequestration, and educated by `credible' NGOs, only the Enthusiasts plan to engage in public education in the near-term. Industry-supported NGOs have already started advertising campaigns to convince the public that geologic sequestration is essential, but they may not be considered as impartial as the traditional public-interest NGOs (**Siegrist and Cvetovich 2000**). Furthermore, the history of Enthusiast activism suggests that policy makers in government and business are more often the targets of their science and advocacy than is the general public, so it is unclear how effective they can be in influencing public opinion directly. On the other hand, the Reluctants *do* have a history of direct public engagement, but they are only lukewarm about geologic sequestration and will place equal or more emphasis on other approaches to climate change.

Our interviews indicate that while most Enthusiast, Prudent and Reluctant NGOs plan to actively advocate for CCS, or at least include this technology in their mitigation portfolios, there are fewer who plan to support nuclear power and terrestrial sequestration as mitigation options. Most NGOs see CCS as a superior option to nuclear power. However, one Reluctant NGO interviewee explained his position thus: `the issue of how we get energy in a carbon constrained world does not allow us the luxury of demonizing anything'. For different reasons, this stance holds true for terrestrial sequestration vis-à-vis geologic. Geologic sequestration was uniformly seen as a better storage technology because of concerns that forested land used for terrestrial sequestration may not permanently remain forested (`how permanent is permanent? I mean you know, Vermont 50 years ago was 20% forested and now it is 70% forested, but it could easily be 20% forested again'). Nearly all of the NGOs agreed that renewables and energy efficiency must be part of a comprehensive mitigation portfolio, and perhaps as superior to CCS. The Enthusiasts, however, seemed more prepared to present CCS as a mitigation solution that was on par with the other two, because `you need to throw everything at it (climate change)', and because `CCS was designed to deal with the coal issue' in a way that renewable energy and energy efficiency are not.

Our review of the interviews and dimensions analysis (history of activism and sources of funding) allows us to hypothesize how other US NGOs not interviewed for this paper might view CCS with geologic sequestration. This technology was in general seen by all but the Opponents as a bridging technology towards a less coal-dependent economy. The perception that geologic sequestration was necessary was driven largely by the beliefs that the technology was already viable, and that the use of coal would continue for some time because a significant reduction in coal was politically infeasible. Our findings indicate that US NGOs that use predominantly cooperative bargaining strategies to manage environmental problems, and receive a significant portion of their funding from governments or private firms, are likely to endorse emissions reductions through a range of technical solutions. Solutions that seem politically viable, such as CCS or cap-and-trade systems, are especially likely to be supported. NGOs that use contentious or extra-institutional politics to address environmental problems, and receive most of their finding from members and other private sources, are likely to pay less attention to political feasibility and to view geologic sequestration negatively. They will prefer `the clean stuff' and mandatory emissions caps. Overall it seems that the majority of US environmental NGOs will accept CCS with geologic sequestration as a mitigation solution, while only a small fraction will not.

Acknowledgments

We thank Elizabeth Wilson and especially Sarah Wade for their comments and suggestions on earlier drafts of this paper. We also report, with great sadness, the tragic passing of our colleague and co-author, Alex Farrell, in April 2008. We miss him greatly, and will continue to do so as this project progresses. This paper is dedicated to his memory.

—IR and GWP

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Notes

Note1 In this paper CCS will refer to carbon capture with geologic sequestration.

Note2 Although AB 705 did not pass in 2007, it is likely to be reintroduced in 2008.

Note3 We are treating chapters of Environmental Defense and Natural Resources Defense Council as distinct organizations, because the regional chapters often have different campaign foci and region-specific views on global environmental issues.

Note4 Snowball or nominated sampling is a non-probabilistic sampling method in which participants already in the study recommend other persons to be invited to participate (Richards and Morse 2007).

Note5 We note that on occasion, an interviewee categorized as positive identified negative aspects of the technology but overall remained extremely positive. The reverse phenomenon also occurred. We looked through each interview several times in its entirety to ensure that we represent, as accurately as possible, the overall views of the organization with respect to geologic sequestration.

Note6 See table 1 for NGO abbreviations.

Note7 A key objective of the Texas bill and similar legislation is to relieve private firms of these uncertainties by transferring any long-term liability to the (state) government.

WEST
COAST
REGIONAL
CARBON
SEQUESTRATION
PARTNERSHIP
westcarb.org

THE ROLE OF SOCIAL FACTORS IN SHAPING PUBLIC PERCEPTIONS OF CCS: RESULTS OF MULTI-STATE FOCUS GROUP INTERVIEWS IN THE U.S.

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DOE Contract No.: DE-FC26-05NT42593

Contract Period: October 1, 2005 - May 11, 2011

Available online at www.sciencedirect.com

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Energy Procedia 00 (2008) 000–000

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GHGT-9

The Role of Social Factors in Shaping Public Perceptions of CCS: Results of Multi-State Focus Group Interviews in the U.S.

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Elsevier use only: Received date here; revised date here; accepted date here

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Abstract

Three of the U.S. Department of Energy's (DOE's) Regional Carbon Sequestration Partnerships analyzed community perspectives on carbon capture and storage (CCS) through focus groups and interviews in five communities. These perspectives were analyzed in the context of each community's history and its social and economic characteristics. The results were considered for their insights into specific concerns within each region, as well as to assess inter-region commonalities. In all cases, factors such as past experience with government, existing low socioeconomic status, desire for compensation, and/or perceived benefit to the community were of greater concern than the concern about the risks of the technology itself. This paper discusses the findings from the joint review of the focus groups and the potential lessons for application to CCS deployment.

Keywords: CCS, public perception, risk communication, public acceptance, communication

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1. Introduction

Over the last decade, many of the experts and advocates working in climate change have recommended further research into whether carbon dioxide (CO_2) capture and sequestration (CCS) may be a viable and important

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technological response to climate change. However, all new technologies face challenges with respect to social acceptability, especially those that may involve new risks, large-scale infrastructure, and significant government involvement—all features of CCS. Some of the most critical challenges to social acceptability may come from the perceptions and preferences of communities near whom CCS infrastructure may be located. Thus, it is important to evaluate what might explain and influence the views of communities that may be directly impacted by the siting of this technology.

The U.S. Department of Energy's (DOE's) Regional Carbon Sequestration Partnerships provide a valuable opportunity for examining this question. Initiated in 2003, the program forms a nationwide network of seven partnerships among government agencies, private companies, universities and non-governmental organizations designed to assess the viability of different approaches to carbon sequestration. The program is being implemented in three phases and is currently in the final year of the second phase of implementing over 20 small-scale field tests and the first year of the third phase of implementing a large-volume test in each region. Public acceptability is recognized as an important aspect of the program; outreach activities and research into public perceptions of the technology are a funded component. This paper reports on a collaborative social research effort among three partnerships—the West Coast Regional Carbon Sequestration Partnership, (WESTCARB), Southwest Regional Carbon Sequestration Partnership (SWP), and the Midwest Regional Carbon Sequestration Partnership (MRCSP). Researchers from these three partnerships conducted a series of focus groups in the states of California, Ohio, Texas, New Mexico and a test interview in Washington, D.C. The results were considered for their insights into particular concerns within each region, and they were also compared to see if common themes emerged from the multi-state effort.

In all cases, social factors, such as existing low socioeconomic status, desire for compensation, benefits to the community and past experience with government were of greater concern than concern about the risks of the technology itself. For example, in California, a community's sense of its own empowerment was an important indicator of its willingness to consider hosting a geologic sequestration project, perhaps even more than the perception of technological risks. Three factors seem to influence a community's sense of empowerment: history of environmental problems, relationship to the oil and gas industry, and socioeconomic status. In New Mexico and Texas, community members' concerns focused on fairness, trust and the logistics of CCS—concerns about surface owner rights, liability, and ownership of the injected $CO_{2.}$ In Ohio, issues of trust were central to focus group participants' perceptions of CCS in that they doubted the ability of the government or the project developers to ensure their safety. This underlying distrust of government and the private sector was an even greater concern than the risks of CCS technology per se.

These and other insights have significant implications for future research and the conduct of public outreach for CCS projects. They also have implications for more fundamental issues such as the design of CCS projects and, most broadly, for appropriate practices for the planning and implementation of large-scale greenhouse gas control technologies. This paper discusses the findings from the joint review of the focus groups and the potential lessons for research and application to CCS deployment.

2. Methodology

Social researchers from the three regional carbon sequestration partnerships collaborated in developing, testing and implementing a common focus group protocol to examine public perceptions of carbon sequestration, including both terrestrial and geologic sequestration. The researchers' intent was to benefit from the opportunity provided by the DOE nation-wide program to compare results from three very different geographic and cultural regions of the United States: the west (California's Central Valley), southwest (New Mexico and Arizona), and Midwest (Ohio). The focus group discussion guides were developed, piloted, and conducted in 2006 and 2007 during the second phase of the program as plans for conducting small-scale tests were being developed.

All focus groups used a similar protocol drawn up collaboratively by the three partnership researchers. The protocol built on previously published surveys in developing a discussion guides that focused on seven broad topics: (1) societal concerns, (2) familiarity with climate change, (3) attitudes about potential climate change impacts, (4) familiarity with carbon sequestration, (5) reactions to carbon sequestration policy frameworks, (6) perceived advantages and disadvantages of carbon sequestration, and (7) attitudes towards potential safeguards to mitigate risks from carbon sequestration. Focus groups were deemed to be an appropriate research tool because the approach allowed enough flexibility for each partnership to focus on regional concerns while also ensuring that its similar structure would enable comparison among the regions. The discussion guides were supplemented by brief, DOE-approved information sheets about both geologic and terrestrial sequestration to provide background information.

The data from the focus groups were supplemented by individual discussions and observations undertaken during implementation of the pilot projects. To assist in interpreting the focus group findings, the WESTCARB and SWP Partnerships conducted individual interviews both locally (WESTCARB) and regionally (SWP). SWP also used a short questionnaire regarding opinions about sequestration. MRCSP compiled information separately from the focus groups in informal public meetings and discussions at each of the three Phase II and their Phase III field test sites. Clearly, the focus group and individual interview data make no claim to statistical significance. However, given the low level of public knowledge about climate change and geologic sequestration, these types of data, collected in a more open-ended manner than a survey questionnaire, avoid the danger of eliciting pseudo opinions, or non-attitudes [1]. Focus groups and probing questions allow multiple dimensions important to participants to emerge through interaction and discussion and allow the researcher to understand differing public perspectives [2]. In an emerging area such as sequestration, they are especially valuable as a first step in identifying fruitful directions for future research.

Selecting the communities for the focus groups proved to be an interesting challenge. The Phase II field demonstrations are primarily scientific research projects designed to contribute to our technical understanding of sequestration processes and techniques. At the same time, an enormous benefit of these projects is that they are providing a wealth of practical experience in the siting, permitting, constructing and implementing of carbon dioxide injection wells. The Phase II projects are so small, involving injection of about 10,000 tons each (note – many were less than 10K, some were huge – 100-200K in one partnership, for example) that they are very unlikely to pose any significant risk. So on one hand, there is an emphasis on getting the projects completed to reap the scientific benefits. Yet on the other hand, a significant part of the practical experience is derived by working with the public to better understand their perceptions and attitudes towards CCS.

In selecting communities for social research, the dilemma is, to what extent do social research activities themselves influence the success of the scientific research projects and/or the public perception of CCS? In response to these considerations, the focus groups were conducted in three types of communities: those under active consideration to be a host community, those that by analogy could potentially host projects but were not under active consideration for the pilots, and communities that would be unlikely to host projects.

WESTCARB conducted its discussions in both a potential and an actively considered host site community where tests of sequestration in depleted natural gas fields were planned. To conduct an injection test, surface rights and often mineral rights have to be acquired in the areas where the carbon dioxide will be injected. The potential host community was a site that otherwise appeared suitable for sequestration but was dropped from consideration because the cost and time necessary to obtain property rights from the large number of property owners involved were prohibitive. WESTCARB conducted two focus groups and a series of interviews in this potential host community as well as three focus groups in a second community that was still actively under consideration for locating the pilot test.

SWP conducted five focus groups as well as a series of interviews in and near (within 50 miles) two communities that were directly impacted by hosting pilot tests. The New Mexico site hosted a test for injecting CO_2 into coal beds to enhance the recovery of coal bed methane, the primary energy source for natural gas. The Texas site hosted tests of sequestration in depleted oil wells to achieve enhanced oil recovery (EOR). One focus group each was conducted at the New Mexico and Texas host sites, and three were conducted in nearby New Mexico communities that were indirectly impacted. Because public interest was insufficient to support focus groups, individual interviews were conducted in nearby Texas communities.

MRCSP selected a community that would be unlikely to host a sequestration project because of population and urban density but was located in a state with significant sequestration potential and historically dependent on coal for electrical power generation. MRCSP conducted two focus groups in Columbus, Ohio.

The focus group communities differed in demographic characteristics. The WESTCARB and SWP communities were rural; MRCSP's was urban. The population in one WESTCARB community had low median incomes, low education levels, and a large proportion of Hispanics; the economy was in a downturn. The other community was largely white, well-educated, and had higher median incomes. Focus group participants largely reflected these sociocultural differences. The SWP communities varied; all had lower median incomes than the State median but the proportions of Hispanic, white and American Indian populations differed (one had a high proportion of American Indian, and another had a high proportion of white persons). However, focus group participants were largely white and well educated. The MRCSP Columbus population was largely white, and focus group participants were well educated.

Recruitment approaches also differed, depending on what was most feasible in each study community. WESTCARB recruited one group to represent people of local standing; others were recruited by snowball or nominated sampling, flyers, and radio advertisements. SWP recruited through newspaper and radio advertisements, local internet-based community calendars, and word of mouth. MRCSP recruited one group of "influentials" from personal contact with environmental groups, business associations, the public sector, civic groups, and another group randomly selected from the local telephone directory.

3. Findings

3.1. Knowledge of Climate Change and CCS

Focus group participants displayed varying levels of knowledge about climate change and its causes. Both WESTCARB populations knew that climate change was occurring. The better-educated groups understood its anthropogenic causes and had thought about its possible impacts on their community, while the groups with lower education levels were just vaguely aware of the phenomenon. Many in the former group had heard of sequestration; almost none in the latter group knew about CCS as a mitigation technology or knew that they were under consideration as a test site.

Although SWP participants had heard of sequestration, they did not appear to have a clear sense of the potential scale of sequestration that might be deployed. They generally supported the idea of supporting research on the topic. They thought landowners should be encouraged to engage in terrestrial sequestration activities. They were not concerned that carbon sequestration might delay a shift away from fossil fuels and strongly supported carbon sequestration as part of a larger energy strategy. When offered potential reasons to support research on carbon sequestration, they were most supportive of doing so because they believed it is important to test new technologies prior to deployment, somewhat supportive of doing so because it would help remove carbon from the atmosphere during a transition of the overall energy system, and uncertain whether the support of DOE and relevant industry provided a good reason to conduct research on carbon sequestration. When asked about solutions, many responded that a wide range of solutions, from nuclear power to conservation measures, are needed.

In Ohio, both focus groups were familiar with climate change and most seemed to think it was happening. The groups differed, however, in their knowledge of sequestration, especially of geologic sequestration. Most of the "influentials" had heard of it and some were even familiar with non-partnership demonstrations being conducted by large locally based utilities; however, the majority in the randomly selected group were not familiar with it. In this location also, none of the participants appeared to have an accurate sense of the potential scale of sequestration that might be deployed. Concern was expressed that moving to sequestration was a short-term solution, but most agreed that if research and development could demonstrate that geologic sequestration was a safe and low-cost alternative to emitting carbon dioxide, they would support it.

3.2. Trust and Fairness

The most striking finding in all three regional focus groups was the predominance of social concerns. Although all of the groups expressed safety concerns, in all cases, trust in authority and concerns about the fairness of CCS implementation procedures were the most strongly expressed concerns. In the Southwest, questions regarding fairness and trust predominated. In the Midwest, trust in the government and in the information they disseminated was a pervasive issue. In the West, communities expressed distrust in both the government and the private sector, but the level of distrust was higher in the lower income, relatively disempowered community.

WESTCARB

In California, a community's sense of empowerment was an important indicator of its willingness to host a geologic sequestration project. The WESTCARB researchers defined a community's sense of empowerment as 1) its ability to mitigate community-defined risks of the technology and 2) its ability to ensure that just procedures would be followed in implementing that technology. They explained this finding by citing Hirschman's [3] argument that a community's sense of empowerment allows it members to exercise "voice" and to seek redress if they are being harmed. Accordingly, empowerment protects against the downside risk of hosting a field test site. The community's history of environmental problems and its history with the oil and gas industry, both of which contributed to trust or distrust in the relevant authorities, seemed to influence its sense of empowerment. In both California communities, a central concern was the perceived deficiency in the quality of expert knowledge in the face of unknown technological risks. Other commonly expressed concerns were potential changes to the quality of the town, decreased property values, the need for benefit to the local community, the desire for transparency and participation and the need for redress should anything go wrong. Most notable, however, was that the two communities differed in terms of their expectation of redress. The community populated by lower income and less educated persons did not expect to have redress, whereas the higher income and educated community believed in their power to achieve recourse. The lower income community members based their fear on their previous experience of neglect both by industry and by government —and their belief that no one would listen to them and the project would go ahead regardless of their opinions. They expressed the belief that CCS sites were likely to be located in similarly poor and voiceless communities: "Why is it here?" The researchers concluded that the key fear was not the risk of sequestration per se but the risk of being neglected or ignored if the project turned out to be more harmful than expected.

SOUTHWEST

In New Mexico and Texas, health concerns (air and water quality) related to the energy industry were a large part of the discussion. However, the predominant themes again centred on social issues, in particular, issues of trust and fairness. In both states, participants expressed distrust of the companies representing the fossil fuel industry and the federal government. All focus groups included participants who expressed strong reservations regarding anything related to DOE and to specific coal, oil, and gas companies. They cited negative experiences with these organizations, sometimes telling detailed stories of wrongs done to them. New Mexico participants were especially likely to express a belief that they had little control over decisions regarding energy production and were unlikely to gain that control. They repeatedly stated that both government and industry had used their region as a "sacrifice zone."

Participants in the SWP focus groups also expressed safety concerns—but again, in relationship to issues of trust. They claimed that sequestration technology was still experimental and that the companies and government wanted to use them as guinea pigs to test the new technology. Information about monitoring did not allay their concerns because they did not trust those who were conducting the monitoring. They also expressed confusion about from whom they should obtain information or whom they should contact if a problem occurred. They told of past frustrations they had experienced when attempting to communicate their concerns and saw no reason why this should change now.

A concern raised was how geologic sequestration operations might impact landowner rights. Related to this were concerns about liability. As with previous concerns, they shared horror stories–for example, the story of a large company that laid a pipeline across someone's pasture, but when leaks rendered the pasture unusable for cattle, the rancher was unable to obtain compensation for his economic loss. Interestingly, despite all their concerns, all the SWP groups expressed generalized support for energy production. They recognized that energy costs were increasing, but felt that they had borne an unfair proportion of the costs.

The Texas and New Mexico groups had one significant difference. While the New Mexico groups were concerned about carbon sequestration as a new development, Texas participants did not see it as anything new. Although they shared the distrust in companies representing the energy industry and the federal government, they saw no particular problem with geologic sequestration. This may be related to the fact that the pilot project was EOR, something that these communities had become accustomed to over the past several years. Also, although

Texas participants were equally likely to distrust both government and industry, they were less likely to be concerned about fairness or procedural justice. Instead, they were more focused on how they might obtain a portion of the economic profit from EOR, even if all they got were the "crumbs" that fell from the table.

MIDWEST

In Ohio, issues of trust were central to focus group participants' perceptions of CCS. This underlying distrust of government and the private sector to protect the public or the environment was an even greater concern than the risks of CCS technology per se. Many in the "influential" group were primarily involved with regional, state and local government; their distrust seemed to stem from the observation that the "science" of sequestration is still being researched, so the answers to some questions just are not yet known. In the case of the randomly selected group, a pervasive lack of trust in government to protect human safety and the environment from the potential adverse effects of sequestration was evident. Their lack of trust was backed up by numerous direct examples of ways in which there had previously been a breakdown – and in some cases it was suggested that there was a knowing breakdown – in governmental oversight and failure to protect the interests of the community.

4. Insights from the Sociocultural and Procedural Justice Literature

While much of the research into CCS has pointed to public perceptions of the technological risks of the technology, sociocultural theorists point to the social processes within which opinions about a particular issue are formed. People bring to their evaluation of that issue their cultural frame of reference—their values, social interactions and differing experiences, and their way of interpreting and responding to the world [4,5,6]. Rather than beginning with the technology and the attributes of that technology, this school of thought would examine first the human value system and how that impacts the proposed technology. As Bradbury et al. [7] concluded in their study of community perspectives on the risks of incineration and other technologies for disposing of the nation's stockpile of chemical weapons, residents did not think about technology or risk in isolation from their broader life experiences. The community conflicts identified in these authors' studies were not only about the technical risk of the proposed technology, but also about a number of broader, social issues that have been hidden by the nearly exclusive focus on technological attributes. Critical social factors included the fairness and openness of the decision-making process, previous experiences and relationships with the project developers and governmental institutions, and accountability (who will take care of our community if something goes wrong?).

Wynne [8] similarly highlights the social nature of technology and risk and argues that technical analyses frequently fail to address the key societal issues at stake. As a result, resolution of the policy problem becomes more difficult as new technical issues are continually raised and the perception of a gap in responsibility for social issues exacerbates the overall level of concern. He emphasizes that technology is social in origin, character, and effects—the implications of technological development are the social relationships involved in innovation and implementation, and the key uncertainties stem not so much from technical uncertainties, as addressed in technical risk analysis for example, but from uncertainties over potential social changes, social relationships, and social institutions. Similarly, as noted by Rayner and Cantor [9], decisions about technology and risk inevitably involve decisions concerning the level, acceptability, and distribution of risk. Thus, the essential policy question is ethical: How fair is safe enough?

These findings from the sociocultural school are reinforced by the procedural justice literature. Lind and Tyler [10] define procedural justice as "the extent to which the dynamics of the decision process are judged to be fair." They argue that whether or not they approve of the final outcome, people respond more positively to outcomes coming from social processes deemed fair than those perceived as biased (see also Thibaut and Walker[11]; Borsuk et al. [12]). Gangl [13] notes a difference between pragmatic and ethical issues: in pragmatic issues the outcome matters more than the fairness of the process, whereas in ethical issues, process is more important. People involved in a process want to have some impact or control over decisions. Moreover, when people deal with third parties and other authorities with which they have little direct contact, their assessments of procedural justice are more strongly influenced by trust in the institutions of the decision makers.

5. Implications for CCS Implementation and Future Research

Consistent with the above literature that essentially critiques the domination of technological risk issues in discussions related to CCS, the data gathered by the three research efforts point very clearly to the overriding importance of social factors in planning and implementing CCS projects. Resolution of safety issues such as those related to potential leakage, seismicity, and long-term containment are, and will continue to be, essential to successful deployment of the technology. But, as highlighted by the focus groups and interviews, *management* of these safety risks is the critical factor for public acceptance.

Based on these data, key management questions for the public are:

- How can we have a say in what happens? Who is in charge? Will the process be fair and will anyone listen to us?
- What will happen if something goes wrong? Can we trust the project developers and the government to take care of any problems—what have our previous relationships with these entities shown us?
- What is the benefit to our community? How does the proposed project fit into or improve our way of life?

From a development and deployment perspective, therefore, it behooves industry and government developers to place greater emphasis on these types of procedural and managerial concerns. Effectively, this will require a greater emphasis on upfront social analysis and planning than is currently practiced. The regional partnerships program is notable for its funding and recognition of the importance of outreach. But none of the three partnerships discussed here included social factors in their selection of potential host sites for field tests of sequestration. Rather, they have focused on the willingness of one of their partners to host a field test (admittedly a considerable challenge) and on the technical aspects of the proposed test. For example, the key criteria laid out by DOE in selecting a large-volume Phase III test focus on the availability of a reliable and sufficient source of carbon dioxide and a potentially effective storage formation. While these are clearly essential, our data suggest that they are not sufficient in meeting the acknowledged need for public acceptance. Indeed, one-way "outreach" after site selection is not the same as a pre-site selection, two-way mutual exchange of information and views between developers and potentially affected communities. Additional criteria would have asked the partnerships to conduct preliminary consultations with potentially affected communities, assess whether the field tests would be perceived as beneficial, and discuss with them requirements for a successful test from the community's perspective.

Based on our findings, key questions for further research are:

1. How can social factors be incorporated and used to develop mutually agreeable projects rather than simply help in the site selection process? In the technical site characterization that typically occurs, a site judged to be basically suitable for CCS requires very site-specific design, construction, and operation activities to ensure safely. Should a comparable characterization be conducted to assess social characteristics? This would, in effect, require both a technical and a social characterization of the proposed project area. What are the disadvantages of such an approach? And should site-specific communication/negotiation/compensation strategies be adopted that address the community's perception of the risk?

2. If adopted, when should such a social site characterization start? How should it be factored into the selection process and how much should be conducted? The development of private enterprise is not always so encumbered – will this always be the case for CCS or just the initial projects?

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Acknowledgment:

We dedicate this paper to the memory of our valued colleague, Alexander E Farrell, who died unexpectedly earlier this year. He was greatly interested in this project and is much missed.

Disclaimer

2011 WESTCARB REGIONAL TECHNOLOGY IMPLEMENTATION PLAN

An Overview of Carbon Storage Technologies in the West Coast Region 2011-2050

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About WESTCARB

The West Coast Regional Carbon Sequestration Partnership (WESTCARB) is one of seven partnerships established by the U.S. Department of Energy to identify and validate the best regional opportunities for keeping CO_2 out of the atmosphere, thereby reducing humankind's impact on the climate. Established in 2003 and managed by the California Energy Commission, WESTCARB's membership has grown to more than 90 public agencies, private companies, and nonprofit organizations; its territory covers Alaska, Arizona, California, Hawaii, Nevada, Oregon, Washington, and the province of British Columbia.

Please cite this work as follows:

Stone, Marian and Richard Myhre (Bevilacqua-Knight, Inc.), *2011 WESTCARB Regional Technology Implementation Plan*, January 2012.

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ACRONYMS AND ABBREVIATIONS

ACR – American Carbon Registry

BLM – Bureau of Land Management

CAA – Clean Air Act

CAR – Climate Action Reserve

CARB – California Air Resources Board

CEQA – California Environmental Quality Act

CCS – carbon capture and storage

CCX – Chicago Climate Exchange

CDM – Clean Development Mechanism

CPUC – California Public Utilities Commission

CT – conservation tillage

DOE – U.S. Department of Energy

ECMB – enhanced coal bed methane recovery

EOR – enhanced oil recovery

EPA – U.S. Environmental Protection Agency

EPRI – The Electric Power Research Institute

EPS – emissions performance standard

EU-ETS – European Union Emissions Trading Scheme

FERC – Federal Energy Regulatory Commission

GHG – greenhouse gas

HECA – Hydrogen Energy California

IGCC – integrated gasification combined cycle

LCFS – low carbon fuel standard

MBF – thousand board feet

MRV – monitoring, reporting, and verification

MW – megawatt

NGCC – natural gas combined cycle

NGO – non-governmental organization

NPDES – National Pollution Discharge Elimination System

PCOR – Plains CO_2 Reduction Partnership

RCSPs – Regional Carbon Sequestration Partnerships

REDD – Reducing Emissions from Deforestation and Forest Degradation

RGGI – Regional Greenhouse Gas Initiative

USDW – underground source of drinking water

VCS – Voluntary Carbon Standard

WCI – Western Climate Initiative

WESTCARB – West Coast Regional Carbon Sequestration Partnership

INTRODUCTION

Purpose of the Regional Technology Implementation Plan

Studies of greenhouse gas (GHG) mitigation pathways internationally and in the United States have identified carbon capture and storage (CCS) as critical to meeting emissions reductions. For timeframes from 2030 to 2050, deployment of CCS technologies is expected to be one of the largest contributors to CO_2 emissions reductions.[1,2]

This Regional Technology Implementation Plan (RTIP) provides an overview of the status of CCS technology evolution and adoption in the western region of North America, where GHG emissions under several climate change mitigation regimes set forth by states and provinces are targeted for significant reductions by 2050.

The RTIP does not predict to what degree CCS will contribute to these reduction goals. Rather it examines factors for successful CCS deployment, as well as issues that could limit or delay application of CCS technologies, and solutions for overcoming these issues. The RTIP aims to inform the discussion among parties concerned with lowering the region's GHG emissions—state and provincial policymakers, public interest nonprofits, regulated industries, and project developers—who recognize the need to include CCS among the technologies that will enable the region to meet climate change mitigation goals.

The RTIP discusses three types of CCS:

- Carbon capture and geologic storage:
  CO_2 from stationary industrial sources such as power plants, oil refineries, cement plants, and ethanol/biofuels plants is separated from fuel or exhaust gases and transported to a storage site for long-term storage in deep underground rock formations.
- Carbon Utilization:
  Revenue-generating uses for captured CO_2 that also contribute to GHG reduction goals (e.g., CO_2 injection for enhanced oil or natural gas recovery or enhanced geothermal energy systems).
- Terrestrial carbon storage:
  Optimizing the earth's natural absorption of CO_2 and retention of carbon in biomass and soil to increase the amount of carbon stored (e.g., tree planting and changes in forest management) or to preserve previously stored carbon (e.g., forest conservation).

Terrestrial carbon storage, carbon capture and geologic storage, and carbon utilization have the potential to significantly reduce GHG emissions in the WESTCARB region. The degree to which these climate change mitigation practices actually contribute to a low-carbon future will depend largely upon policy and

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[1] *Advanced Coal Power Systems with CO_2 Capture: EPRI's CoalFleet for Tomorrow Vision—2011 Update: A Summary of Technology Status and Research, Development and Demonstrations.* EPRI, Palo Alto, CA: 2011 1023468.

[2] *Energy Technology Perspectives 2008: Scenarios & Strategies to 2050,* International Energy Agency, 2008: http://www.iea.org/textbase/nppdf/free/2008/etp2008.pdf

economic drivers and the commitment of the citizens of the western region to pursue a course toward lower GHG emissions.

RTIP Findings for Carbon Capture and Geologic Storage

The RTIP examines carbon capture and geologic storage in six areas: policy and regulatory development, technology infrastructure, economics, project finance, legal considerations, and public acceptance. Major findings are outlined below. The RTIP concludes that geologic storage does not face significant barriers in the western region in terms of available storage space or the technical feasibility of injecting and monitoring CO_2 in the subsurface.

Estimated capacity in the region's broadly distributed sedimentary basins is enough to store hundreds of years of CO_2 emissions from industrial point sources. Opportunities for enhanced oil recovery combined with long-term CO_2 storage may be found in southern California and Alaska. CO_2 storage in coal seams, along with enhanced coal bed methane production, may prove beneficial in Alaska, Oregon, and Washington. Source-sink matching studies indicate generally favorable distances between the region's large point sources and potential sinks.

Injection and monitoring of CO_2 is unlikely to present industry-wide barriers. Both nationally and internationally, experience in oil and natural gas extraction and storage, the use CO_2 for enhanced oil recovery, and a small number of successful CO_2 storage projects lend confidence that CO_2 can be injected safely and monitored to establish long-term storage security.

The RTIP identifies and discusses three significant challenges to CCS, which are not unique to the western region.

1. **Lack of climate change legislation to serve as a driver, and lack of a clear pathway for CCS where climate change legislation exists**

In the United States, anticipation of climate change legislation has served as a driver for developing CCS technologies. In the continuing absence of such legislation, the impetus for lowering GHG emissions is coming from rulemaking by the U.S. Environmental Protection Agency (EPA) under the Clean Air Act and from legislation enacted by some states. This "patchwork" approach fails to provide the legislative/regulatory certainty desired by industries when undertaking long-term planning and financial investments.

In California, where cap and trade regulations are being developed for implementation beginning in 2013, CCS has only been partially integrated into the state's GHG compliance framework. A further gap may open up if adoption of the 2050 GHG emissions reduction goal of 80% below 1990 levels is not enacted. Achieving this target without widespread deployment of carbon capture and geologic storage is considered by many analysts to be unlikely. However, the impetus for undertaking a long-term CCS project with high capital investment is missing until the 2050 target is codified into law.

In Washington, CO_2 injection and storage regulations that were adopted in 2007 as part of ESSB 6001 will now be subject to review and revision to be in compliance with the U.S. EPA's UIC Class VI well category, established in 2010.

2. Costs

The RTIP discusses the relatively high current costs of CO_2 capture and geologic storage. At this early stage, project developers are challenged to make a business case for a government-supported demonstration, let alone a commercial project. It is anticipated that costs will decrease as CCS technologies—particularly for CO_2 capture and compression—evolve and incorporate lessons learned. Ideally, CCS technologies will reach this stage of maturity before regulations compel widespread deployment. Under this scenario, the economic impact of achieving GHG emissions reductions would be significantly less.

3. Public awareness and understanding

Geologic CO_2 storage is often not well understood in public discourse. CO_2 itself is sometimes mistaken for a toxic or explosive substance. The risk profile for CO_2 storage is sometimes confused with pressurized pipelines at the surface or natural CO_2 releases associated with volcanic activity. Although misperceptions can be corrected through outreach and education, this takes time and resources, and depends upon the willingness of audiences to participate in the process.

CCS projects tend to be better understood and accepted in communities where oil and gas production or natural gas storage are common or where local educational institutions contribute to an understanding of subsurface operations, where project developers have an established presence and are trusted, or where benefits such as jobs creation or retention are aligned with community interests. Nonetheless, good geology for CO_2 storage will not always align with the locations of communities predisposed to hosting CCS projects, and this could affect siting.

RTIP Findings for Carbon Utilization

The RTIP notes the economic benefit of coupling CO_2 injection for enhanced oil recovery (EOR) with long-term CO_2 storage where opportunities exist. Revenue and CO_2 storage may also be realized from CO_2 injection for enhanced coal bed methane production, enhanced natural gas recovery, and enhanced geothermal energy systems. Novel CO_2 utilization technologies such as incorporation into building materials, use in fuel and chemical production, and expanded industrial applications are in earlier stages of development.

Successful deployment of CO_2-EOR in the WESTCARB region will require affordable supplies of CO_2. In California, sufficient volumes of CO_2 are not available locally and CO_2 pipeline transport from outside the state has not been economic. Thus, CO_2-EOR awaits the development of local CO_2 supplies via capture at industrial facilities and power plants. Additionally, in order to quantify and credit emissions reductions for CO_2-EOR projects, monitoring, reporting, and verification methods will need to be established and incorporated into state regulations and coordinated with federal regulations.

RTIP Findings for Terrestrial Carbon Storage

Terrestrial carbon storage projects have been a staple of voluntary carbon markets since their inception. Public perception of terrestrial carbon storage is generally positive when it accords with land-use practices such as conservation and restoration. Many landowners are motivated to undertake projects both as a means of generating income and to improve the state of their lands. Development and evolution of protocols/methodologies by independent carbon registries enable more project types to enter the voluntary carbon market and provide a basis for the development of offset protocols for compliance markets.

The RTIP finds that terrestrial carbon storage faces four primary challenges, which are not unique to the western region:

1. **Limitations on support due to lack of climate change legislation or structuring of policy instruments**

Widespread deployment of terrestrial sequestration depends upon climate change legislation and policy provisions allowing terrestrial carbon storage as a compliance option under a cap and trade program or offering other financing/incentive mechanisms. Although some states in the WESTCARB region have passed climate change legislation and are moving forward with GHG reduction programs, others await federal legislation, which is not an eminent prospect. This limits the compliance-driven demand for terrestrial carbon storage, as well as other types of offset projects.

Policy mechanisms include terrestrial carbon storage to varying degrees. For example, California's cap and trade program limits offsets to 8% of a regulated business's compliance obligation. However, given the projected size of the California carbon market and the assumption that regulated entities will utilize offsets to the fullest extent possible, this 8% limit is not expected to be a significant barrier to offset projects during the early years of the program.

In the case of Oregon's Climate Trust, the price of an offset is determined by the state's Energy Facility Siting Council and was about \$1.40 per metric ton of CO_2 in 2011. By law, this can be raised every other year by 50%. These parameters constrain the cost of GHG compliance to facilities and customers but limit the level of funding the Trust has available for offset projects. Thus, project developers would be expected to seek funding from multiple sources.

Within a carbon market, terrestrial carbon storage projects compete with other types of offset projects. Internationally, forestry projects under the Clean Development Mechanism have been placed at a disadvantage because the risk of reversals has been handled by issuing credits that have to be replaced upon expiration by the buyer, and which therefore command lower prices than credits from other offset activities. The EU-ETS, the world's biggest carbon market, does not accept these temporary credits, which has limited funding for forest projects.

As the above examples illustrate, terrestrial carbon storage receives varying degrees of support under carbon regimes, which balance multiple objectives including cost containment, achievement of GHG reductions across multiple sectors, and assurance of offset quality and permanence.

2. **Establishing standards to ensure the quality of offsets**

The integrity of a carbon regime requires that GHG reductions be real. Offsets must be additional, verifiable, enforceable, and permanent. Thus far, there is little experience in the United States with GHG offsets in a compliance market.[3] A 2008 report by the Government Accounting Office on the voluntary market found that "participants in the offset market face challenges ensuring the credibility of offsets, including problems determining additionality, and the existence of many quality assurance mechanisms. GAO, through its purchase of offsets, found that the information provided to consumers by retailers offered limited assurance of credibility."[4]

Factors that help assure the quality of offsets include transparent, publically accessible project documentation, tracking, and accounting systems; third-party verification by qualified reviewers; and regular review and adjustment of offset program requirements to allow the program to respond to changes in science, technology, regulations, market conditions, or other relevant factors.[5]

Regional cap and trade programs in the United States and Canada are pursuing a standardized approach to qualifying offset projects, which establishes program requirements up-front, instead of evaluating projects on an individual basis, as is the case for the Clean Development Mechanism. A standardized system minimizes the potential for subjective evaluation in determining project eligibility. Projects are limited to certain categories for which sufficient market data are available and for which robust quantification, monitoring, and verification protocols already exist or can be readily developed.[6]

3. Competition from other land uses

Many lands in the western region that are favorable to terrestrial carbon storage can command high values from uses such as forest products, viticulture or other high-value crops, or conversion to development. In most instances, income from carbon storage alone will not provide sufficient incentive for landowners to undertake projects. The RTIP notes how increased carbon storage can be accomplished in conjunction with other land uses or, in the case of development, how CO_2 emissions can be kept to lower levels. Nonetheless, competition from other lands uses will undoubtedly limit the application of terrestrial carbon storage projects in some instances.

4. Climate change impacts to habitats

Although terrestrial carbon storage is a climate change mitigation strategy, there is a recognized need to incorporate adaptation planning into longer-term terrestrial carbon storage project planning. Successful adaptation will depend upon landowners and managers having timely access to information on anticipated changes in local conditions (e.g., soil moisture) and response options (e.g., which species can thrive in lower moisture/warmer temperature regimes and resist threats such as pest infestations). Climate change will also become an increasingly relevant factor in land-use decisions where the timing of costs and returns is spread over decades.

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[3] The Regional Greenhouse Gas Initiative accepts five types of offsets including CO_2 sequestration from afforestation.

[4] *Carbon Offsets: The U.S. Voluntary Market Is Growing, but Quality Assurance Poses Challenges for Market Participants*, GAO-08-1048, August 2008.

[5] *Ensuring Offset Quality: Design and Implementation Criteria for a High-Quality Offset Program*, developed by the Three-Regions Offsets Working Group, May 2010.

[6] Ibid.

Strategies for adapting to changing climate conditions will come from many sources. Analysts call for improved coordination among federal, state, and local agencies in conducting research and addressing situations where jurisdictions overlap.

DEPLOYING CARBON CAPTURE AND GEOLOGIC STORAGE IN THE WESTCARB REGION

Geologic Carbon Storage Resource Is Substantial

Opportunities for geologic CO_2 storage in the WESTCARB region can be found in saline formations, unmineable coal seams, and oil and natural gas fields. Basaltic rock formations, found in Hawaii and eastern Washington and Oregon, may also prove to be suitable for CO_2 storage. The region's overall geologic storage resource[7] does not present a barrier to widespread CCS deployment, however, the suitability of any particular site will depend on many factors including proximity to CO_2 sources and reservoir-specific qualities such as porosity and permeability and integrity of sealing formations.

Saline Formations – The Region's Largest Storage Resource

Many areas of the WESTCARB region contain deep sedimentary basins with saline formations that could be used for CO_2 storage. Saline formations are sedimentary rocks saturated with brines, water that is too salty (defined as containing greater than 10,000 parts per million total dissolved solids) for agriculture or human consumption.

Sites with saline formations suitable for CO_2 storage consist of an extensive, thick layer of high-porosity, high-permeability rock (such as sandstone) located at a depth of over half a mile. The saline storage formation must be overlain by a thick, pervasive layer of low-permeability cap rock (such as shale or mudstone). When CO_2 is injected into the saline formation, it spreads through the pore spaces of the rock. The cap rock overhead acts as a seal to prevent the CO_2 from migrating above the saline storage formation.

Within geologic formations, three mechanisms work to trap the CO_2 in the pore spaces and increase storage capacity and security:

- Residual – CO_2 is immobilized in the pore spaces of the rock by the capillary pressure of the formation waters

- Dissolution – the CO_2 dissolves in the brine, forming a denser fluid with a tendency to sink

- Mineralization – over long periods of time, the CO_2-saturated brine reacts with minerals in the surrounding rock to form new minerals within the pore spaces

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[7] In the *2010 Carbon Sequestration Atlas of the United States and Canada*, CO_2 storage resource is defined as the fraction of pore volume of sedimentary rocks available for CO_2 storage and accessible to injected CO_2. It does not include economic or regulatory constraints. Estimates are based on the assumption that in situ fluids will either be displaced by the injected CO_2 or managed by means of fluid production, treatment, and/or disposal in accordance with current technical, regulatory, and economic guidelines. Storage resource estimates are screened by criteria such as isolation from potable groundwater, isolation from other strata, total dissolved solids concentrations of 10,000 ppm or more, and maximum allowed injection pressure to avoid fracturing. Resource estimates take into account geologic-based physical considerations, such as vertical thickness, fraction of porosity available for CO_2 storage, and fraction of the total area accessible to injected CO_2. In these CO_2 storage resource estimates, only physical trapping of CO_2 is considered.

Figure 1. Maps showing location of saline formations for Alaska, Arizona, California, Oregon, Nevada, and Washington

Saline formation storage estimates for the broadly distributed deep sedimentary basins of the WESTCARB region (Figure 1) range from 82 to 1,124 billion metric tons (90 to 1,239 billion tons). Even at the low end value, this is sufficient to store hundreds of years' worth of the region's CO_2 emissions from large stationary sources.

In Oregon and Washington, the total CO_2 storage resource of 10 western coastal basins is in the range of 40 billion to 590 billion metric tons (50 billion to 650 billion tons).[8] The largest is Washington's Puget Trough (Figure 2).

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[8] *2010 Carbon Sequestration Atlas of the United States and Canada*, Third Edition, U.S. Department of Energy, NETL.

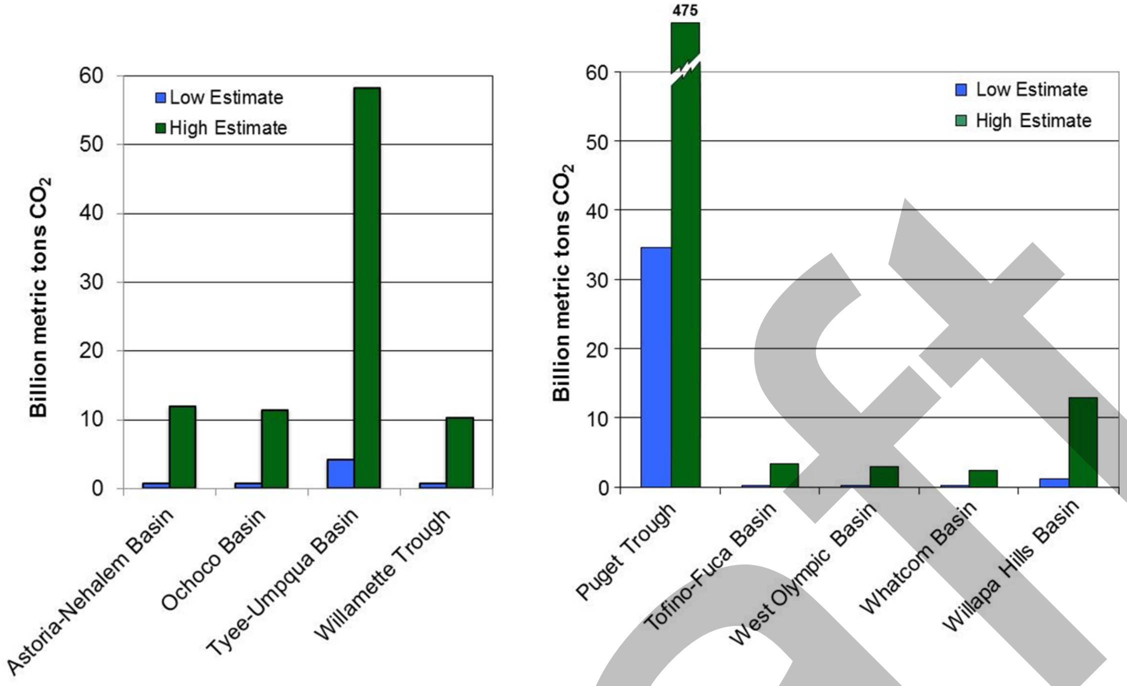

Figure 2. Estimated CO_2 storage resource for the largest on-shore basins in Oregon (left) and Washington (right)

In Arizona, the Colorado Plateau, where most the state's large coal-fired power plants are located, offers potential CO_2 storage strata with sealing cap rocks that are laterally extensive and up to hundreds of feet thick (Figure 3). However, geologic data needed for CCS project development are generally lacking because there are few exploratory oil or gas wells in this area. A characterization well drilled in 2009 by WESTCARB and utility industry partners near Arizona Public Service Company's Cholla Power Plant on the southern edge of the Plateau found insufficient permeability to warrant CO_2 injection at commercial scale.[9] More characterization in other areas of the Colorado Plateau is needed to determine if this was a localized finding. Cenozoic basins located near populations centers in the southern part of Arizona are also being investigated to determine if they could be suitable for storing CO_2 from existing and newly developed point sources in that area.

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[9] http://www.westcarb.org/AZ_pilot_cholla.html

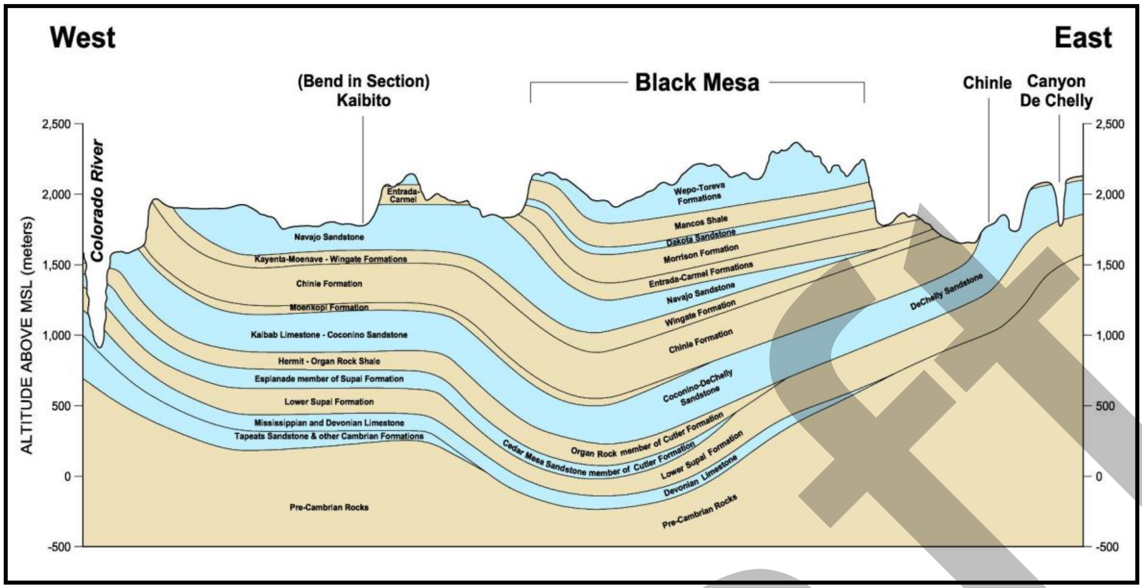

Figure 3. Geologic cross-section from Colorado River, through Black Mesa to Canyon de Chelly[10]

Areas of potential for CO_2 sequestration in Nevada are Granite Springs Valley in Pershing County, Antelope and Reese River Valleys in Lander County, and Ione Valley in Nye County. Each is larger than 30 square kilometers (12 square miles) and filled with sediments and volcanic rocks more than 1,000 meters (3,300 feet) thick. Site characterization studies are needed to determine if CO_2 storage capacity exists beneath these valleys.

In California, the California Geologic Survey created an inventory of 104 basins, outlines of which were digitized to produce a California sedimentary basin GIS layer. This layer was combined with a California oil and gas field layer to illustrate the distribution of known oil and gas fields. Basins were then screened to determine preliminary suitability for potential CO_2 storage. Screening involved literature searches and analysis of available well logs. Criteria included the presence of significant porous and permeable strata, thick and pervasive seals (cap rocks), and sufficient sediment thickness to provide critical state pressures for CO_2 injection (>2,625 feet). Accessibility was also considered. Basins overlain by national and state parks and monuments, wilderness areas, Bureau of Indian Affairs-administered lands, and military installations were excluded. Structural closure or stratigraphic trapping was not considered a prerequisite for saline aquifers at the screening level.

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[10] Courtesy of Montgomery & Associates, Inc.

Of the 27 basins that met the screening criteria, favorable attributes include: 1) geographic diversity; 2) thick sedimentary fill with multiple porous and permeable aquifers and hydrocarbon reservoirs; 3) thick, laterally persistent marine shale seals; 4) locally abundant geological, petrophysical, and fluid data from oil and gas operations; and 5) numerous abandoned or mature oil and gas fields that might be reactivated for CO_2 storage or benefit from CO_2 enhanced recovery operations.

The aggregate CO_2 storage resource of California's ten largest onshore sedimentary basins is estimated in the range of 30 billion to 420 billion metric tons (30 billion to 460 billion tons) of CO_2[11] (Figure 4). The largest of these basins is the Central Valley, consisting of the Sacramento Basin (Figure 5) to the north and the San Joaquin Basin to the south.

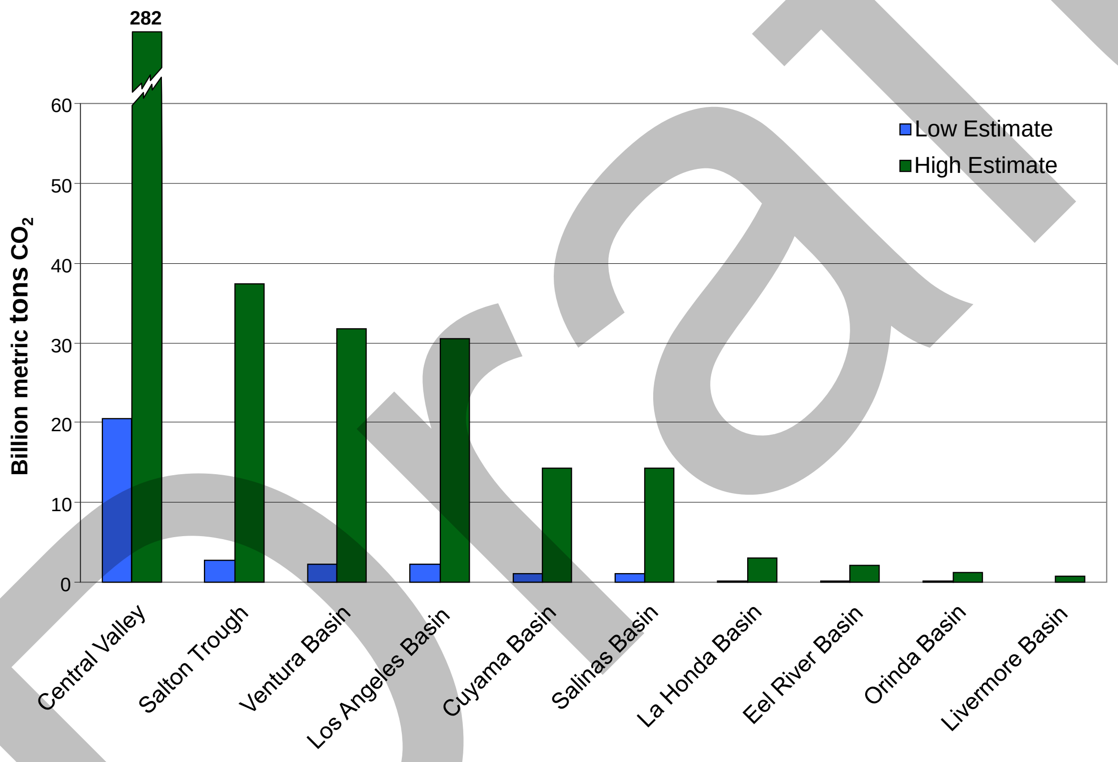

Figure 4. Estimated CO_2 storage resource for California's ten largest on-shore basins

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[11] *2010 Carbon Sequestration Atlas of the United States and Canada.*

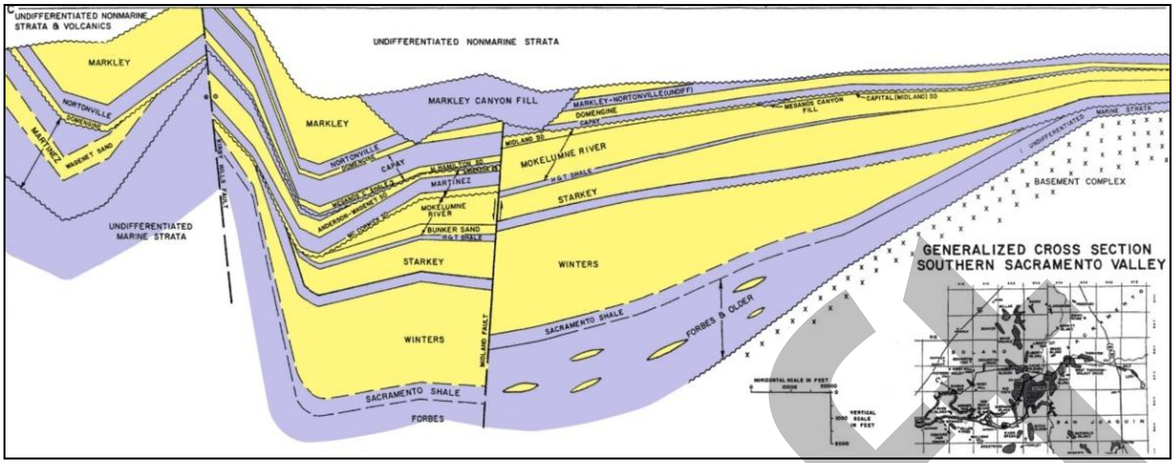

Figure 5. Geologic cross-section of the southern Sacramento Basin showing sandstones (yellow) and shales (purple)[12]

In December 2011, to more precisely characterize the CO_2 storage potential of regionally extensive geologic formations in the southwestern part of the Sacramento Basin, WESTCARB drilled a stratigraphic well in the King Island gas field, which is part of northern California's natural gas producing region and is in proximity to major industrial and power plant CO_2 sources.

The Citizen Green #1 well, which reused the pad and surface casing of an existing depleted natural gas well, was drilled directionally to a vertical depth of 6,900 feet. Whole core recovered during drilling included 19 feet of the transition between the Nortonville Shale and Domengine Sandstone (Figure 6) and 58 feet of the upper Mokelumne River Sandstone. In addition, 43 sidewall cores were recovered from the Domengine, Mokelumne, and upper Starkey (or lower H&T) sandstones, and the Nortonville, Capay, and H&T shales. A suite of wireline logs was run over a vertical depth range of 3,250 to 6,880 feet to provide data on the porosity, permeability, mineralogy, and geomechanical properties of the formations and formation fluids.

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[12] Courtesy of the California Geological Survey.

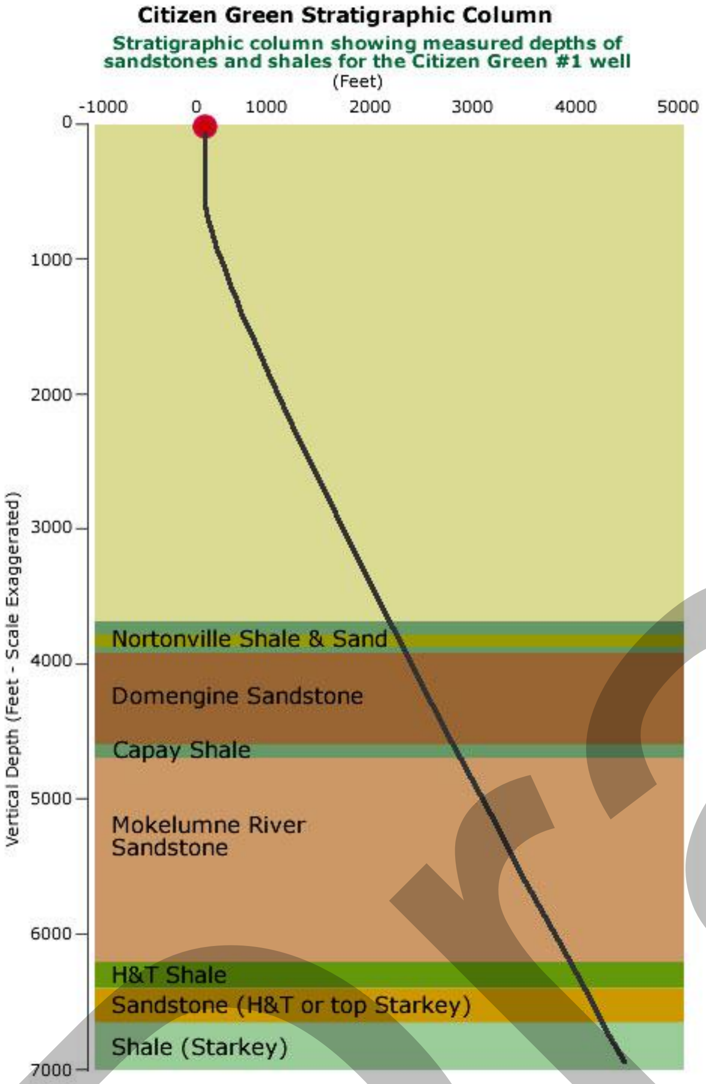

Figure 6. Stratigraphic column of the Citizen Green well in the Sacramento Basin, California

California also has numerous offshore sedimentary basins, however, the lack of available data has thus far limited the assessment of their CO_2 storage potential to areas where oil and gas exploration has occurred. A WESTCARB study identified a total of 30 offshore oil and gas fields with conventional sandstone reservoirs within the Ventura and Los Angeles basins. Of these, 24 fields are producing or have been depleted and are likely the most promising options for offshore carbon sequestration based on existing production figures and reserve estimates. These fields have a cumulative estimated CO_2 storage capacity of over 236 million metric tons.[13]

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[13] Downey, Cameron and John Clinkenbeard. (California Geological Survey) 2011. *Studies Related to Geologic Carbon Sequestration Potential in California.* Draft report.

The Southern California Carbon Sequestration Research Consortium (SoCalCarb) is characterizing Pliocene and Miocene sediments for CO_2 storage in the offshore Wilmington Graben of the Los Angeles Basin.[14] These formations (more than 3,000 feet of interbedded sand and shale sequences at depths of 3,000–7,000 feet) are known to provide excellent traps for oil and gas, and have been used for large-scale underground storage of natural gas at half a dozen locations.

Oil and Natural Gas Fields in Alaska and California Represent Economically Beneficial Opportunities for CO_2 Storage and Enhanced Hydrocarbon Recovery

Depleted oil and natural gas reservoirs are generally considered to be excellent candidates for CO_2 storage because buoyant hydrocarbons were held in these reservoirs for millions of years, thus demonstrating their suitability for long-term CO_2 storage. Storage of CO_2 in oil and gas reservoirs will have the advantage that the geology of reservoirs is well known and existing infrastructure may be adapted for CO_2 injection. Use of depleted oil and gas reservoirs as secure storage sites for CO_2 will require existing (and previously abandoned) wells to be located. If such wells penetrate through to the storage formation and were not properly closed, they may require replugging to eliminate a possible escape path for the CO_2.

Mature oil and gas fields that are still producing may be suitable for both CO_2 storage and increased production. CO_2-enhanced oil recovery (CO_2-EOR) is one of a series of engineering strategies designed to increase the rate and ultimate amount of oil produced. For lighter oils at depths of more and a half mile, as reservoir energy and mobility of oil decrease, operators can increase production by injecting CO_2, which dissolves into the oil, causing it to swell and become less viscous. Where suitable, this approach can be used to extend the economic and productive life of the field, while providing long-term storage for CO_2 left behind in the formation.

During CO_2-EOR operations, the CO_2 that is returned to the surface via the production wells is separated and re-injected. However, a significant quantity of CO_2, estimated to be one third to one half of the injected volume, becomes trapped and cannot be extracted.[15] The U.S. Department of Energy (DOE) has identified “next generation” CO_2-EOR technology options that could dramatically increase the performance of CO_2-EOR and increase the volume of CO_2 that could be stored compared to current practices.[16]

Oil fields with the potential for CO_2 storage or CO_2-EOR in the WESTCARB are found predominantly in Alaska and California. In Alaska, research is focused on two areas: (1) the Cook Inlet Basin, where proximity to industrial CO_2 sources and extensive infrastructure, as well as characterization data from oil and gas exploration and production, make CO_2 storage and EOR more feasible; and (2) the North Slope, where natural gas reserves could provide a CO_2 source to extend the productive life of the area’s oil

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[14] http://socalcarb.org/wilmington.html

[15] Hovorka, S. and Tinker, S.W. “EOR as sequestration: Geoscience perspective,” presented at the Symposium on the Role of Enhanced Oil Recovery in Accelerating the Deployment of Carbon Capture and Storage, Cambridge, MA, July 23, 2010. GCCC Digital Publication Series #10-12.

[16] *Storing CO_2 with Next Generation CO_2-EOR Technology*, DOE/NETL-2009/1350, January 9, 2009.

fields.[17] However, production of large volumes of natural gas awaits development of a pipeline to bring supplies to market.

In California, most onshore oil reservoirs are located in the southern San Joaquin Basin, Los Angeles Basin, and Ventura Basin, where WESTCARB investigators have identified approximately 1.3 billion to 3.4 billion metric tons (1.4 billion to 3.7 billion tons) of CO_2 resource potential.

A DOE study of CO_2-EOR in California placed the incremental economically recoverable oil reserves at 5.4 to 8.1 billion barrels.[18] Currently, sufficient volumes of CO_2 are not available locally and CO_2 pipeline transport into California is still considered uneconomic given historical ranges of oil prices. An initial project, Hydrogen Energy California, has filed permit applications to build an IGCC plant with CO_2 capture in Kern County, with plans to sell the CO_2 for EOR in the nearby Elk Hills oil fields.

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[17] Natural gas from the North Slope typically contains about 10% CO_2, which would need to be separated before pipeline transport.

[18] *Storing CO_2 with Next Generation CO_2-EOR Technology.*

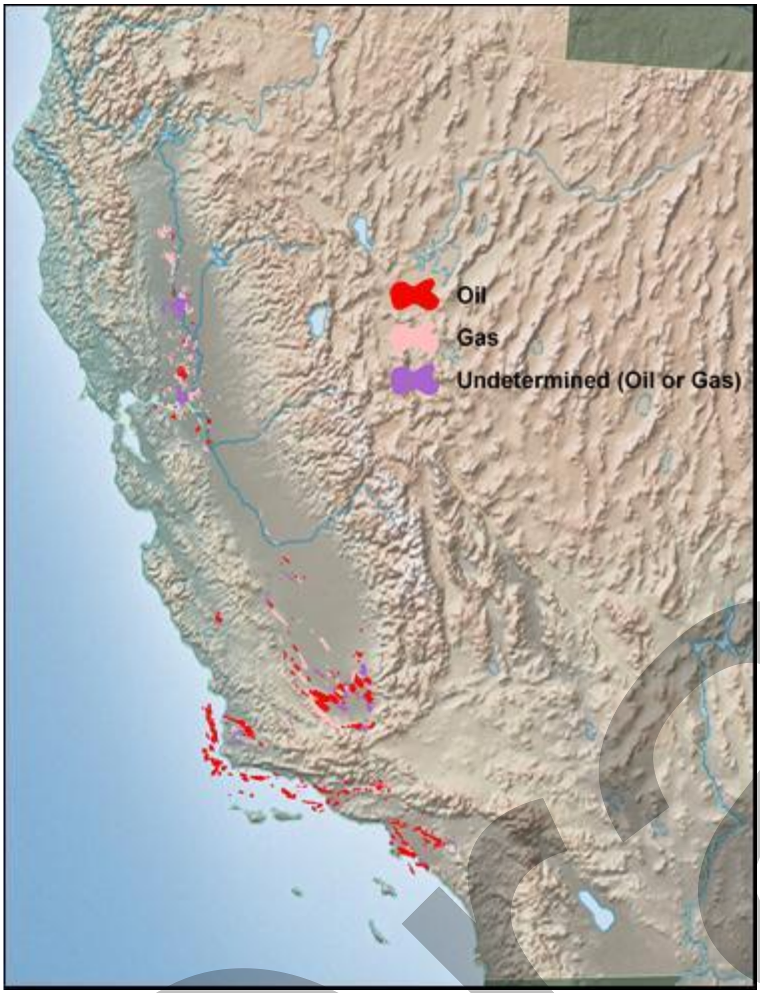

Figure 7. Map showing location of major oil and gas fields in California

WESTCARB estimates the CO_2 storage potential in California's depleted natural gas reservoirs at 3.0 billion to 5.2 billion metric tons (3.3 billion to 5.7 billion tons). Regionally, the Sacramento Basin has the largest CO_2 storage potential, in the range of 2.0 billion to 4.1 billion metric tons (2.2 billion to 4.5 billion tons). The southern portion of the basin is home to some of California's largest natural gas fields. Now largely depleted, these fields may represent opportunities for CO_2 storage following cessation of commercial natural gas production.[19] There may also be opportunities for using CO_2 for enhanced natural gas recovery (EGR) in these fields, or as a cushion gas at natural gas storage sites.

Offshore California, oil and gas accumulations have been found in the Santa Maria, Ventura, and Los Angeles basins. Most known reservoirs in the Santa Maria Basin, as well as numerous reservoirs in the Ventura Basin, occur within highly fractured shales, which are not good candidates for CO_2 storage. Estimated CO_2 storage capacity for the known developed and undeveloped offshore oil and gas fields

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[19] *2010 Carbon Sequestration Atlas of the United States and Canada.*

within conventional sandstone reservoirs of the Los Angeles and Ventura Basins is 240 million metric tons (265 million tons).

Coal Bed Storage and Methane Recovery Possible in the Pacific Northwest and Alaska

Coal beds that are too deep and/or thin to be mined may prove suitable for CO_2 storage because CO_2 readily adsorbs to coal. In some cases, CO_2 injection can be used to displace methane for enhanced coal bed methane (ECBM) recovery. Although ECBM has been successfully demonstrated in several locations at pilot-scale, including in the San Juan Basin of northern New Mexico, no commercial-sized projects have been undertaken. In suitable gas-bearing coal fields, geologists estimate the process of injecting CO_2 can increase the amount of methane produced to nearly 90% of the gas originally in place, compared with conventional recovery of 50% of the original gas by reservoir-pressure depletion alone.

In the Pacific Northwest, three deep coal bed deposits offer promise: the Bellingham Basin in northwestern Washington; the coals of the upper Puget Sound Region, south and east of the Seattle-Tacoma metropolitan area; and small, deep coal deposits in southwestern Oregon. Coal seams in the Puget Sound Region have been previously tested for CBM production. Initial studies show that the subsurface extent of the coal basins represents an area greater than 2,500 square kilometers (950 square miles). The estimated CO_2 storage potential in this area is 2.8 billion metric tons (3.1 billion tons), and the estimated recoverable CBM is 57 billion to 570 billion cubic meters (2 to 20 trillion cubic feet). In the Centralia-Chehalis Basin, a targeted study estimates up to 345 million metric tons (380 million tons) of storage capacity.

Alaska contains major coal deposits, and CBM resources are estimated to be approximately 22 trillion cubic meters (780 trillion cubic feet), which is comparable to the CBM resources in all of the lower 48 states. However, only a portion of this resource is considered favorable for CO_2 storage due to coal quality, permeability, seam geometry, surface access, faulting, permafrost, and other site-specific conditions. The highest potential lies in the North Slope and Cook Inlet Regions, which are accessible and have coals of suitable thickness, depth, and permeability. Preliminary estimates of geologic CO_2 storage resource in Alaska identify about 26 billion metric tons (24 billion tons) of storage in these deep coal seams.[20]

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[20] *2010 Carbon Sequestration Atlas of the United States and Canada.*

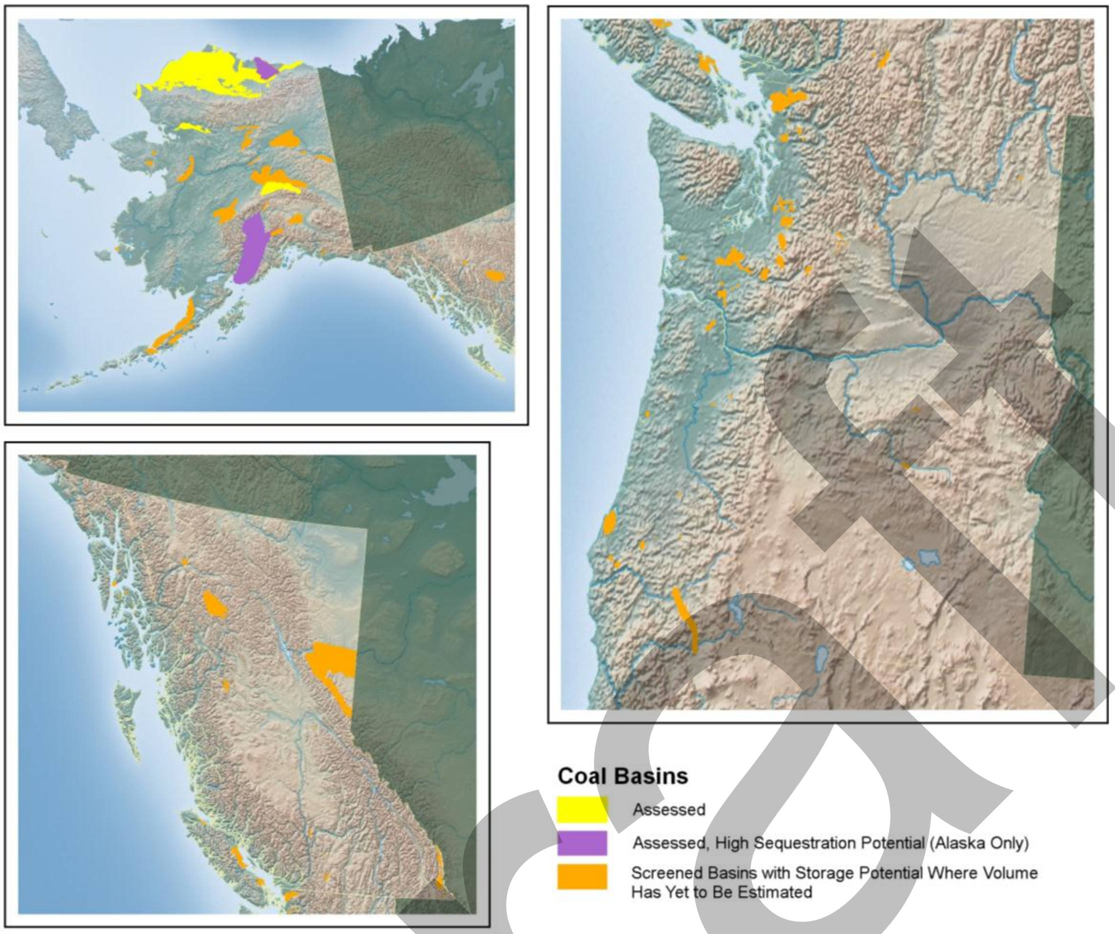

Figure 8. Map showing coal basins in the WESTCARB region

Researching Basalt Storage in Washington and Hawaii

The Big Sky Carbon Sequestration Partnership plans to inject 1,000 tons of supercritical CO_2 into a deep basalt formation near Wallula, Washington, to assess the mineralogical, geochemical, and hydrologic impact of CO_2 in basalts.[21] Because basalts contain minerals that are more reactive with CO_2, they could potentially convert injected CO_2 into a solid form much faster than other rock types, thus providing excellent storage security. Research is focused on enhancing and utilizing the mineralization reactions and increasing CO_2 flow and distribution within a basalt formation. Basalts may also be an opportunity for CO_2 storage in Hawaii.

Assessing CO_2 Industrial Sources

A survey of the WESTCARB region's large industrial sources or "point sources" that could reduce GHG emissions though carbon capture and geologic storage shows that electric power plants predominate, although the fuel mix used for power generation varies considerably. Arizona has some of the region's

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[21] http://www.bigskyco2.org/research/geologic/basaltproject

largest coal-fired plants. Natural gas combined cycle (NGCC) plants are significant in California and other WESTCARB states, except for Hawaii, which relies chiefly on oil-fired generation. Oil and natural gas processing dominate CO_2 emissions in Alaska, and oil refining is also a major emissions source in California. Other significant industrial CO_2 sources throughout the region include cement and lime plants, aluminum smelters, ethanol fermenters, steel mills, agricultural and forest products processing plants, and fertilizer plants.[22]

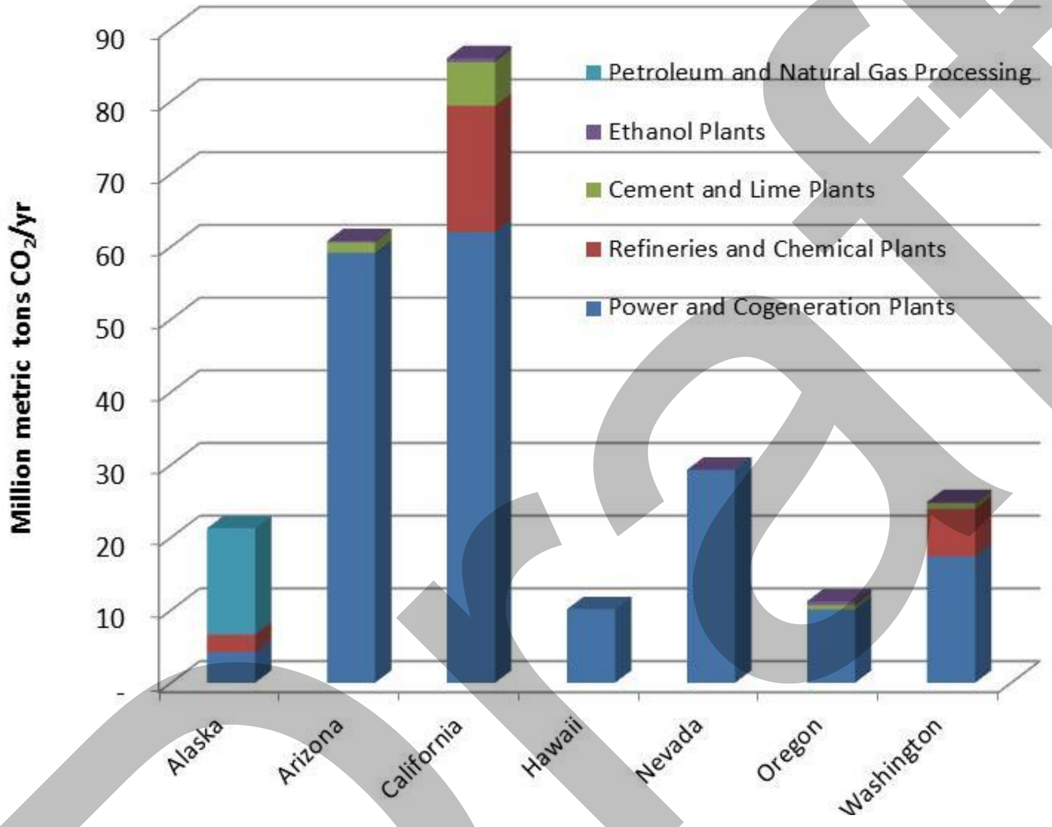

Figure 9. Emissions from large point sources in the WESTCARB region by state and type, as of 2010

As shown in Table 1, estimates from geologic characterization studies show that the sedimentary basins could store hundreds of years' worth of the region's industrial CO_2 source emissions.

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[22] Ibid.

Table 1. Comparison of point source CO_2 emissions with total storage resource[23]

	Estimated CO_2 Emissions from Point Sources (MMT/yr)	Total* Estimated (Low to High) Geologic Storage Resource (MMT CO_2)
Alaska	20	8,980–20,530
Arizona	55	130–1,590
British Columbia	15	1,600–2,130
California	84	33,510–416,930
Oregon	11	7,080-97,390
Washington	21	29,930–411,570

*Saline formations, unmineable coal seams, and oil and gas reservoirs

Major Industrial CO_2 Sources Are Generally Well Matched To Sinks[24]

An important consideration in planning for regional CCS deployment is source-sink matching, which maps the location and CO_2 emission volumes of stationary sources within a certain area to the locations and capacities of potential geologic storage sites (sinks).

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[23] Ibid. Storage resource estimates for Hawaii and Nevada have not yet been undertaken. Data for Alaska do not include saline formations.

[24] A natural or artificial reservoir that can accumulate and store carbon for an indefinite period.

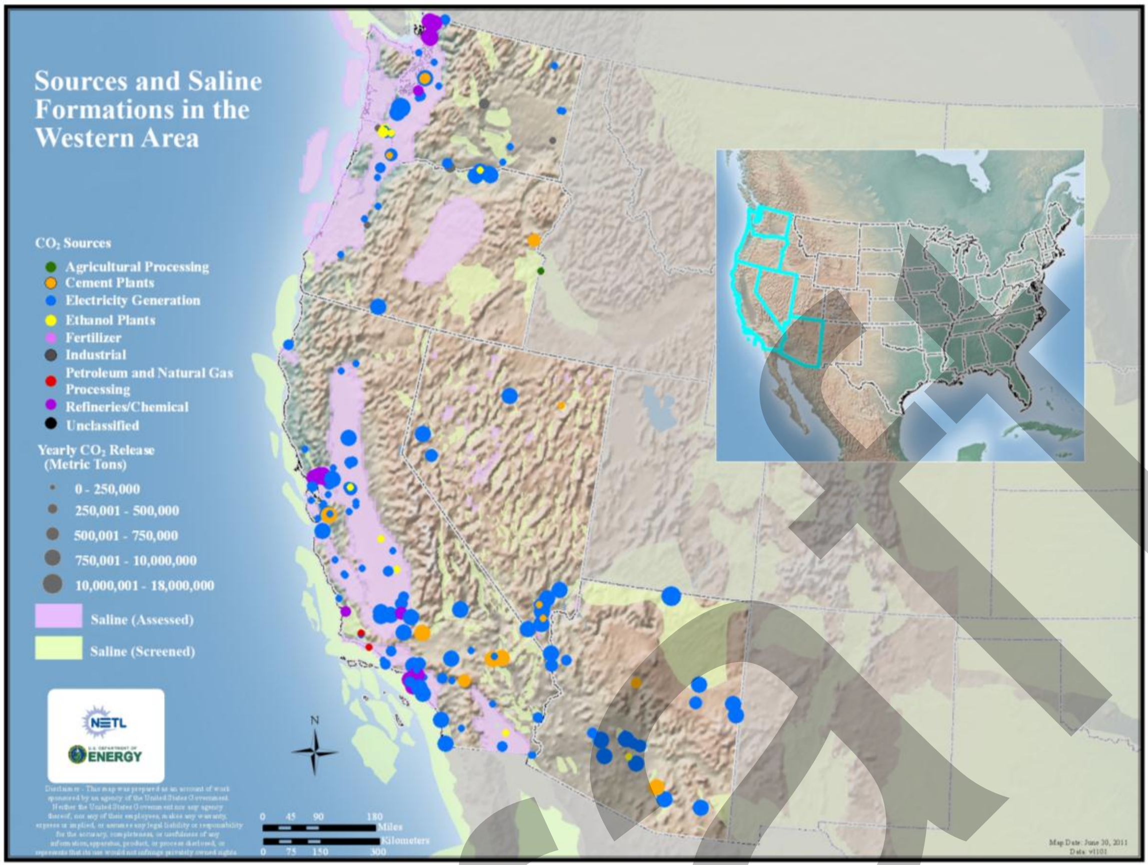

Figure 10. Map showing major stationary sources of CO_2 and in relation to saline formations[25]

A 2007 WESTCARB study[26] identified the major regional CO_2 industrial sources with emissions data and analyzed their proximity to geologic sinks using straight-line distance-based matching. A total of 58 CO_2 sources were studied, which include 10 coal-fired power plants, 27 natural gas-fired power plants, 11 cement plants, and 10 oil refineries, with combined annual emissions of 200 million tons (184 million metric tons) of CO_2 to be sequestered.[27]

If EOR sites were the only sinks used for sequestration, about one-third of the CO_2 sources (by volume) could be matched with a sink that is less than 30 miles (50 kilometers) away,[28] while about one-half of the sources could be matched with a sink that is less than 155 miles (250 kilometers) away. If all sink types

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[25] Courtesy of NATCARB custom map service.

[26] Herzog, Howard, Weifeng Li, Hongliang (Henry) Zhang, Mi Diao, Greg Singleton, and Mark Bohm. 2007. *West Coast Regional Carbon Sequestration Partnership: Source-Sink Characterization and Geographic Information System-Based Matching.* California Energy Commission, PIER Energy- Related Environmental Research Program. CEC-500-2007-053.

[27] Based on 80% operation capacity for power plants, full production capacity for non-power stationary CO_2 sources, and a capture efficiency of 90% for all sources.

[28] Distance selected to reflect a "reasonable" distance on which to base pipeline economic assessments.

are considered (i.e., unmineable coal, oil, natural gas, and saline), more than four-fifths of CO_2 sources could be matched with appropriate sinks within 30 miles (50 kilometers).[29]

In 2010, WESTCARB began a study to assess the suitability of California's utility-scale NGCC power plants for CCS retrofit, including their proximity to potential storage or CO_2-EOR sites. As part of this study, researchers at the Lawrence Livermore National Laboratory reviewed the geology at 42 NGCC sites considering:

- Distance to nearest potential CO_2 sink
- Proximity to oil or gas fields
- Subsurface geology
- Surface expression of nearby faults, and
- Groundwater – depth to base of freshwater aquifer and depth to saline aquifer

The study concluded that, based on geologic features, CO_2 storage is likely practicable for many of California NGCC plants.[30]

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[29] Herzog. *West Coast Regional Carbon Sequestration Partnership: Source-Sink Characterization and Geographic Information System-Based Matching.*

[30] Myers, Katie and Jeff Wagoner. "Geologic CO_2 Sequestration Potential of 42 California Power Plant Sites," presentation at WESTCARB's Annual Business Meeting, October 25, 2011, Lodi, California.

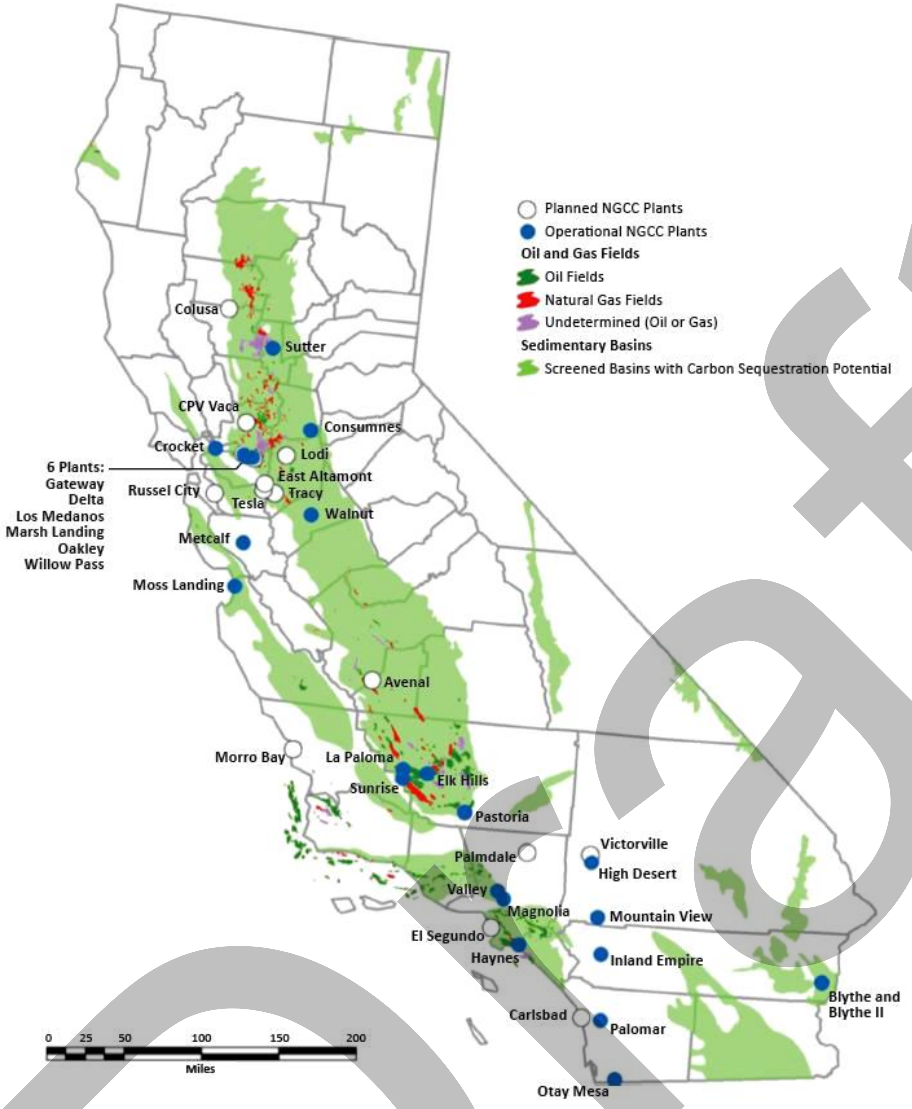

Figure 11. Map of California showing location of operational and planned NGCC plants in relation to potential CO_2 storage sinks[31]

Changes in Source Composition and Location in the Coming Years

As the region initiates policies to lower GHG emissions, changes in the overall makeup and location of stationary sources are anticipated. CO_2 emissions from bioethanol and alternative fuel plants have the potential to grow as the industry expands in response to the state and federal requirements and incentives to increase renewable fuels.

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[31] Ibid.

The region is seeing an increasing rate of coal plant retirements or conversions. Portland General Electric has agreed to shut down its coal plant in Boardman, Oregon, by 2020.[32] TransAlta expects to shut down the first of two coal-fired units at its Centralia, Washington, plant in 2020, with the second to follow in 2025.[33] The company plans to convert the site to an NGCC plant. In addition to fuel switching from coal to natural gas, biomass and petroleum coke could become more commonly used for electricity generation. For new power plants and industrial facilities, access to geologic CO_2 storage sites could become an additional factor in siting.

Bioethanol plants have inherently high CO_2 concentrations in fermenter discharge streams, which make them good candidates for low-cost capture, provided they are large enough to realize economies of scale. Because biomass-derived fuels are already considered carbon neutral, these plants offer the potential for "net negative" CO_2 emissions if they are combined with geologic CO_2 storage.

A large-scale demonstration of CCS on a bioethanol plant began operation in November 2011 in Decatur, Illinois. The project, which is sponsored by DOE/NETL and involves the Midwest Geological Sequestration Consortium, is designed to sequester ~2,500 metric tons CO_2 per day in the saline Mount Simon Sandstone formation at a depth of approximately 7,000 feet.[34]

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[32] http://www.oregonlive.com/business/index.ssf/2010/04/pge_files_to_close_boardman_co.html
[33] http://seattletimes.nwsource.com/html/localnews/2014412221_coalplant06m.html?syndication=rss
[34] http://www.netl.doe.gov/publications/press/2011/111121_co2_injection.html

ELEMENTS FOR SUCCESSFUL COMMERCIAL DEPLOYMENT OF CCS

While the outlook for CCS in the WESTCARB region on the basis of storage volume and source-sink matching does not appear to present significant barriers, widespread deployment of CCS technologies will also depend upon the resolution of many other issues. These will be examined under the following headings: policy, technology infrastructure, economics, finance, legal, and public acceptance.

Policy Drivers and Regulatory Development

GHG policy and regulatory programs that drive the development of CCS can take a number of approaches including cap-and-trade programs, carbon taxes, sector-specific performance standards, conventional command-and-control regulations, or a combination of one or more of these. Under any program, CCS, to become commercially viable, needs to be recognized as a compliance option; regulators have to assure themselves that CO_2 injected to create an emission reduction remains sequestered; and policymakers need to decide what financial incentives (if any) are necessary to encourage commercial deployment of CCS.[35]

U.S. Federal Climate Change Drivers

Within the United States, anticipation of federally mandated climate change legislation has served as a signal to diverse economic sectors to prepare for regulation of GHG emissions. However, none of the proposed climate change bills has been passed into law. This presents a significant gap in terms of providing a clear pathway around which industry planners can base investment decisions for future growth.

Federal actions affecting CCS have originated with the U.S. EPA, which has taken steps to begin regulation of GHG emissions from the nation's largest stationary sources and develop permitting guidelines for underground injection and storage of CO_2. EPA's GHG Reporting Program, launched in October 2009, requires the reporting of GHG data from large emission sources across a range of industry sectors, as well as suppliers of products that would emit GHGs if released or combusted. A proposed rule released in December 2010 would allow companies to postpone providing much of the underlying data until they send in their GHG emissions reports for the 2013 calendar year in March 2014.

On May 13, 2010, EPA issued a Prevention of Significant Deterioration and Title V Greenhouse Gas Tailoring Rule, limiting air permitting guidelines to the largest stationary sources of GHGs. The Rule, which initially applied to facilities that would have to go through air permitting for non-GHG pollutants anyway, specified that as of July 2011, Clean Air Act permitting requirements would cover all new facilities with GHG emissions of at least 100,000 tons per year (tpy) and modifications at existing facilities that would increase GHG emissions by at least 75,000 tpy.[36]

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[35] *Carbon Capture and Sequestration: Framing the Issues for Regulation,* An Interim Report from the CCSReg Project, January 2009: http://www.ccsreg.org/pdf/CCSReg_3_9.pdf.

[36] 75 Fed. Reg. 31514 (June 3, 2010).

EPA had originally targeted September 30, 2011, for the release of proposed GHG guidelines under the "New Source Performance Standards" (NSPS) but announced in mid-September that this would be delayed. A three-year deferral of GHG permitting guidelines for biomass facilities had been previously finalized in July 2011.

In a permitting guidance issued in November 2010, EPA stated that CCS merits initial consideration in best available control technology (BACT) analysis for fossil fuel-fired power plants and industrial facilities with high-purity CO_2 streams, but further indicated that it does not believe CCS will be a technically or economically feasible BACT option in many cases. EPA noted that "a number of ongoing research, development, and demonstration programs may make CCS technologies more widely applicable in the future."[37]

In November 2010, EPA amended the Greenhouse Gas Reporting Program to cover monitoring and reporting requirements for facilities injecting CO_2 underground either for long-term storage (subpart RR) or for enhanced oil and gas recovery or any other purpose (subpart UU).[38] Simultaneously, acting under the authority of the Safe Water Drinking Act, EPA issued a final rule establishing a new well classification (Class VI) under the Underground Injection Control Program for CO_2 injection for geologic storage.[39] States are allowed to seek primacy for Class VI well regulation, independent of other well classes, and several states, including North Dakota and Wyoming, began the process in 2011.

An additional federal permitting requirement for CCS projects will arise through Phase II of the National Pollutant Discharge Elimination System (NPDES) program authorized under the Clean Water Act of 1977. The Phase II NPDES portion is relevant to geologic CO_2 storage because it controls discharges from construction activities greater than one acre in size. The drilling and development of CO_2 injection wells and the construction of related surface facilities will likely exceed the one acre limitation and trigger discharge permitting requirements.[40]

CCS State/Provincial Drivers

Several states in the WESTCARB region, as well as the province of British Columbia, have passed climate change legislation committing to a range of GHG reduction targets (Table 2). It is instructive to look more closely at the contrasting developments in Washington, British Columbia and the Canadian federal government, and California.

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[37] *PSD and Title V Permitting Guidance For Greenhouse Gases*, United States Environmental Protection Agency, Office of Air and Radiation, November 2010.

[38] 75 Fed. Reg. 75060 (December 1, 2010).

[39] 75 Fed. Reg. 77230 (December 10, 2010).

[40] Ibid.

Table 2. Summary of state and provincial climate legislation in the WESTCARB region

British Columbia	2007: Greenhouse Gas Reductions Target Act • Reduce GHG emissions by at least 33 percent below the 2007 level by 2020 • Reduce GHG emission to at least 80 percent below the 2007 level by 2050 2008: Greenhouse Gas Reduction (Cap and Trade) Act
California	2006: Global Warming Solutions Act (AB 32) – reduce statewide GHG emissions to below 1990 levels by 2020
Hawaii	2007: Hawaii's Global Warming Solutions Act (Act 234) requires Hawaii to reduce its statewide GHG emissions to 1990 levels by January 1, 2020. The State Department of Health will pass rules on mandatory reductions for large emitters beginning in 2012.
Oregon	1997: Oregon's CO_2 Emission Standard (1997) • In 2007, Oregon passed House Bill 3543 which mandates a reduction in Oregon's greenhouse gas emissions to 10 percent below 1990 levels by 2020 and to 75% below 1990 levels by 2050. HB 3543 also created the Oregon Global Warming Commission.
Washington	2007: ESSB 6001 – established three GHG emissions reduction targets: • By 2020, reduce state climate-pollution emissions to 1990 levels • By 2035, reduce emissions to 25% below 1990 levels • By 2050, cut emissions to 50% of 1990 levels or 70% below the state's expected emissions that year

Washington State's Experience in Permitting CCS Projects

Total GHG emissions in Washington for 2008 were 101.1 $MMTCO_2e$ (CO_2 equivalent), ~9% above 1990 emissions.[41] Nearly half the state's GHG emissions are attributable to transportation, however, some 35 large stationary sources, which could be candidates for CCS, contribute roughly 20% of total emissions.[42]

In May 2007, Washington passed ESSB 6001, which established an emission performance standard (EPS) requiring all new baseload power generation, whether in-state or imported, to have emissions equal to or less than those associated with gas-fired generation (i.e., ~1,100 pounds of CO_2 per MWh).[43]

The law specified that CO_2 injected permanently into geological formations is not counted when determining compliance with the EPS. Washington has primacy for administering its UIC wells, and in 2008, the Department of Ecology adapted the state's UIC rules to allow Class V wells to serve for CO_2 injection and storage.[44] The rules required that operators obtain a state waste discharge permit and specify additional requirements including financial assurance mechanisms to cover remediation and well closure costs should the operator not "perform as required in accordance with the permit or cease to exist."

The rules defined a post-closure period that would continue until "the department determines that modeling and monitoring demonstrate that conditions in the geologic containment system indicate that there is little or no risk of future environmental impacts and there is high confidence in the effectiveness

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[41] Department of Ecology News Release - February 7, 2011, 11-040: http://www.ecy.wa.gov/news/2011/040.html

[42] *2010 Carbon Sequestration Atlas of the United States and Canada.*

[43] Wash. Rev. Code. § 80.80.040(1).

[44] http://apps.leg.wa.gov/wac/default.aspx?cite=173-218-115

of the containment system and related trapping mechanisms."[45] Two issues left undetermined were long-term liability for the stored CO_2 and clarification of pore space ownership, which would need to be settled under existing law.[46]

For pending power plant applications, ESSB 6001 required a detailed GHG reduction plan (GGRP) demonstrating how the project would meet the EPS. Energy Northwest filed a GGRP in July 2007 for the Pacific Mountain Energy Center, a 793 MW IGCC plant, proposed for Kalama, Washington. The state ruled that GGRP was inadequate, describing it as "a plan to make a plan," and further proceedings on the project were stayed. As of late 2010, the company was moving forward with plans for an NGCC plant.

The second proposed IGCC plant, the Wallula Energy Resource Center, withdrew its site-study request in March 2008 and was subsequently cancelled.

Recent CCS activity in Washington focuses on a research project involving Battelle and the Big Sky Carbon Sequestration Partnership near Wallula. In early 2009, a borehole, permitted as a Class V experimental well, was drilled 4,110 feet into the Columbia River basalt. A small-scale CO_2 injection is planned.

British Columbia's Carbon Tax and Canada's Proposed Performance Standard

British Columbia set a goal of reducing GHG emissions 33% below 2007 levels by 2020, and by at least 80% below 2007 levels by 2050. Electricity generation accounts for just 2% of total provincial GHG emissions; fossil fuel production accounts for 21%.[47] NATCARB estimates 15 $MMTCO_2$/yr from 53 stationary sources. The province has no coal-fired power plants but produces 23 to 27 million metric tons of coal annually, primarily for export. In 2008, 59% of British Columbia's coal exports were destined for steel production in Asia.[48]

British Columbia enacted a carbon tax in July 2008 for purchasers and users of fossil fuels. The tax is currently set at C$25 per metric ton CO_2e, rising to C$30 per metric ton CO_2e in July 2012, with no further increases planned as yet. In order to make the tax revenue-neutral for the government and to cushion the impact to the overall economy, the revenue from the carbon tax is returned to corporations and residents via tax credits and incentives.

The overall impact on electricity users is minimized by the fact that ~85% of the province's generation comes from hydropower. The province's cement industry, however, seems to be negatively affected.

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[45] Ibid.

[46] Pollak, Melisa F. and Elizabeth J. Wilson. "Regulating Geologic Sequestration in the United States: Early Rules Take Divergent Approaches," *Environmental Science & Technology,* 2009, 43 (9), pp 3035–3041, DOI: 10.1021/es803094f.

[47] British Columbia Climate Action Plan: http://www.gov.bc.ca/premier/attachments/climate_action_plan.pdf

[48] *Coal Resources in British Columbia: Opportunities, Logistics and Infrastructure*, British Columbia Ministry of Energy, Mines and Petroleum Resources: http://www.em.gov.bc.ca/Mining/investors/Documents/Coal15Feb2010web.pdf

According to the Cement Association of Canada, cement imports from Asia rose from 5% in 2008 to 20% in 2011.[49]

The Greenhouse Gas Reduction (Cap and Trade) Act of 2008[50] provides a statutory basis for British Columbia to develop a GHG cap and trade system, and the province is in the process of developing a proposed Emissions Trading Regulation and a proposed Offsets Regulation.

In August 2011, the Canadian government proposed a performance standard of 375 metric tons of CO_2/GWh (equal to the emissions intensity level of high-efficiency natural gas generation) to be applied to new and old coal-fired electricity generation units. New units are defined as starting electricity production commercially on or after July 1, 2015. Old units are generally defined as having reached the end of useful life, which is 45 years from a unit's commissioning date or the end of its power purchase agreement, whichever is later. Existing units that were operating before July 1, 2015, but have not reached their end of useful life date are not directly subject to the performance standard.

New and old units would be able to apply for a temporary deferral until January 1, 2025, from the application of the performance standard if they incorporate CCS. Existing units that employ CCS technology and that capture at least 30% of their CO_2 for 5 years before they are required to meet the performance standard would be able to transfer an 18-month deferral from the performance standard to old units in recognition for early action. The existing units also have to have equal or greater capacity than the end-of-life units, have a common owner, and be located in the same province.

In northeastern British Columbia, DOE's Plains CO_2 Reduction (PCOR) Partnership, in collaboration with Spectra Energy, is conducting site characterization activities near Spectra's Fort Nelson natural gas processing plant to ascertain the feasibility of permanently storing over 1.3 $MMTCO_2$/yr.[51]

Accommodating CCS Under California's GHG Emissions Policies

California's gross GHG emissions were at 477.7 MMT CO_2e in 2008, a 4.3% increase from 2000.[52] Emissions from transportation, the largest source, had declined due to the recession, but still accounted for 36.5% of the gross inventory.[53] Some 84 $MMTCO_2$/yr were attributable to 182 large point sources, primarily power and cogeneration plants.[54] Several legislative and policy drivers for reducing CO_2 emissions are relevant to the deployment of CCS in California.

The Global Warming Solutions Act of 2006 – AB 32

AB 32 committed the state to GHG emissions reductions of 20% lower than 1990 levels by 2020. The California Air Resources Board (CARB) subsequently approved a 2020 emission limit of 427 $MMTCO_2e$

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[49] Marshall, Christa. "British Columbia Survives 3 Years and $848 Million Worth of Carbon Taxes," *The New York Times*, March 22, 2011.

[50] http://www.env.gov.bc.ca/cas/mitigation/ggrcta/emissions-trading-regulation/#summary

[51] http://www.netl.doe.gov/publications/proceedings/08/rcsp/factsheets/19-PCOR_Fort%20Nelson%20Demonstration_PhIII.pdf

[52] http://www.arb.ca.gov/cc/inventory/data/tables/ghg_inventory_trends_00-08_2010-05-12.pdf

[53] Ibid.

[54] *2010 Carbon Sequestration Atlas of the United States and Canada.*

and adopted a Mandatory Reporting Regulation (MRR) requiring the largest industrial sources to report and verify their GHG emissions.

CARB, in its Climate Change Scoping Plan,[55] proposed to implement such a program, which would place an overall limit on GHG emissions from sources in most of California's economic sectors. Within capped sectors, some emissions reductions will be attained through direct regulations (e.g., low carbon fuel standard [LCFS], vehicle efficiency measures, and renewable portfolio and electricity standards), while additional reductions will be incentivized by the price placed on GHG emissions through the imposition of a cap. Together, direct regulations and price incentives will ensure that emissions are reduced cost-effectively to the level of the overall cap.

CARB approved a state-wide cap-and-trade regulation in December 2010. The Board directed the Executive Officer to "initiate a public process to establish a protocol for accounting for sequestration of CO_2 through geologic means and recommendations for how such sequestration should be addressed in the cap and trade program, including separate requirements for carbon capture and geologic sequestration performed with CO_2-enhanced oil recovery; carbon injected underground for the purposes of enhanced oil recovery will not be considered to be an emissions reduction without meeting CARB's monitoring, reporting, verification, and permanence requirements."[56]

The California cap and trade program was scheduled to start in January 2012, but was delayed for a year in order to give CARB time for additional testing and deployment of the program infrastructure in 2012 to ensure program readiness before the start of compliance obligation. The modification to the start of the first compliance period does not result in any changes to the cap stringency. The program will achieve the same level of GHG reductions as if the compliance obligation had started in 2012.[57]

The program was challenged in court by environmental justice groups who objected to mechanisms such as allowances and offsets that allow regulated entities to comply with GHGs emissions regulation in a manner that does not alleviate local impacts to the communities in which these entities operate.

The lawsuit resulted in a May 2011 ruling from a California Superior Court Judge,[58] which held that CARB's analysis did not comply with state environmental law in that it failed to provide adequate consideration of alternatives to cap-and-trade, such as carbon taxes or fees. CARB challenged this ruling, but opted to complete a new environmental analysis that considered alternatives to the cap-and-trade program.

In August 2011, CARB approved an expanded environmental analysis of strategies for implementing the A.B. 32 and readopted the Climate Change Scoping Plan including the emissions trading program. On October 20, 2011, CARB formally adopted the cap-and-trade program.

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[55] *Climate Change Scoping Plan – A Famework for Change,* California Air Resources Board, December 2008.

[56] State of California, Air Resources Board, California Cap-and-Trade Program, Resolution 10-42, December 16, 2010, Agenda Item No.: 10-11-1: http://www.arb.ca.gov/regact/2010/capandtrade10/res1042.pdf

[57] Scheehle, Elizabeth. "California's Cap on Greenhouse Gas Emissions and Market-Based Compliance Mechanisms: Emphasis on Geologic Sequestration," presentation at WESTCARB's Annual Business Meeting, Lodi, CA, October 26, 2011.

[58] Ass'n of Irritated Residents v. CARB, Cal. Super. Ct., No. CPF 09-509562, 5/20/11.

Low Carbon Fuel Standard

Executive Order S-01-07 directed CARB to create a LCFS to help meet the 2020 goal outlined in AB 32. The order calls for a reduction of at least 10% in the carbon intensity of California's transportation fuels by 2020. The LCFS is separate from the mandatory reporting regulation and the cap-and-trade program and has its own reporting tools and credit-trading requirements.

Providers of transportation fuels must demonstrate that the mix of fuels they supply meet the LCFS intensity standards[59] for each annual compliance period by reporting all fuels and tracking the fuels' carbon intensity through a system of credits and deficits. CCS is specified as an option for producers of high carbon intensity crude oil to reduce emissions for production and transport of crude oil. CCS could also be considered when used for the production of alternative transportation fuels such as hydrogen, compressed natural gas, and electricity. For CCS to be incorporated into the LCFS, a quantification methodology would be necessary.

An assessment by the California Council on Science and Technology of strategies for achieving the 2050 goal of to reduce GHG emissions to 80% below 1990 levels stated that "for California, the utility of CCS in achieving a low carbon fuel portfolio could be as important as the utility of CCS for electricity production per se."[60]

Emissions Performance Standards

The California Public Utilities Commission (CPUC) [61] (in the case of investor-owned utilities) and the Energy Commission[62] (in the case of public power) implement California's emissions performance standards (EPS) for power plants, which was instituted under Senate Bill 1368.[63]

The current regulations allow for the use of CCS to meet California's EPS, but the mechanisms for determining compliance are unclear. The Energy Commission regulation states that for covered procurements that employ geologic CO_2 storage, successfully sequestered CO_2 emissions shall not be included in the annual average CO_2 emissions. The EPS for such power plants shall be determined based on projections of net emissions over the life of the power plant. CO_2 emissions shall be considered successfully sequestered if the sequestration project:

- Includes the capture, transportation, and geologic formation injection of CO_2 emissions
- Complies with all applicable laws and regulations
- Has an economically and technically feasible plan that will result in the permanent sequestration of CO_2 once the sequestration project is operational

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[59] The standards are expressed as the carbon intensity of gasoline and diesel fuel and their alternatives in terms of grams of CO_2 equivalent per megajoule (gCO_2E/MJ).

[60] *California's Energy Future – The View to 2050: Summary Report*, California Council on Science and Technology, May 2011.

[61] http://www.cpuc.ca.gov/PUC/energy/Climate+Change/070411_ghgeph.htm

[62] http://www.energy.ca.gov/emission_standards/index.html

[63] Perata, Chapter 598, Statutes of 2006.

These requirements differ from AB 32 requirements in a few key ways.[64] First, the EPS is based on emissions over the lifetime of the plant whereas AB 32 is based on annual emissions, and the LCFS considers life-cycle emissions (including indirect emissions). Second, the EPS requires an economically and technically feasible plan for permanent storage, while AB 32 accounting would need a quantification methodology for any emissions and verification of permanent storage. The definition of permanent storage is not included and may have different criteria than those under the AB 32 regulations (which have yet to be defined).

CPUC modified its rules implementing the EPS in July 2009, to further clarify the content of the plan a load-serving entity must file as part of an application for a Commission finding that a power plant with CCS complies with the EPS.[65]

In 2010, in recognition of the need for a coordinated approach to developing CCS regulations, the CPUC, Energy Commission, and CARB convened a CCS Review Panel of experts from industry, trade groups, academia, and environmental organizations. The Panel was instructed to:

1. Identify, discuss, and frame specific policies addressing the role of CCS technology in meeting the State's energy needs and greenhouse gas emissions reduction strategies for 2020 and 2050;
2. Support development of a legal/regulatory framework for permitting proposed CCS projects consistent with the State's energy and environmental policy objectives.[66]

The Panel held five public meetings in 2010 featuring testimony from technical experts and key stakeholders, and deliberations among the Panelists. At the end of the year, the Panel issued twelve recommendations[67] addressing key permitting, legal, and socio-economic issues for CCS in California.

The panel recommended that California evaluate current EPA regulations and determine which, if any, state agency should seek "primacy" for permitting Class VI wells under the UIC program. California currently has primacy for UIC Class II wells, which are administered by the Division of Oil, Gas and Geothermal. It would take enabling legislation for the state to assume primacy for Class VI wells.

Other significant panel recommendations include:

- The state legislature should declare that the surface owner is the owner of the subsurface "pore space" needed to store CO_2. The legislature should further establish procedures for aggregating and adjudicating the use of, and compensation for, pore space for CCS projects.

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[64] "AB 32 Regulations and CCS," *Background Reports for the California Carbon Capture and Storage Review Panel*, Appendix M, California Institute for Energy and Environment, Berkeley, California, December 2010.

[65] Decision 10-07-046 of July 29, 2010 modified the existing rules (set forth in Decision 07-01-039) to clarify that the plan must comply with federal and/or state monitoring, verification, and reporting requirements applicable to projects designed to permanently sequester carbon dioxide and prevent its release from the subsurface, and (2) to further specify how a plan may meet monitoring, verification, and reporting requirements if federal and/or state requirements do not exist or have not been finalized: http://docs.cpuc.ca.gov/PUBLISHED/FINAL_DECISION/121474.htm

[66] *Background Reports for the California Carbon Capture and Storage Review Panel.*

[67] http://www.climatechange.ca.gov/carbon_capture_review_panel/documents/2011-01-14_CSS_Panel_Recommendations.pdf

- The state should consider legislation establishing an industry-funded trust fund to manage and be responsible for geologic site operations in the post-closure stewardship phase. In addition, California should proactively participate in federal legislative efforts to enact similar post-closure stewardship programs under federal law.

- The state legislature should establish that any cost allocation mechanisms for CCS project should be spread as broadly as possible across all Californians.

CCS Legislation (SB 669[68]) was introduced to the state legislature in February 2011 and was later made into a “2 year bill,” thus extending the timeframe for development through the 2012 session. SB 669 echoed the recommendations of the California CCS panel for establishing permitting authority among the relevant state agencies, as follows:

The Energy Commission as lead agency for California Environmental Quality Act (CEQA) review; the Division of Oil, Gas and Geothermal Resources for activities related to the subsurface; the State Fire Marshal for CO_2 pipelines; the State Water Resources Control Board for impacts to water quality; and the State Air Resources Board for air-related aspects of CO_2 monitoring, reporting, and verification requirements, as well as the development of an accounting protocol for stored CO_2.

Looking Beyond 2020 for California

Executive Order S-3-05 established a GHG reduction target of 80% below 1990 levels by 2050, which has yet to be passed into law by the California legislature. This creates uncertainty for some project sponsors who need to be confident about climate change regulation beyond 2020 to justify the capital investments required for GHG reduction technologies such as CCS. Analysts believe that CCS will be important to meeting 2050 GHG reduction goals.[69] Providing legislative certainty for the state’s commitment to the 2050 target would be a significant step to ensuring that the technologies for meeting the target are developed in time to be of use.

Carbon Market Evolution and Coordination

The Western Climate Initiative[70] (WCI) began in 2007 when the Governors of Arizona, California, New Mexico, Oregon, and Washington signed an agreement directing their respective states to develop a regional target for reducing GHG emissions, participate in a multi-state registry to track and manage GHG emissions in the region, and develop a market-based program to reach the target. The WCI has grown to include the states of Montana and Utah and the provinces of British Columbia, Manitoba, Ontario, and Quebec.

The main component of the WCI strategy is a regional GHG cap-and-trade program,[71] which is scheduled to begin in January 2012. Inherent in this joint effort is the understanding that a carbon market covering a diverse set of emission sources and a broad geographic area provides a wider range of reduction opportunities, reduces overall compliance costs, and can help minimize leakage. The roadmap for a

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[68] http://www.leginfo.ca.gov/pub/11-12/bill/sen/sb_0651-0700/sb_669_bill_20110323_amended_sen_v98.html

[69] *California’s Energy Future – The View to 2050*.

[70] http://www.westernclimateinitiative.org/

[71] *Design for the WCI Regional Program:* http://westernclimateinitiative.org/the-wci-cap-and-trade-program/program-design

broad-based carbon market would start with state/province-based markets merging into a regional market, followed by linking of regional markets, followed by a federally inclusive market, and ultimately the emergence of a market covering all of North America.

This is the vision behind the North America 2050 partnership, which involves state and provincial representatives from WCI, the Regional Greenhouse Gas Initiative (RGGI), and the Midwestern Greenhouse Gas Reduction Accord (Midwest Accord), who share information, engage federal agencies on policy matters, and support progress on energy and climate topics at the state and provincial level.

Among WCI participants, British Columbia, Ontario, and Quebec are still developing cap and trade programs. Of the WCI states, only California has enacted cap and trade. The program is set to launch in January 2012, with the first compliance period starting in January 2013. Quebec's program is on the same schedule.

Technology Infrastructure

A commercial-scale CCS infrastructure will involve three major components:

- Modification of multiple large point sources (power plants, oil refineries, cement plants, etc.) to separate (capture) CO_2 from combustion exhaust gases, or in some cases from fuel gases before combustion
- A pipeline or other transportation network that delivers CO_2 to geologic storage sites (including sites for EOR or other subsurface utilization technologies)
- Infrastructure to inject CO_2 into deep underground porous rock formations, along with monitoring, reporting, and verification (MRV[72]) activities to account for the volume of CO_2 injected and the efficacy of the storage sites

Capturing CO_2[73,74]

Three approaches to CO_2 capture—post-combustion, oxy-combustion, and pre-combustion—are currently the focus of extensive research, development, and demonstration (RD&D). Coal-fueled power plants are often targeted for research because of high emissions, however, many of the processes being developed are applicable to other industrial facility types as well.

Post-Combustion Capture Technologies

CO_2 capture technologies are applied after fuel combustion by separating CO_2 from the flue gas at process pressure (typically atmospheric) before the flue gas is exhausted from the plant. Post-combustion capture can be used on pulverized coal power plants, biomass power plants, NGCC plants, cement plants, and fired-furnaces or industrial boilers if large enough to be commercial. The most established of these technologies pass the flue gas through an absorber (scrubber), where a solvent (typically an amine or

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[72] Other similar terms are frequently used including MVA for monitoring, verification, and accounting, and MMV for monitoring, measurement, and verification.

[73] *DOE/NETL Carbon Dioxide Capture and Storage RD&D Roadmap*, December 2010: http://www.netl.doe.gov/technologies/carbon_seq/refshelf/CCSRoadmap.pdf

[74] *Advanced Coal Power Systems with CO_2 Capture*, EPRI, 1023468.

ammonia compound) selectively absorbs the CO_2. The CO_2-rich solvent passes to a regenerating column (stripper), where it is heated to release a nearly pure CO_2 stream. The solvent is recycled back to the absorber to capture more CO_2. The separated CO_2 is dewatered and passed through a further stage of clean up before compression for sale or storage.

Technologies for amine scrubbing have been in use for over 60 years in the natural gas processing, oil refining, and chemical industries, however, only a few smaller facilities use amines to capture CO_2 from oxidized gases, such as flue gas. Thus, existing post-combustion capture technologies need to be scaled up to handle the higher emission volumes from power plants and other large combustion facilities. This requires larger absorption and stripping equipment and associated pumps and heat exchangers. A second challenge is posed by the energy needed to regenerate the solvent and compress the CO_2, which also adds considerably to costs.

In the United States and internationally, an extensive R&D effort is focused on improving the performance of post-combustion CO_2 capture processes that are closest to commercial readiness for large applications. Many candidate solvent formulations have been developed and tested, with the goal of achieving greater absorption capacity, faster reaction rates, less energy demand for regeneration, greater ability to accommodate flue gas contaminants, and reduced corrosivity to allow use of less expensive materials.

Two pilot-scale projects at coal-fired power plants in the United States demonstrating post-combustion CO_2 capture are AEP's Mountaineer Plant in West Virginia using Alstom's Chilled Ammonia process and Southern Company's Plant Barry in Alabama using Mitsubishi Heavy Industries' KM-CDR amine solvent technology.

The Chilled Ammonia pilot operated for more than 6,500 hours between October 2009 and May 2011, and captured more than 50,000 metric tons of CO_2, of which some 37,000 metric tons were injected for geologic storage. A planned scale-up of this technology at the Mountaineer Plant was placed on hold in July 2011. AEP cited the "current uncertain status of U.S. climate policy" as one of the reasons for its decision.[75] The Plant Barry project started CO_2 capture in June 2011, with a goal of 100,000 to 150,000 tons per year. The CO_2 will be supplied to the Southeast Regional Carbon Sequestration Partnership (SECARB) for transport by pipeline and injection 9,500 feet underground at a site within the Citronelle Oil Field.[76]

Table 3 shows projects focused on gaining larger-scale post-combustion CO_2 capture operating experience in integrated power generation.

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[75] Wells, Ken and Benjamin Elgin. "Carbon Capture Hopes Dim as EPA Say it Got Burned at Coal Plant," *Bloomberg*, July 20, 2011.

[76] http://www.secarbon.org/files/anthropogenic-test.pdf

Table 3. Major post-combustion CO_2 capture projects in North America[77]

Project, Utility	Net MW, Coal Type	Capture Technology	Storage, (Projected Startup Date)
Parish 5, NRG Energy, USA	60 MW, subbituminous	Fluor Econamine (amine)	0.5 MMT/yr for EOR (2013)
Boundary Dam, SaskPower, Canada	100 MW, lignite	Cansolv (amine)	1 MMT/yr EOR, saline (2015)
Keephills 3, TransAlta, Canada	250 MW, subbituminous	Alstom chilled ammonia	1 MMT/yr for saline formation storage (2015)

While the current generation of post-combustion technologies are being scaled up and integrated into real-world power plants, research into a second generation of post-combustion technologies is advancing through lab- and small-scale testing. Promising second generation technologies include:

- Cryogenic separation processes that “freeze” out the CO_2
- Molecular sieves and solution-diffusion membranes
- Biological and mineral fixation processes
- Chemical looping

In the WESTCARB region, DOE provided funding to Membrane Technology and Research (MTR) of Menlo Park, California, in July 2010, to construct a membrane skid capable of 90% CO_2 capture from a slipstream of coal-fired flue gas. A six month field test at Arizona Public Service’s Cholla Power Plant will provide data to clarify the relative potential of membrane-based CO_2 capture from power plant flue gas.[78]

Oxy-Combustion

The process of burning fuel in high-purity oxygen instead of nitrogen-rich air is called oxy-combustion. This approach, which requires an oxygen plant on site (typically an air separation unit) to produce moderately pure oxygen, integrates CO_2 capture into the combustion process because the resulting flue gas, consisting primarily of CO_2 and water, is significantly reduced in volume. After dewatering and minimal purification it can be compressed for sale or storage.

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[77] Wheeldon, John. “Coal-Fired Power Plant Project Update,” EPRI *CoalFleet for Tomorrow* Meeting, Louisville, KY, November 16, 2010.

[78] http://fossil.energy.gov/news/techlines/2010/10023-DOE_Selects_Carbon_Capture_Project.html

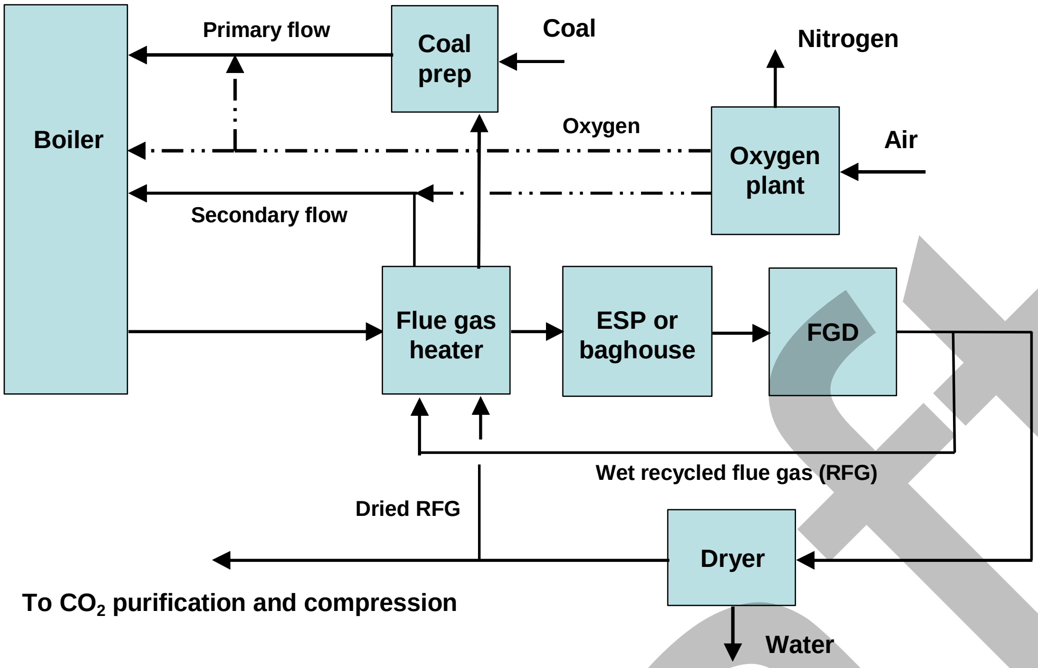

Figure 12. Schematic of PC oxy-combustion process[79]

A key to deploying oxy-combustion economically will be the development of less energy-intensive technologies for oxygen production and CO_2 purification. Table 4 shows demonstrations of oxy-combustion for power generation at up to about 30 MWth. A larger project, Endesa/CIUDEN/Foster Wheeler Energia Oy's 300 MWe Compostilla project in Spain, is targeted for startup in 2015–2016. Another project, Vattenfall's 250 MWe demonstration in Janschwalde, Germany, is currently on hold.

Table 4. Significant oxy-combustion projects in North America[80]

Project, Utility	Location	Capacity	ASU/Emissions Control/CPU/CCS	In Service
Jupiter Oxygen Corp.	Hammond, Indiana	15 MWth – NG/PC multi-fuel, high-temperature burner test facility	B&W package boiler, 25 MWe Maxon burner, 150 t/d cryo O_2, variable FGR, baghouse, cyclone, slipstream capture w/ NETL IPR^{TM} system	2007–2008
B&W Clean Energy Development Facility	Alliance, Ohio	30 MWth – PC	Air Liquide cryogenic ASU; ESP, dry scrubber/baghouse, wet FGD/cooler	2007
Alstom Test Facility	Windsor, Connecticut	15 MWth – PC (tangential fire)		Aug 2009

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[79] Wheeldon, John and Des Dillon. "Oxy-Combustion of Coal," EPRI CoalFleet Meeting, Greenville, South Carolina: July 26, 2007.

[80] Wheeldon, John. "Coal-Fired Power Plant Project Update." EPRI CoalFleet Meeting, Greenville, South Carolina: July 26, 2007.

Natural gas-based power vendors are showing interest in the California-based Clean Energy Systems (CES) “rocket engine” oxygen-fired gas generator and associated power turbine. CES’s process is based on natural gas, heavy oil emulsion, or gasification-based CO-rich syngas firing with oxygen plus water injection in a modified high-temperature steam turbine that operates somewhat like a gas turbine. A 5 MW pilot unit has been successfully tested at the Kimberlina Power Plant near Bakersfield, California. In March 2011, CES acquired the 63 MW Placerita power plant in Newhall, California, northeast of Los Angeles, where it will conduct a scaled-up demonstration of its technology.

Pre-combustion CO_2 Capture

Pre-combustion capture technologies separate CO_2 from gaseous fuels prior to combustion and are being scaled up, with a focus on integrated gasification combined cycle (IGCC) technology. At an IGCC plant, fuels such as coal, petroleum coke, and biomass are partially reacted at high pressure with oxygen or air and, in some cases, steam, to produce synthesis gas (syngas)—a fuel mixture of carbon monoxide (CO) with some hydrogen and methane. For CO_2 capture, the syngas is processed in a water-gas-shift reactor, which converts CO into CO_2 while producing additional hydrogen. An acid gas removal system then separates the CO_2 from the hydrogen, which is combusted in a gas turbine to generate electricity. With the addition of CO_2 capture, turbine modifications may be required to allow the firing of hydrogen-rich syngas.

Technologies for pre-combustion CO_2 capture are already in use for removal of hydrogen sulfide (H_2S) and CO_2 from syngas produced in chemical industry gasifiers. Chemical (amine) and physical solvents have been used for many years at a scale approaching that needed for IGCC units, as have the water-gas shift processes that convert CO to CO_2 while producing a high-hydrogen fuel.

Much of the resurgent interest in IGCC is motivated by the potential for IGCC plants to capture CO_2 at a lower incremental cost relative to CO_2 capture for supercritical PC units, due to the inherent advantage of higher CO_2 partial pressure at the point of capture.

IGCC technology is currently represented by five coal-fed plants worldwide. Two of these are in the United States and were built in the 1990s, with partial funding from DOE’s Clean Coal Technology demonstration program. Duke Energy’s 618 MWe IGCC plant in Indiana, scheduled for startup in 2012, will be the first IGCC plant built in the United States in over a decade. Although this project does not include CO_2 capture, other IGCC projects in the United States that include plans CO_2 capture are listed in Table 5.

Table 5. IGCC projects with CO_2 capture in the United States

Project	Net MW, Fuel	Acid Gas Recovery Technology	Storage, (Projected Startup Date)
Summit Texas Clean Energy Project (TCEP)	250 MW, subbituminous coal	Selexol	3 MMT/yr for EOR with Urea Co-Production (2014)
Southern Company (Kemper County)	524 MW, lignite	Selexol	2 MMT/yr for EOR (2014)
Hydrogen Energy California (HECA)	250 MW, pet coke/coal	Rectisol	2 MMT/yr for EOR with Urea Co-Production (date uncertain)

CO_2 Purification and Compression

Water, oxygen, and other contaminants are normally removed in conjunction with CO_2 compression. CO_2 from some capture processes may contain impurities that, without an added purification step, would rapidly corrode pipeline, injection well, and possibly compressor component materials. In general, the purity requirements of the receiving pipeline or geologic formation will determine which contaminants must be removed. A capture technology that maximizes the pressure and purity of the CO_2 product from the capture system will reduce the costs of purification and compression equipment. These costs become relatively higher when a purer CO_2 product is required.

Most CO_2 will be compressed to about 2000 psi where it is a supercritical fluid that makes transportation and subsurface injection and storage more efficient. With current technology, compression of the CO_2 produced at a pulverized coal power plant may require as much as 8% of the plant's net power output.

Power Plant Efficiency Improvements Reduce Emissions

Improving the thermodynamic efficiency of power plants is a sound CO_2 emissions reduction strategy, which reduces all other emissions, as well. Increased thermodynamic efficiency lowers fuel consumption and reduces the amount of CO_2 generated per unit of plant output. A two percentage-point gain in plant efficiency, for example, provides a reduction in fuel consumption of roughly 5% and can provide similar reductions in CO_2 emissions.[81]

A more efficient power plant can also use a smaller, less-expensive CO_2 capture system. DOE's Advanced Materials Research Program is focused on developing high-temperature, corrosion-resistant alloys and coatings that will enable power plants to operate at higher temperatures and pressures, with fewer emissions and reduced CO_2 capture costs. Other efficiency gains, with corresponding reduced emissions, are expected through innovations or improvements across a range of existing power plant processes, as their costs and benefits relative to CO_2 capture are better understood.

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[81] *Advanced Coal Power Systems with CO_2 Capture,* EPRI, 1023468.

Retrofits

It is expected that CO_2 capture will be installed on some existing generating units, and there is potential for CO_2 capture to be retrofitted to existing plants as a component of a repowering project, which would regain some of the efficiency and capacity loss inherent to the CO_2 capture process, and make good use of plant downtime required during modifications.

Coal-fired power plant economics suggest retrofits are most likely for larger, younger plants with high capacity factors. Additional considerations include:

- Sufficient space for new CO_2 capture system and compression equipment (typically about 6 acres for a 500 MW unit)
- Adequate cooling water supply (to accommodate increased water demand)
- High-performance NO_X and SO_X controls to reduce concentrations in the flue gas entering the CO_2 absorber to about 10 ppm or less
- Access to a geologic storage or opportunity to sell captured CO_2

Water Use[82]

The need for additional water for CO_2 capture and compression processes may pose a challenge in arid regions or wherever water supplies are restricted, and it may not be feasible to implement CO_2 capture if a plant cannot secure additional water supplies.

A variety of cooling system tradeoffs may be considered when adding or retrofitting CCS, such using air cooling for the capture and compression system, or adding an air-cooled condensor for steam turbine exhaust cooling and reserve cooling water for capture/compression. For IGCC plants, increased heat integration between the gasification, capture, and/or compression process, and the steam cycle may reduce cooling water demand and fuel consumption.

Many plants now use “zero liquid discharge” (ZLD) wastewater treatment systems to upgrade and reuse power plant wastewater. ZLD systems use evaporative or reverse osmosis processes to concentrate the impurities in the wastewater while also producing a high purity water stream for reuse. A further evaporative process may then be used to recover most of the remaining water, leaving the impurities as solid salt cake.

Alternative water sources include treated municipal wastewater, degraded surface waters such as agricultural runoff, water extracted for mitigation of groundwater contaminants, and produced water from oil and gas production. Additional treatment may be required before these waters are used in power plant cooling systems.

With geologic CO_2 storage, it may also be possible to supplement the plant water supply with formation water extracted to increase CO_2 storage capacity and reduce pressure build up. Initial calculations show that the displaced water could meet about a third of the power plant’s raw water requirements, and the

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[82] Ibid.

cost impact could be less than that of implementing dry cooling technology.[83] The saline water option may also lead to lower costs in the CO_2 storage operation (for example, smaller storage zone foot print and lower CO_2 injection pressure).

CO_2 Pipeline Transport, Safety, and Siting

Because geologic formations capable of storing CO_2 do not always underlie the facilities where CO_2 will be captured, transport will be needed to move the CO_2 from the facility to a site where long-term storage can take place. For large quantities of CO_2, pipelines are generally the most economic mode of transportation. Although there are no large-capacity CO_2 pipelines in the WESTCARB region at present, future development can draw on an experience base that spans almost 40 years and 3,600 miles of CO_2 pipelines used in CO_2-EOR operations in Texas, New Mexico, and Wyoming, as well as a 200-mile pipeline that transports CO_2 from the Dakota Gasification Company's Great Plains synfuels plant in North Dakota to the Weyburn-Midale EOR operation in Saskatchewan, Canada.

Figure 13. Map showing location of major CO_2 pipelines for EOR in the United States[84]

CO_2 does not manifest hazardous properties (i.e., toxicity, reactivity, flammability, or explosivity) that would result in regulatory classification as a hazardous material. However, current U.S. Department of Transportation requirements for pipelines transporting CO_2[85] direct the operator to perform a risk

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[83] Ibid.

[84] Simbeck, Dale. "CO_2 Capture Technologies," Working Group Meeting on AB-1925 Report to the California Legislature on Accelerating Geologic Carbon Sequestration Strategies, Sacramento, CA, June 28, 2007.

[85] 49 Code of Federal Regulations [CFR] 195.

assessment. Considerations that inform pipeline design include leak detection, potential hazards (river erosion, seismic activity, etc.), environmental requirements, materials selection based on CO_2 specifications, access to valve sites, and operations and maintenance requirements.[86] Regular safety inspections and monitoring, which are established procedures in pipeline transport, are necessary during operation, as well as keeping mitigation plans up-to-date in case of an equipment failure or leak.

CO_2 pipelines are designed and built to last for the commercial life of a project. Common CO_2 pipeline carriers have set specifications that limit some species to very low concentrations.[87] For example, Kinder Morgan mandates oxygen concentration of less than 10 ppm, but will tolerate gases such as nitrogen, carbon monoxide, and light hydrocarbons at concentrations up to a total of 9%. With regards to acid gases, there does not appear to be an industry consensus. In some cases, the allowable concentration of sulfur dioxide is as low as 5 ppm. For a contract pipeline, the specifications will be up to the CO_2 supplier and user; for example, the Weyburn-Midale EOR operation can tolerate oxygen up to 50 ppm and H_2S up to 20,000 ppm[88] because the gas is extremely dry.

Pipeline Networks in California

A preliminary analysis by the Clinton Foundation[89] identified three areas in California that could serve as hubs for CCS pipeline network development, based on the concentration of CO_2 emissions from industrial sources and proximity to sinks. In the northern East Bay, 11 facilities within about a twenty mile radius account for 14 million metric tons CO_2/yr and lie within relative proximity to the Sacramento Basin. In the Bakersfield area, 10 facilities within a 40 mile radius account for 12.5 million metric tons CO_2/yr, with both potential storage sites and EOR opportunities in the San Joaquin Basin. In Los Angeles, 11 facilities account for 15.3 million metric tons CO_2/yr, for which storage in offshore basins could be an option.

CO_2 Injection

The injection techniques that will be used for geologic CO_2 storage are in commercial use today. The oil and gas industry in the United States has been injecting and monitoring of CO_2 in the deep subsurface for the purposes of enhancing oil production for nearly 40 years. This experience provides a strong foundation for the injection and monitoring technologies that will be needed for commercial-scale CCS.

An experience base is also developing for injection of CO_2 into saline formations, which are much more prevalent than depleted hydrocarbon reservoirs or EOR sites. Operations in Norway[90] and Algeria[91] are each injecting over one million metric tons per year. The first injection in the United States of CO_2 from coal-derived flue gas was performed in October 2009 at the Alstom Chilled Ammonia capture pilot at

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[86] Barrie, J., et al. *Carbon Dioxide Pipelines: A Preliminary Review of Design and Risks:* http://uregina.ca/ghgt7/PDF/papers/peer/126.pdf

[87] *Carbon Dioxide Compression and Transportation: Issues and Research & Development Plans.* EPRI, Palo Alto, CA: 2008. 1016794.

[88] *Advanced Coal Power Systems with CO_2 Capture*, EPRI, 1023468.

[89] Springer, Daniel and Dorota Keverian. “California Carbon Capture and Storage,” presentation at WESTCARB’s Annual Business Meeting, October 26, 2011, Lodi, California.

[90] http://www.statoil.com/en/TechnologyInnovation/ProtectingTheEnvironment/CarboncaptureAndStorage/Pages/CarbonDioxideInjectionSleipnerVest.aspx

[91] http://www.insalahco2.com/

AEP's Mountaineer plant. A larger injection of CO_2 from a coal plant is now underway in at Southern Company's Plant Barry in Alabama. Multiple small-scale CO_2 injections into saline formations were successfully conducted as part of DOE's Regional Carbon Sequestration Partnerships program,[92] adding to confidence that many saline formations can effectively store CO_2.

An important distinction between CO_2 injection for storage and CO_2 injection for EOR has to do with managing subsurface flow rates and pressure in the formation or reservoir. Both practices increase reservoir pressure, however, a storage-only project may contend with greater overall pressure increases because there is no concurrent production of hydrocarbons. This issue is highly site specific, depending on the type of the reservoir and the extent of geological heterogeneities, however, more experience with industrial-scale CO_2 storage projects is needed because formation pressures in storage formations may exceed those found in CO_2-EOR projects.

Monitoring, Reporting, and Verification[93]

Monitoring, reporting, and verification (MRV)[94] refers to activities for collecting and reporting data about the characteristics and performance of the injection and storage of CO_2. These activities span the duration of CCS projects, starting with site characterization and continuing through injection operations, site closure, and post-closure phases.

Most current monitoring and measuring technologies for CCS are drawn from other applications such the oil and gas industry, natural gas storage, and groundwater monitoring. These established practices provide numerous measurement techniques and options—a monitoring toolbox—which enables development of tailored, flexible monitoring programs for CCS.

The value of a tailored approach is threefold: first, optimum performance of many techniques depends on site-specific geologic attributes; second, the risks that need to be monitored will vary from site to site; and third, a tailored approach will enable the most cost-effective use of monitoring resources. A tailored approach is compatible with regulations that are largely performance-based and non-prescriptive with regard to measurement methods. The downside of a tailored approach (from the perspective of a project developer) lies with the timeframe required for a permitting/compliance agency to review a tailored plan, and potentially coordinate reviews amongst several agencies, which will take longer that what would be required for a prescriptive approach.

EPA, in developing rules for CO_2 injection under the UIC program, generally adopted a performance-based approach to monitoring whereby project-specific testing and monitoring plans must receive approval from the UIC Director. States seeking primacy for Class VI wells will need to develop monitoring requirements that are consistent with EPA guidance, although states may choose to be more stringent.

DOE is actively pursuing research, including field testing, of monitoring techniques and practices for CCS with a goal of achieving a level of accountability such that greater than 99% of injected CO_2 can be

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[92] http://www.fe.doe.gov/programs/sequestration/partnerships/

[93] Myer, Larry. "Monitoring, Verification, and Reporting Overview," Appendix Q, *Background Reports for the California Carbon Capture and Storage Review Panel*.

[94] The term monitoring, verification, and accounting (MVA) is also commonly used.

credited and contribute to the economic viability of a storage project.[95] DOE has also published a first edition best practices guide to MVA,[96] and plans to complete a final edition by 2020.

The Importance of Baselines and Subsurface Modeling

Establishing a baseline for existing site conditions is an essential early step for successful monitoring of CCS projects. CO_2 is ubiquitous in the environment, both at the surface and in the subsurface, so it is important to establish initial levels before injection operations begin. A well-defined baseline includes not only the average value of the parameters measured, but accounts for how they vary in space and over time before the project begins. Referred to as "time-lapse," this approach is the foundation for monitoring CO_2 storage projects. Without time-lapse measurements, it may not be possible to separate storage-related changes in the environment from the naturally occurring spatial and temporal variations as seen in the monitoring parameters. For most CCS projects, baseline data will be obtained during the pre-injection phase of the project.[97]

A key output of site characterization is the subsurface model, which is used to predict the spread of the CO_2. As the collection and analysis of monitoring data continues throughout the project, comparisons of monitoring measurements with model predictions are made repeatedly to determine if the project is performing as expected, and what adjustments can be taken if it is not. Monitoring data are used to improve the initial subsurface model, which leads to increased confidence in subsequent model predictions.

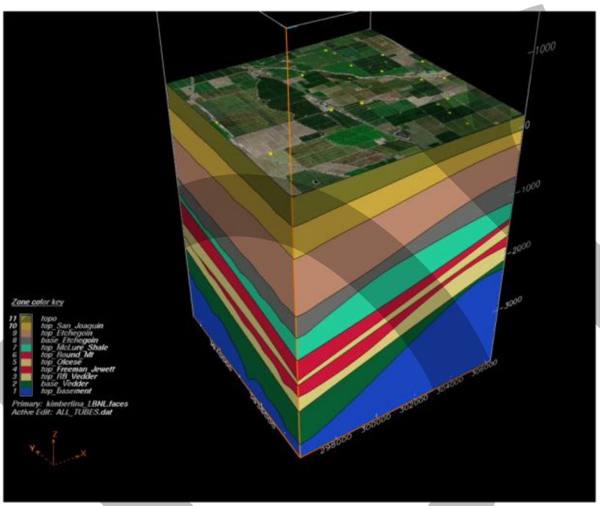

Figure 14. Initial geomodel for the formations underlying the Kimberlina Power Plant in the San Joaquin Valley, California[98]

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[95] *DOE/NETL Carbon Dioxide Capture and Storage RD&D Roadmap*.
[96] *Monitoring, Verification, and Accounting of CO_2 Stored in Deep Geologic Formations*, DOE/NETL-311/081508 National Energy Technology Laboratory, January 2009.
[97] Myer. "Monitoring, Verification, and Reporting Overview," *Background Reports for the California Carbon Capture and Storage Review Panel.*
[98] Developed by Lawrence Livermore National Laboratory.

Monitoring CO_2 Distribution in the Subsurface

Most CCS projects will utilize monitoring wells to take measurements and samples of the CO_2 at a distance from the injection well(s). In addition, indirect methods of monitoring make it possible to track the CO_2 distribution over broad areas. 3-D seismic reflection surveys provide images of the subsurface that have been used successfully to track the migration of the CO_2 at several project sites including the Frio Brine Pilots in Texas, the Sleipner project in the North Sea, the Nagaoka project in Japan, and the Weyburn-Midale project in Saskatchewan. Satellite monitoring that detects minute vertical surface movements, which reflect shifts in the CO_2 in the subsurface over time, has been used at the In Salah project in Algeria.

Managing Leakage Risks

Experience with storing CO_2, as well as experience gained from CO_2-EOR, shows that the risks and potential quantities of CO_2 leakage will likely be minimal. However, measures must be taken to guard against human error, natural hazards, and other risk factors.

Actions central to preventing and correcting leakage of CO_2 from geological formations include a rigorous site selection process to make sure geological seals are present, assuring well integrity, modeling of the CO_2 plume, monitoring of the injected CO_2 (including early identification of leakage), and prompt mitigation and remediation actions should any leakage occur.

During site characterization, identification and risk assessment of potential leakage pathways (e.g., existing wells and fractures and faults) and identification of specific potential consequences (e.g., brine contamination of UDSWs, CO_2 infringement on mineral rights, or seepage into the atmosphere) serves as a basis for developing site-specific operational standards, as well as monitoring and verification requirements, and mitigation plans.

Wellbores that intersect the storage formation could provide pathways for CO_2 migration. Pre-existing wellbores are considered to present a higher risk for leakage than new wellbores because of uncertainty about their condition. Locating nearby wellbores and assessing their leakage potential will be part of site characterization for many CCS projects. Ongoing monitoring of wellbores that are considered to pose a risk will need to be included in monitoring program, and repairs to some wellbores may be required to ensure their integrity.

Subsurface geologic features such as fractures and faults also need to be identified and assessed during site characterization. Fractures are essentially cracks in the rock, which could provide leak paths if they are present in the seals overlying the storage formation. Faults are cracks where the two surfaces forming the crack have experienced relative movement, or slip. It should be noted that some faults will act as effective seals and traps for CO_2 storage, however, others may provide potential leak paths to the surface.

There are several approaches to mapping the movement of CO_2 in the subsurface that can also detect leakage out of the storage reservoir from fractures and faults. These can be incorporated into the monitoring plan, as needed, depending on the risk assessment. Formations that have a high risk of leakage or are known to be leaking hydrocarbons are not good candidates for CO_2 storage and should be avoided.

Remediation and Mitigation

Despite site characterization to rule out inappropriate sites and other procedures to minimize risk, CCS projects will need to establish contingency plans to mitigate and remediate any situation in which public health, economic activity, or the environment could be negatively affected by releases of CO_2.

Should unacceptable project risk arise, existing oil and gas field mitigation and remediation practices and technologies are sufficient to address most of the concerns related to CO_2 injection and sequestration in association with EOR. Many of these practices are also directly transferable to CCS projects without EOR. Another close analog for CO_2 sequestration, the natural gas storage industry, has a portfolio of technologies to monitor, detect, and remediate natural gas leakage, which should be applicable or adaptable to CCS. These include reservoir pressure control, shallow gas recycling, wellbore remediation, well re-plugging, and in extreme cases, project termination and site closure. Nonetheless, further studies that address CO_2 storage monitoring over longer timeframes and at greater spatial scales are needed to fully adapt these practices to CCS.

Monitoring Seismicity

In the WESTCARB region where several states are tectonically active, careful seismic profiling will factor in site selection for CCS projects. Public sensitivity to earthquakes will likely focus special attention on regulatory requirements to assure that projects do not increase seismic hazard risk.

Many small unfelt earthquakes are characteristic of injection activities and can help to image shallow sub-surface fluid movement. Data are limited for CO_2 injection, however, only low levels of induced seismicity, with no large events, have been observed. In other instances, subsurface pressure increases—from direct injection of fluids for waste disposal and geothermal energy development—have caused seismicity that people have felt, and in rare instances, have caused harm.[99]

Monitoring for induced seismicity begins with establishing a record of the natural background seismicity in the region encompassing the project. This record is fairly good in the coastal states of WESTCARB because of earthquake monitoring networks already in place. In most instances, an existing network would need to be augmented by a local network designed for the site, and consisting of seismometers located on the ground surface or in shallow boreholes. The local network would enable more accurate location of events and detection of smaller events than the regional network. The record of the natural background seismicity is important because it gives a baseline to determine if an event, which occurs after injection starts, is due to injection or natural tectonic processes.

Induced seismicity is directly related to fluid pressure in the subsurface, so reduction of fluid pressures reduces seismicity. The potential for induced seismicity will decrease during the post-injection phase of a storage project due to the natural reduction of fluid pressures and it can be controlled during the operational phase by adjusting the rate of injection. Since there is a cause and effect relationship between fluid pressures and seismicity, direct monitoring of subsurface fluid pressures should also be part of the induced seismicity monitoring program.

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[99] http://www.livescience.com/9777-earthquake-concerns-shake-geothermal-energy-projects.html

In 2010, WESTCARB scientists analyzed the potential risk for induced seismicity from a proposed small-scale (6000 metric tons) CO_2 injection project in Northern California. This work led to the formation of an initial set of best practices to address seismic hazard issues associated with commercial-scale CO_2 injection.

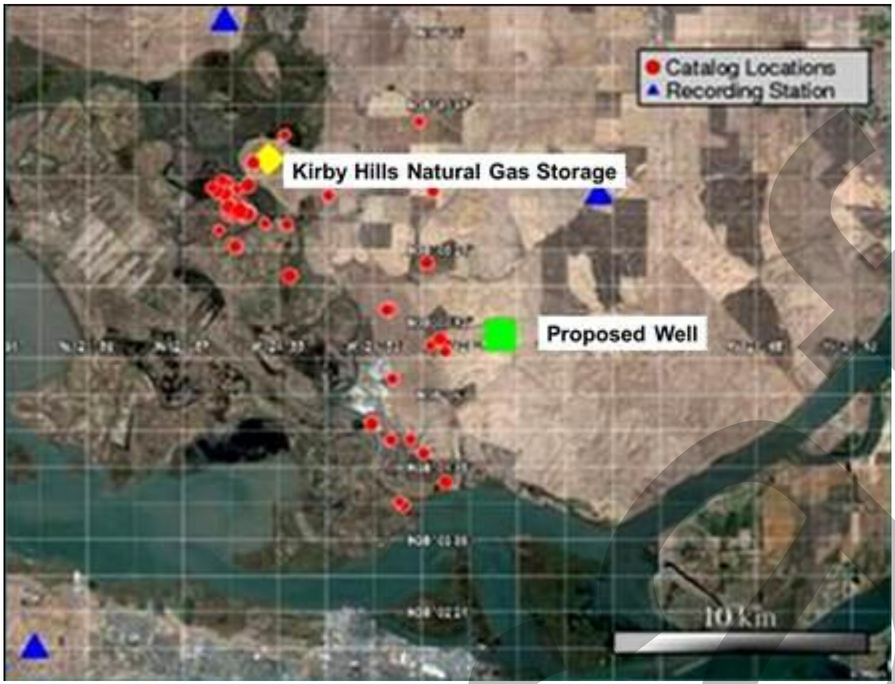


Figure 15. Aerial view of a WESTCARB study site in northern California

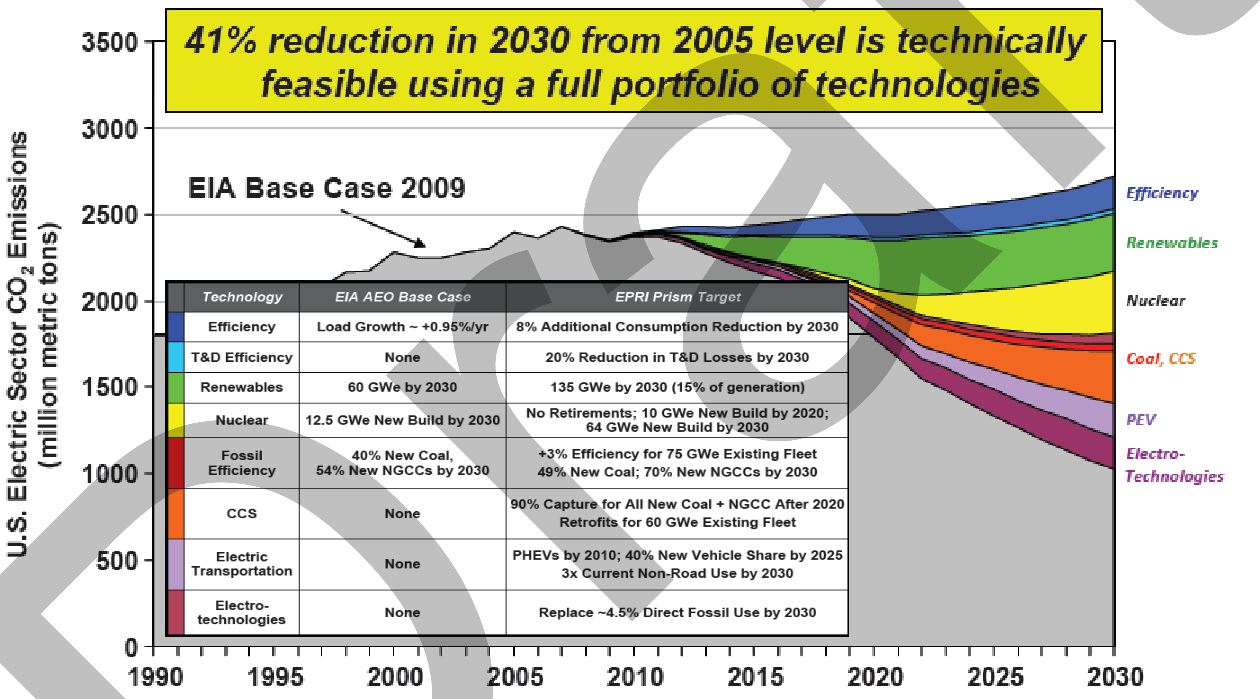
[Blue triangles are seismic recording stations. Red dots indicate seismic events of 2.5 magnitude or greater for 1978–2010 near a proposed injection well. The largest event had a magnitude of 3.7.]

Economics

The cost of CCS technologies is generally recognized as a challenge to widespread deployment. A comprehensive view encompasses the multiple factors affecting both the cost of CCS and its competing low-carbon alternatives over time, taking into account economic drivers and policy decisions on how and when progressively steep GHG emissions reductions can be achieved. Such a multi-faceted analysis suggests that CCS must transition from niche to broad application in the 2020 to 2050 timeframe, assuming that current projections of the need for (and commitment to) deep GHG emissions reductions hold and that emissions trading markets evolve in relative stability.

The IPCC Special Report on Carbon Dioxide Capture and Storage cites several studies that conclude that widespread deployment of CCS technologies would achieve GHG emission reductions at significant savings compared to scenarios without CCS (e.g., trillions of dollars for stabilization of GHGs at a concentration of 450 ppm).[100]

The Electric Power Research Institute (EPRI) examined the technical feasibility of achieving large-scale CO_2 emissions reductions for the U.S. electricity sector using a full portfolio of low-carbon technologies (energy efficiency, renewables, electric transportation, nuclear, and fossil power plants, both NGCC and high-efficiency coal plants—with CCS). Economic modeling showed that without advanced coal technologies and CCS (and without any expansion of nuclear power), wholesale electricity prices in 2050 could be nearly double what they would be otherwise. EPRI's analysis underscores the economic value of deploying multiple low-carbon technologies and the cost increases that would follow if any technology is prohibited by policy or insufficient RD&D investment, thereby forcing emission reductions to be achieved using a more limited set of options.



	Technology	EIA AEO Base Case	EPRI Prism Target
🟦	Efficiency	Load Growth ~ +0.95%/yr	8% Additional Consumption Reduction by 2030
🟦	T&D Efficiency	None	20% Reduction in T&D Losses by 2030
🟩	Renewables	60 GWe by 2030	135 GWe by 2030 (15% of generation)
🟨	Nuclear	12.5 GWe New Build by 2030	No Retirements; 10 GWe New Build by 2020; 64 GWe New Build by 2030
🟥	Fossil Efficiency	40% New Coal, 54% New NGCCs by 2030	+3% Efficiency for 75 GWe Existing Fleet 49% New Coal; 70% New NGCCs by 2030
🟧	CCS	None	90% Capture for All New Coal + NGCC After 2020 Retrofits for 60 GWe Existing Fleet
🟪	Electric Transportation	None	PHEVs by 2010; 40% New Vehicle Share by 2025 3x Current Non-Road Use by 2030
🟥	Electro-technologies	None	Replace ~4.5% Direct Fossil Use by 2030

Figure 16. EPRI's analysis showing CO_2 reductions for U.S. electric sector[101]

Timeframes for Technology Development to Reduce Costs

Ideally, CCS technologies will reach the stage of maturity where experience from early projects can be incorporated into the design process—thereby improving performance and reducing costs—before regulations compel widespread deployment. Under this scenario, the economic impact of achieving GHG emissions reductions would be significantly less.

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[100] IPCC, 2005: *IPCC Special Report on Carbon Dioxide Capture and Storage.* Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[101] *Advanced Coal Power Systems with CO_2 Capture*, EPRI, 1023468.

The typical path for commercializing a technology runs from the conceptual modeling to laboratory testing, then to pilot-scale tests, larger-scale tests, full-scale demonstration, and finally to deployment of multiple systems commercial operation. For capital-intensive technologies such as advanced power plants with CCS, each stage can take several years to complete and entails increasing levels of investment.[102]

The historical record of technology development shows that costs, which are highest at the start of the demonstration phase, tend to fall subsequently due to:

- Experience gained from “learning by doing”
- Increasing economies of scale in design and production as order volumes rise
- Removal of contingencies covering uncertainties and first-of-a-kind costs
- Competition from second- and third-to-market suppliers

An International Energy Agency study conducted by Carnegie Mellon University and others predicted a similar reduction in the cost of CO_2 capture technologies as their cumulative installed capacity grows.[103] Understanding of this cost-reduction pathway is reflected in the accelerated efforts on the part of DOE and technology researchers and developers worldwide to scale up and integrate CO_2 capture and capture-related.

Current and Anticipated Costs of CCS Projects

The costs of CCS comprise the additional equipment required to capture, transport, inject, and store CO_2, as well as the additional energy requirements for these processes.

Pipeline transport costs are highly non-linear for the amount of CO_2 transported, with economies of scale being realized at about 10 $MMTCO_2$/yr. For 10 MMT per year or greater, the levelized cost is about $0.80 per metric ton of CO_2 per 100 miles. However, this cost doubles at 5 MMT/yr and is greater than $4.80 per metric ton of CO_2 per 100 miles for 1 MMT per year. Pipeline costs will also vary by project, based on the distance between the CO_2 source and the storage site, as well as the terrain covered, with pipelines through congested areas or across difficult terrain costing more.[104]

For a 1,000 MW coal-fired power plant with CCS, a pipeline would need to carry about 6 to 7 $MMTCO_2$/yr. This would result in a pipe diameter of about 16 inches and a transport cost of about $1.60 per metric ton of CO_2 per 100 miles. At a certain regional market size, developing pipeline networks, as opposed to building dedicated pipelines between each major source and sink, reduces aggregate transport costs.[105]

Costs for well drilling and CO_2 injection are dependent on the geological characteristics of the storage site. For example, costs increase as reservoir depth increases or as reservoir injectivity decreases (lower

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[102] Ibid.
[103] *Estimating Future Trends in the Cost of CO_2 Capture Technologies*. IEA Greenhouse Gas R&D Programme (IEA GHG): February 2006. Report 2006/6.
[104] *Geologic Carbon Sequestration Strategies for California, Report to the Legislature*.
[105] Ibid.

injectivity results in the need to install more injection wells for a given rate of CO_2 injection). A range of injection costs has been reported as \$0.50–8.00 per metric ton CO_2. Monitoring costs have been assumed to be about \$0.10–0.30 per metric ton CO_2.[106]

Roughly 70–80% of the total cost of CCS, using the current suite of technologies, can be attributed to CO_2 capture and compression. Because capturing large volumes of CO_2 from process or exhaust gases at industrial facilities is a relatively new climate change mitigation strategy, the technologies for undertaking this endeavor are in varying stages of commercial readiness. However, no CO_2 capture technology has been applied at full scale on a large power plant or industrial combustion facility. Initial applications will encounter a cost premium for first-of-a-kind issues.

DOE estimates that today's most-developed CCS technologies would add about 80% to the levelized cost-of-electricity (COE) for a new pulverized coal (PC) plant, and about 35% to the COE for a new IGCC plant.[107] DOE's RD&D effort is pursuing developments to reduce these costs (90% capture basis) to a less-than-30% increase in COE for PC power plants and a less-than-10% increase COE for new gasification-based power plants.

Cost estimates for power plants with CO_2 capture span a range, and comparisons suggest that no single technology holds clear-cut advantages across all fuel types, operating environments, and site-specific characteristics. Thus, project developers are advised to begin technology selection through a broad option screening process.

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[106] *IPCC Special Report on Carbon Dioxide Capture and Storage.*

[107] *DOE/NETL Carbon Dioxide Capture and Storage RD&D Roadmap.*

Table 6. Representative cost and performance of fossil-fuel generation technologies for 2015 without CCS, and for 2025 with CCS[108]

	Nominal Plant Capacity, MW	Operating Life, years	Heat Rate (Btu/kWh)	CO_2 Emissions, Metric Tons/MWh	Fuel Price, $/MMBtu	LCOE, $/MWh*
Pulverized Coal	750	40	8,750	0.84	1.8-2.0	54-60
Pulverized Coal w/CCS	600	40	9,840-11,800	0.09-0.11	1.8-2.0	87-105
IGCC	600	40	8,940	0.86	1.8-2.0	68-73
IGCC w/CCS	500	40	9,100-11,000	0.09-0.15	1.8-2.0	85-101
NGCC	550	30	6,900	0.37	4.0-8.0	49-79
NGCC w/CCS	450	30	7,140-8,000	.04	4.0-8.0	68-109

**LCOE includes transportation and storage cost of $10/metric ton CO_2, which on a per MWh basis, adds $3, $6, and $7 to NGCC, IGCC, and pulverized coal, respectively.*

The Importance of Developing Multiple Technologies

Power industry experience shows that no single generation technology holds clear-cut advantages in all regions and across the diversity of market structures. Thus, for CCS, support for comprehensive pre-commercial RD&D and early demonstrations covering multiple technologies (pre-combustion, post-combustion, oxy-combustion, and novel processes) is a recommended approach.

Moreover, because technologies do not remain static over time, with each undergoing modification and improvement through operating experience and supporting research programs, their relative competitive strengths and weaknesses do not remain constant. Thus, attempting to pick "winners" and focusing investments on these select technologies is not advised. To address environmental concerns with minimal economic impact, the best strategy lies in developing a portfolio of technologies from which power producers (and regulators) can select the options most suited to preferred fuel types, local conditions, and compliance needs.[109]

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[108] *Electric Power Research Institute, Program on Technology Innovation: Integrated Generation Technology Options,* 1022782, Technical Update, June 2011.

[109] *Advanced Coal Power Systems with CO_2 Capture: EPRI's CoalFleet for Tomorrow Vision,* EPRI, Palo Alto, CA: 2008. 1016877.

High-Purity Sources Offer Lower-Cost Opportunities for CCS

The physics of CO_2 capture favor sources that produce gas streams with higher concentrations of CO_2 and at high pressure. As a result, the cost of CO_2 capture is usually lower for higher-purity CO_2 sources. Conversely, sources with low CO_2 concentrations in atmospheric pressure exhaust gases have higher costs per unit of CO_2 removed.[110]

Relatively large industrial sources that produce high-purity CO_2 streams as an integral part of their processes include natural gas plants separating CO_2 from produced gas, ethanol fermentation processes, ammonia plants, and some types of hydrogen production, such as those used in oil refineries. In these cases, any cost for CO_2 separation is already part of the process cost. The remaining costs to produce supercritical CO_2 for transport are usually just for compression and drying. For a moderately large-scale stream of 2 $MMTCO_2$/yr and an electricity price of 0.05¢/kWh, the cost of compression and drying is about $10 per metric ton of CO_2 avoided.[111] Barring other issues, large high-purity CO_2 streams should be the most economic sources of CO_2 capture.

Natural gas processing plants remove CO_2 in excess of about 2% in produced natural gas to meet commercial specifications for natural gas heating value and to avoid pipeline corrosion. The processing plant vents streams that are typically high-purity CO_2 and can represent significant point sources of CO_2. Worldwide, three major CCS projects, Sleipner and Snohvit in the North Sea and In Salah in Algeria, are each capturing about 1 $MMTCO_2$/yr from natural gas processing facilities for storage in deep geologic formations.

Hydrogen production entails the separation of CO_2 from the desired H_2 product. Traditional hydrogen purification processes using amine-based absorption systems are capable of producing a CO_2 stream that is 99.8% CO_2 by volume. Newer hydrogen plants tend to use pressure swing absorption, which produces a CO_2 stream that is only about 50% CO_2 by volume.[112] Further, hydrogen production by steam reforming of natural gas involves high-temperature fired heaters, which entails additional flue gas streams with a low CO_2 concentration. The cost of CO_2 capture from these flue gas streams would be much higher. Large amounts of hydrogen are produced in association with oil refining, and in the future, hydrogen production for vehicle fuel may also become substantial.

Fermentation-related CO_2 emissions are about 3,480 metric tons per million gallons of ethanol produced. A typical plant will have a nearly pure CO_2 emissions stream of about 0.2 MMT/yr, which is too small to have much economy of scale. As with hydrogen production, these facilities also have flue gas streams from fired heaters and steam generators that have low CO_2 concentrations.

Offsetting CCS Costs

Sale CO_2 as a Commodity

Finding value for CO_2 independent of any carbon credit markets can improve the economics of CO_2 capture. Such incremental revenue may be especially important in the near term when CCS project developers face first-of-a-kind costs and other cost premiums. To date, technologies making beneficial

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[110] *Geologic Carbon Sequestration Strategies for California, Report to the Legislature.*
[111] Ibid.
[112] Ibid.

use of CO_2 have had a negligible impact on overall anthropogenic CO_2 emissions. The bulk of CO_2 in the merchant market[113] is used for EOR—a demand that has been met primarily by supplies from natural sources—along with a significant portion used in the food and beverage industry. CO_2 in captive chemical processes[114] is most commonly used for the production of urea fertilizer.[115]

CO_2 for EOR

A white paper by Advanced Resources International states that "revenues from CO_2 sales to the oil industry can offset some of the costs of CO_2 capture from both natural gas- and coal-fired power plants, as well as other industrial facilities producing large volumes of CO_2. The support provided by CO_2-EOR for early implementation of CCS will help drive down the costs of capture, the largest cost hurdle for CCS, through 'learning by doing.'"[116]

The WESTCARB region has oil fields in Alaska and California that could benefit from CO_2-EOR to increase oil production if affordable, reliable supplies of CO_2 can be obtained. For the proposed Hydrogen Energy California (HECA) IGCC power plant in Kern County, California, sale of captured CO_2 for EOR is one of four revenue streams, the others being hydrogen, urea, and electricity. The CO_2 captured at the HECA power plant will be delivered via pipeline to the Elk Hills oilfield, approximately five miles away. EOR operations at Elk Hills will sequester 90% of the HECA plant's CO_2 output.

Longer-Term Opportunities for Generating Revenue from CO_2

In addition to using CO_2 for EOR, there are other possible beneficial and revenue-generating uses for captured CO_2, many of which are in relatively early stages of development. Technologies using CO_2 could contribute to GHG reduction goals by either preventing captured CO_2 from entering the atmosphere, or by using the CO_2, or a chemical product produced from CO_2, in a way that displaces other emissions of GHGs.

Revenue and CO_2 storage may be realized from enhanced coal bed methane production, enhanced natural gas recovery, and enhanced geothermal systems, however, these technologies are not sufficiently developed to help the first deployers of CCS projects. The use of CO_2 as a working fluid in geothermal systems, which has the advantage of both sequestering CO_2 and creating renewable power, is at an early stage of development but could prove applicable in areas of significant geothermal potential.[117]

DOE is funding a project led by GreenFire Energy in Arizona to investigate the potential for low-temperature CO_2-based geothermal power production technologies. The project will test several energy recovery techniques in existing shallow wells and the performance of CO_2 as a working fluid.[118]

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[113] Market in which CO_2 is bought and sold competitively by multiple market participants.

[114] CO_2 produced onsite by the user of the CO_2 and not sold to outside customers.

[115] *IPCC Special Report on Carbon Dioxide Capture and Storage*.

[116] *U.S. Oil Production Potential From Accelerated Deployment of Carbon Capture and Storage*, Advanced Resources, International, Inc., Arlington, VA, March 10, 2010.

[117] *Research Roadmap for Carbon Sequestration Alternatives*, draft. California Energy Commission, PIER Energy-Related Environmental Research Program. March 2011.

[118] http://apps1.eere.energy.gov/news/progress_alerts.cfm/pa_id=401

Other longer-term prospects for benefical uses for CO_2 include mineralization to carbonates directly through conversion of CO_2 in flue gas; the use of CO_2 from power plants or industrial applications to grow algae/biomass; and conversion of CO_2 to fuels and chemicals.

Within the WESTCARB region, Calera Corporation has been developing a process that uses brines such as seawater to mineralize CO_2 from flue gas to make carbonates for use in cement and other construction materials. The company, which operates a small-scale facility in Moss Landing, California, has received funding from DOE through stimulus allocations to demonstrate its process at larger scale.

An evaluation of beneficial use technologies noted the lack of a systematic methodology for comparing the various technologies and called for the use of life-cycle analyses to assess the relative merits of each beneficial technology in a quantified way. The study noted that although such analyses may be particularly complex for some technologies, they would be useful for identifying the best directions for technology development.[119]

Government Incentives[120]

Cost barriers faced by developers and early users can pose a funding gap that stifles technology development/investment that is in the public interest (e.g., cleaner, more efficient ways of producing electric power).

Financial incentives to encourage investment in CCS demonstrations and early commercial projects tend to address one of three cost centers: capital cost, financing cost, and operating cost. Much of the research for CCS, as well as demonstration projects, in the WESTCARB region and nationally, is proceeding with assistance from federal funding.

State government incentives can also address first-of-a-kind CCS costs through programs similar to those offered by the federal government, such as investment tax credits and accelerated depreciation, and through credits or exemptions to taxes uniquely imposed at the state/county level, such as property taxes.

Utility rate regulation is another area where states traditionally have jurisdiction. In many states, Public Utilities/Service Commissions have authority over cost recovery for power plants built or owned by investor-owned utilities, and for long-term power purchase contracts by investor-owned utilities from plants developed and operated by independent generators. PUCs can approve “above market” costs for power from generation sources deemed to be in the public interest, although substantially above-market costs may still adversely affect overall economic competitiveness in the service territory. In states where customers have access to energy service providers other than a local investor-owned utility, cost allocation mechanisms may be needed to “socialize” the above-market costs to all customers so no single utility’s customers bear the cost for the public-interest benefit.

In 2011, failure to obtain PUC approval for cost recovery, in conjunction with a lack of federal regulation, led to American Electric Power’s termination of its agreement with DOE to develop a commercial-scale

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[119] *Research Roadmap for Carbon Sequestration Alternatives.*

[120] *Background Reports for the California Carbon Capture and Storage Review Panel*.

demonstration of CCS technology at its Mountaineer Plant in West Virginia, following a successful pilot-scale project.[121]

The Division of Ratepayer Advocates, an independent division within the California PUC, has put forth the suggestion that CCS research and development could be supported by funding from all (statewide) electric utility ratepayers equally.[122] This approach, albeit broader in scope, was recommended by the California Carbon Capture and Storage Review Panel: It should be state policy that the burdens and benefits of CCS be shared equally among all Californians.[123]

Where CO_2 emissions are regulated, annual allowances for emissions have been distributed to affected sources on the basis of historic emissions or benchmark values or via auction, or some combination thereof. In cases where allowances are auctioned, various proposals have been made to direct the resulting revenue to new technology demonstrations. For example, revenue from the New Entrants Reserve in the European Trading Scheme will be directed toward renewables and CCS demonstrations. At the federal level, bonus allowances for early CCS adopters have been proposed as a means to offset early mover challenges (e.g., proposed Waxman-Markey federal legislation in 2008).

Because CCS changes the production cost profile of power plants or other industrial manufacturing operations, they may be temporarily uncompetitive relative to plants without CCS, particularly in the era immediately after regulations take effect, when allowance price caps and other measures limit the price of CO_2 emission allowances. For power plants with CCS, for example, high dispatch rates are essential to minimizing levelized cost impacts on a per-kWh basis. The Independent System Operator (dispatch center) has mechanisms to prevent dispatch curtailment for fossil power plants with CCS, typically designation as “must run” units.

Project Finance

Project Insurance Coverage

CCS projects are frequently conceived of as occurring in three phases: operations (injection), post-injection or closure, and post-closure. The risks during the operational and closure periods of CCS projects are similar to current industrial activities that are underwritten in the financial and insurance sectors and are generally not considered a significant barrier to CCS deployment. At least one major insurer now offers liability insurance during the operational life of a storage facility, as well as a separate financial assurance policy for the post-closure phase. Together, coverage would conceivably run for the 30–50 year life of a fossil-fueled power station, then for another 10–30 years after well closure.[124]

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[121] http://insurancenewsnet.com/article.aspx?id=268856&type=newswires

[122] http://www.climatechange.ca.gov/carbon_capture_review_panel/meetings/2010-08-18/comments/Division_Ratepayers_Advocates_Comments.pdf

[123] *Findings and Recommendations by the California Carbon Capture and Storage Review Panel:* http://www.climatechange.ca.gov/carbon_capture_review_panel/documents/2011-01-14_CSS_Panel_Recommendations.pdf

[124] http://www.environmental-finance.com/news/view/865

Models for Long-Term Liability Coverage

Geologic CO_2 storage projects include a period of post-injection monitoring, which is intended to verify that the injected CO_2 is stable and will not migrate. No consensus has been reached on the duration of the post-injection monitoring phase, however, timeframes of 10 to 50 years have been proposed. Under EPA's UIC Class VI rule, the well owner or operator must continue to conduct monitoring as specified in the UIC Director-approved post-injection site care and site closure plan for a nominal period of 50 years following the cessation of injection, or until (either more or less than 50 years) the owner or operator can demonstrate to the Director that the project no longer poses an endangerment to USDWs.

Long-term liability for CCS refers to the legal responsibility for any damages attributed to a project in the post-closure phase. Some CCS stakeholders consider this to be a barrier to the commercialization of CCS, primarily because businesses are not comfortable assuming risks over timeframes that could be longer than a company could reasonably be expected to exist. In addition to potential claims for damage to other resources (e.g., natural gas or fresh water), or for remediation related to CO_2 migration and/or leakage, there is also potential for financial exposure under GHG regulatory regimes if leakage results in escaped emissions that need to be accounted for through the surrender of allowances or other compliance instruments.[125]

In the United States, there is currently no comprehensive, integrated federal framework defining or allocating long-term liability for stored CO_2, however, there are several long-term liability models for CCS projects under consideration, some of which are being enacted at the state level.

Government assumption of liability – The rationale for a government role in indemnifying long-term liability is based on the belief that CCS is in the public interest and that long-term liability issues should not, particularly at this early stage, be a barrier to further development. Additionally, given that the CO_2 is expected to remain stored indefinitely, governments traditionally offer greater financial stability and institutional longevity than do corporations, although this thinking may no longer reflect the current state of affairs where some multi-national corporations have greater financial resources and resiliency than some governments.

A "certificate of completion" model has been adopted by Louisiana, Montana, North Dakota, and Wyoming[126] whereby the operator of a geologic storage site can transfer title and liability for the stored CO_2 to the state after demonstrating to the relevant state agency that the site has been stable for a certain period of time after the last CO_2 injection period, and that the site has been properly closed. Until the time of transfer, the operator remains liable for any damages related to any CO_2 migration or leaks.

One concern with government assumption of liability is that it could result in "moral hazard," which is the term used to describe the potential for increased risks due to actions the responsible party takes because it is partially insulated from being held liable for resulting harm and attendant damages. Moral hazard is a concern with any system of risk pooling because corporations are not liable for the entire costs of their

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[125] "Long-Term Stewardship and Liability of Storage Sites," Appendix P, *Background Reports for the California Carbon Capture and Storage Review Panel*.

[126] Ibid.

own accidents.[127] For stored CO_2, having the project owner/operator remain liable through the post-injection monitoring period may reduce such risks.

Industry-funded trust fund – An example of this approach was contained in the Bingaman bill, which was part of the American Clean Energy Leadership Act of 2009, and proposed a per-ton sequestration fee to be accrued by the U.S. Department of Treasury in a DOE-administered trust fund.[128] Such a fund could also be administered by private or public corporation with a specific charter for overseeing the fund.

Private insurance – This approach could mirror the insurance requirement of the Price-Anderson Act, which mandates that the owners/operators of nuclear reactors obtain private insurance at prescribed levels, thereby creating a pool of insured entities and a stream of premiums that may in turn allow insurers to provide coverage.[129] However, at present, insurers are reluctant to issue policies for long-term post-closure operations of CCS project because of the difficulty in assessing risks. Possible workarounds include requiring insurance only for a defined level of exposure and/or allowing shorter-term policies and the periodic re-rating of insurance company risks.[130]

It is worth noting that the Price-Anderson Act provides two additional tiers of coverage beyond private insurance: a collective financing mechanism requiring that each company in the pool contribute up to a statutory cap of $95.8 million in the event of a nuclear accident, and a federal financing mechanism that requires the federal government to “backstop” the remaining balance owed to claimants through the general treasury once the individual and collective caps are reached. A similar multi-tiered design for CCS long-term liability is also a possibility.

Legal Considerations for CCS Projects

Pore Space Ownership and Mechanisms for Acquiring Pore Space Rights

Geologic CCS projects are contingent upon the project operators obtaining the right to inject and store CO_2 within subsurface pore space. Common law from some states provides that pore space belongs to the surface owner. Where subsurface minerals exist, surface owners may server ownership of the subsurface mineral rights and convey them to third parties. In these arrangements, the subsurface owner generally has the legal right to reasonable use of the surface estate (with just compensation) for production of the minerals. CO_2 storage requires similar rights to use and access the subsurface, but it does not entail mineral production.

Clarification of pore space ownership may be addressed by legislative declaration that pore space belongs to surface owners (at least by default). This approach has been followed by Montana, North Dakota, and Wyoming. Wyoming led the way by vesting ownership of subsurface pore space to the surface owner, but allowing severance of pore space from the surface interest. North Dakota similarly vests subsurface pore space with the surface owner but expressly forbids severance of the pore space from the surface estate.

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[127] *Report of the Interagency Task Force on Carbon Capture and Storage,* August 2010: http://www.fe.doe.gov/programs/sequestration/ccs_task_force.html

[128] “Long-Term Stewardship and Liability of Storage Sites,” Appendix P, *Background Reports for the California Carbon Capture and Storage Review Panel*.

[129] *Report of the Interagency Task Force on Carbon Capture and Storage.*

[130] Ibid.

Montana, however, neither allows nor forbids it. All three states maintain the dominance of the mineral estate over both surface and subsurface.[131]

Alternatively, a legislature could declare pore space to be a public resource or choose to recognize private interests in pore space only when the property owner has a reasonable and foreseeable use of it.

Mechanisms to acquire rights to multiple adjoining subsurface estates can be addressed by establishing authority for CCS projects to obtain these rights either by eminent domain or by unitization. Eminent domain is commonly used to acquire easements for projects that have a public purpose. Unitization is a long-established mechanism used in the context of oil and natural gas production, whereby hold-out property owners share in the revenues from production but cannot stop production from occurring. Louisiana has established a process for using eminent domain for carbon sequestration, and Montana, North Dakota, and Wyoming have authorized the use of unitization.[132]

Issues about pore space rights and access can hamper CCS deployment in areas where no clear guidance is provided, thus making project developers reluctant to pursue CCS projects. Another limiting factor could arise from the complexity and expense of acquiring multiple property rights given the large areas CCS projects will cover. Additionally, because of the novelty of CCS, there is a potential for test-case lawsuits.

Pipeline Rights-of-Way Acquisition Authority[133]

Siting long CO_2 pipelines can be complex and costly, especially in populated or environmentally sensitive areas. It may be difficult for project sponsors to obtain rights-of-way, and the lack of eminent domain rights can necessitate the costly rerouting of pipelines, potentially leading to project cancellation. Another consequence of lacking state condemnation authority is that rights-of-way may tend to target federal and state lands for crossing. The ability to get a land use agreement across government lands, both federal and state, could prove to be a significant incentive and may result in less desirable locations being sought.

No federal agency exercises authority over the siting of interstate CO_2 pipelines on non-federal land. In 1979, the Federal Energy Regulatory Commission (FERC) ruled that the Natural Gas Act (NGA) did not give it jurisdiction over a proposed interstate pipeline that would transport 98% pure CO_2. In the last five years, FERC has reaffirmed that it does not have jurisdiction over CO_2 pipelines. Consequently, unless the federal government amends NGA to cover CO_2 pipelines, the federal power of eminent domain is not available for interstate CO_2 pipelines.

The Bureau of Land Management (BLM) has authority under the Federal Land Policy and Management Act to issue rights-of-way on and beneath federal land for pipelines carrying anthropogenic CO_2. BLM also currently authorizes pipelines for the transportation of naturally-occurring CO_2 under the Mineral

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[131] Reed, John, et al., *CCS Regulatory and Statutory Approaches in Other States,* prepared for the California Carbon Capture and Storage Review Panel, April 2010: http://www.climatechange.ca.gov/carbon_capture_review_panel/documents/2010-04-01_Other_States.pdf

[132] Fish, Jerry R. and Eric L. Martin, "Approaches to Pore Space Rights," Appendix J, *Background Reports for the California Carbon Capture and Storage Review Panel*.

[133] Fish, Jerry R. and Eric L. Martin, "Carbon Dioxide Pipelines," Appendix I, *Background Reports for the California Carbon Capture and Storage Review Panel*.

Leasing Act. Pipelines authorized under the Mineral Leasing Act become “common carriers” that must accept and transport all gas delivered to the pipeline.

A handful of states have enacted statutes allowing the use of eminent domain for CO_2 pipeline rights-of-way acquisition. In some cases, these eminent domain statutes may be restricted to CO_2 use for enhanced oil recovery. Pipelines used for carbon storage outside of enhanced oil recovery would not be able to utilize the eminent domain authority granted by these statutes. Other eminent domain statutes require the CO_2 pipeline (for any purpose) to function as a common carrier. For example, Texas only authorizes the use of eminent domain for CO_2 pipelines if the pipeline company agrees to serve as a common carrier. This obligation could pose a problem if a particular CO_2 pipeline is built with just enough capacity to transport CO_2 generated from a particular source.

Public Acceptance

For CCS to be successfully deployed at scale, it will be critical to have some degree of public acceptance or tacit consent. Although there is a growing awareness among state and regional policymakers that meeting GHG emission reduction targets without CCS is unfeasible given societies’ current and projected use of fossil fuels, broad public recognition of the capability and role of CCS in climate change mitigation falls short of this understanding.

Even among people who believe that manmade GHG emissions need to be curbed, CCS can be viewed as prolonging reliance on fossil fuels (coal tends to be singled out), or as too expensive relative to other options (i.e., the money would be better spent on renewables).

Thus, discussion of CCS often needs to be framed within the context of energy supply, including consideration of electric system dispatch requirements, and even within a broader framework of what is realistically achievable over the next century as societies seek to balance energy demand fulfillment with lowering GHG emissions, while minimizing economic impacts.

At a community level, CCS projects sometimes find favor in areas where people are knowledgeable about geologic storage of hydrocarbons. Other communities have ties to fossil-fueled power generation or other industries that are likely candidates for CCS, and foresee the benefits in having these businesses remain viable. Job creation or retention can figure prominently in local and regional planning, and CCS projects that are linked to EOR or represent new opportunities in the emerging low-carbon economy may be welcomed. Concern for the environment and a desire to help reduce GHG emissions can also motivate community members to support CCS projects.

Some communities have opposed CCS projects because of perceived risks. People are naturally wary of new technologies or technologies with which they are unfamiliar. CCS is sometimes compared to nuclear waste storage, and the risk profile of CO_2 has been confused with substances that are explosive or with highly toxic pollutants. People can be surprised to learn about the mechanics of CO_2 trapping, or that the earth stores CO_2 naturally, or that EOR operators are responsibly injecting millions of tons of CO_2 each year.

Nonetheless, the benefits and risks of CCS projects, as well as the safety and mitigation measures that may be taken to manage risks, need to be acceptable to nearby communities. It is possible that public concern about the risks of CCS will decline, provided early projects are conducted without significant incidents and the volume of CO_2 injected remains safely stored.

To further public education on CCS, WESTCARB has teamed with universities and environmental organizations to hold informational meetings, and has participated in teachers' trainings for middle and high school teachers. Community meetings in Arizona and California have allowed for a two-way exchange of information between community members and WESTCARB researchers. These experiences illustrated the diversity of values and concerns that go into shaping people's responses to CCS, underscoring the importance of allowing sufficient time for outreach and engagement efforts that encompass multiple stakeholder groups.

Figure 17. A 2010 meeting on CCS in California hosted by WESTCARB and partners

As CCS becomes established in the WESTCARB region, the development of CCS curricula and training programs, and inclusion of CCS in science programs will be needed to support the creation of a qualified workforce. In 2009, using ARRA funding, DOE/NETL launched seven Regional Carbon Sequestration Training Centers to offer courses on applied engineering and science of CCS for site developers, geologists, engineers, and technicians, and to provide a technology transfer platform for CO_2 storage. As part of this program, the Carbon Tech Alliance,[134] a partnership of EOS Alliance, the Pacific Northwest National Laboratory, and the Washington Society of Professional Engineers, offers training courses and lectures on multiple CCS topics.

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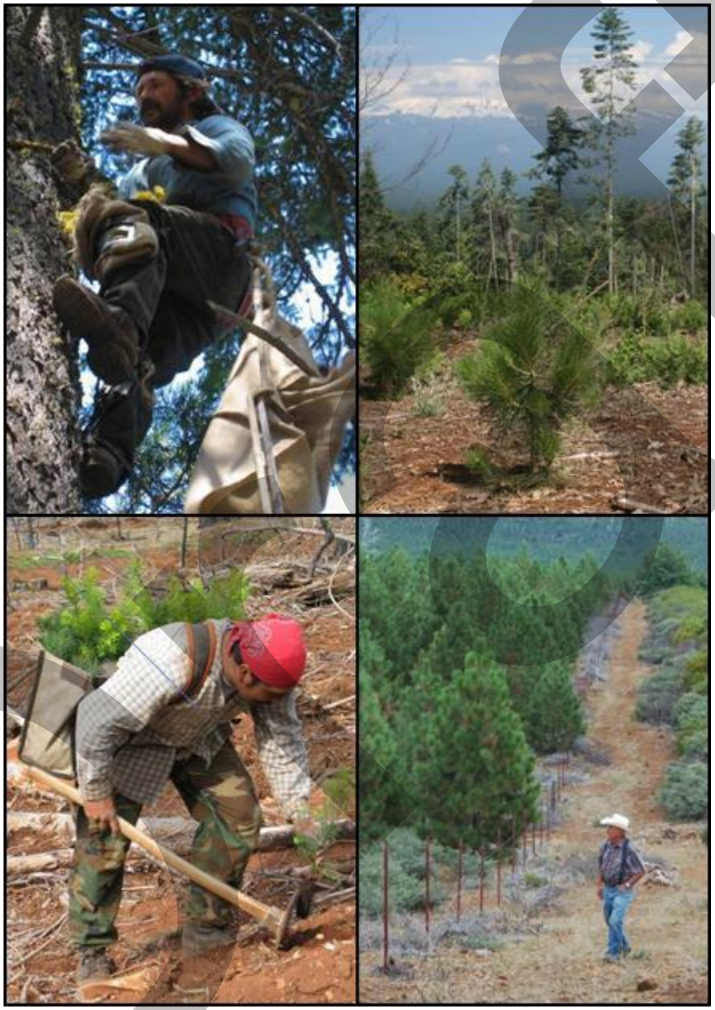
[134] http://www.carbontechalliance.org/

DEPLOYING TERRESTRIAL CARBON SEQUESTRATION IN THE WESTCARB REGION



Terrestrial carbon storage is the process through which CO_2 from the atmosphere is absorbed by vegetation through photosynthesis and stored as carbon compounds in soils and biomass (e.g., tree trunks, branches, foliage, and roots). Projects for terrestrial carbon storage involve changing land management practices to (1) remove more CO_2 from the air for long-term storage as carbon in biomass and soil, and/or (2) reduce carbon losses from ecosystems.

The potential for increased terrestrial carbon storage depends largely upon land use, types of vegetation or cover, and precipitation. Opportunities in the vast forests of the Pacific coast states can take the form of tree planting (afforestation or reforestation[135]), changes in forest management such as lengthening the time between timber harvests, and changes in land development practices to protect forest tracts. Removing forest fuels to reduce the severity of wildfires and the use of removed fuels in biomass energy facilities, where practical, may also be a successful strategy in addition to offering benefits beyond carbon storage.

Other biomes where increased carbon storage or reduction in GHG emissions may be realized include rangelands, where WESTCARB researchers estimate the highest regional afforestation potential lies; croplands, where changes in management, as well as crops for biomass fuels and energy are among the practices being pursued; increased biomass in wetlands, which could also contribute to preservation and/or restoration of shorelines and levees; and afforestation of riparian areas.

Estimating Regional Potential for Terrestrial Carbon Storage

Assessing the potential for increased terrestrial carbon storage starts with baseline surveys to establish carbon stocks—how much carbon is typically stored for a given area and land type—and by projecting and quantifying carbon storage and emissions from a business-as-usual approach (i.e., carbon stocks and flows that would occur if current management practices were to continue into the future).[136]

Baselines provide a reference against which to measure changes in levels of carbon stocks that occur over time, including those that would result from altering land management practices or uses. Establishing baselines is a critical early step in determining where the best opportunities for increased carbon storage lie. Baselines are also used on a project basis to provide a measurement of carbon stocks before any project activities are undertaken.

WESTCARB's early baseline studies highlight the impact of land use changes on carbon stocks. In Oregon, for example, an estimated net increase in forest area of 2.1 million acres (850,000 hectares) between 1987 and 2003 translated into an estimated gross sequestration of 23 $MMTCO_2e$/yr between

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[135] Under DOE's revised 1605(b) guidelines for greenhouse gas reporting, "afforestation" is the establishment of new forests on lands that have not been forested for some considerable length of time, and is in essence a land-use change; "reforestation" is the re-establishment of forest cover, naturally or artificially, on lands that have recently been harvested or otherwise cleared of trees.

[136] *Best Practices for Terrestrial Sequestration of Carbon Dioxide*, National Energy Technology Laboratory, November 2010.

1987 and 1997, and 34.4 $MMTCO_2e$/yr between 1997 and 2003. GHG emissions for Oregon (excluding forests) for 2000 were estimated at 67.7 $MMTCO_2e$.[137]

Over the same timeframe, net forested area in Washington decreased by 0.9 million acres (364,000 hectares). Emissions from this development average out to ~7 $MMTCO_2e$/yr and represent about 55% of the total gross emissions from the forest sector. Compared with total GHG emissions for the state as a whole, emissions from deforestation on non-federal land represented more than 5% of the state's total.[138]

A California study found little impact to forests from development; however, between 1987 and 1997, 573,000 acres of agricultural land were converted to non-agricultural uses. Eighty-eight percent of this change was in non-woody crops. The change in area was estimated to equal a net loss of 3.5 $MMTCO_2e$ over the 10-year period, of which 63% was due to the decrease in non-woody croplands.[139]

WESTCARB researchers evaluated changes that could lead to significant increases in carbon stocks for forests, rangelands, and crop lands in California, Oregon, and Washington. These analyses are depicted by maps and by carbon "supply curves," which illustrate how much additional carbon could be stored as the value of carbon increases and more terrestrial storage projects become economically viable.

For rangelands and croplands (lands growing wheat and hay), the potential for carbon sequestration was estimated for afforestation using native species. Historical evidence suggests that large tracts of forest once stood in many areas of these three states that currently support grazing and agriculture.

The study (1) identified existing rangelands and croplands where biophysical conditions are suitable for forests, (2) estimated carbon accumulation rates for the forest types projected to grow, and (3) assigned values to each contributing cost factor (opportunity, conversion, maintenance, measurement, and monitoring). The carbon supply was estimated for three durations of forest growth—20, 40, and 80 years—to provide an assessment for the near-term and longer-term planning horizons.

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[137] Pearson, Timothy, Sandra Brown, Nicholas Martin, Sebastián Martinuzzi, Silvia Petrova, Ian Monroe, Sean Grimland, and Aaron Dushku. 2007. *Baseline Greenhouse Gas Emissions and Removals for Forest and Agricultural Lands in Oregon.* California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-2007-025.

[138] Pearson, Timothy, Sandra Brown, Nicholas Martin, Sebastián Martinuzzi, Silvia Petrova, Ian Monroe, Sean Grimland, and Aaron Dushku. 2007. *Baseline Greenhouse Gas Emissions and Removals for Forest and Agricultural Lands in Washington State.* California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-2007-026.

[139] Brown, S., T. Pearson, A. Dushku, J. Kadyzewski, and Y. Qi. 2004. *Baseline Greenhouse Gas Emissions and Removals for Forest, Range, and Agricultural Lands in California*. Winrock International, for the California Energy Commission, PIER Energy-Related Environmental Research. 500-04-069F.

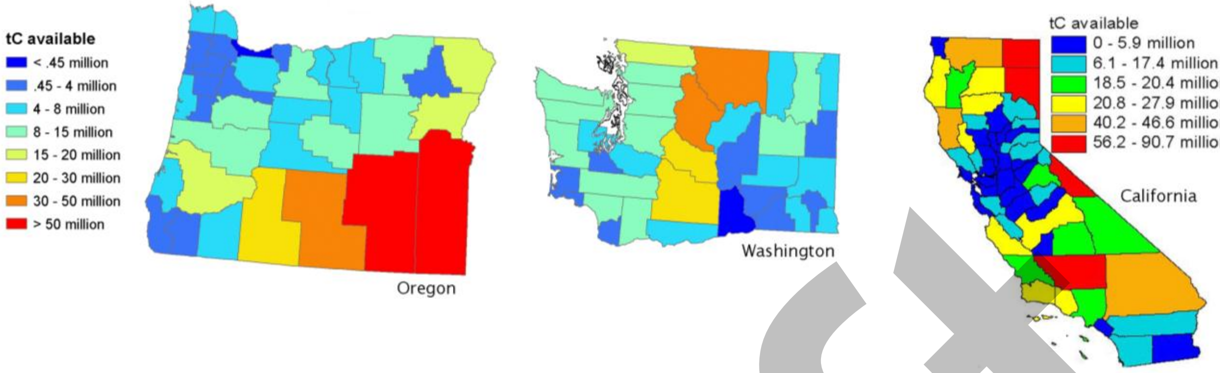

Figure 18. Total estimated storage (metric tons carbon, tC) through afforestation after 40 years

Afforestation/Reforestation

The baseline and cost-curve analyses described above led to the conclusion that the biggest potential for increased terrestrial carbon storage in the WESTCARB region is through afforestation of rangelands. In contrast, the potential for afforestation of agricultural lands is smaller because the generally high productivity and land values associated with agriculture make the opportunity costs of displacing agricultural production with carbon forestry projects unfavorable.

Afforestation can have substantial environmental and economic co-benefits in creating a healthier forest with mixed species and wildlife habitat diversity, providing timber and biomass fuel values, and reducing fire risk by interrupting the "brush-and-burn" cycle. In some cases, projects on rangelands could be carried out concurrently with the grazing of livestock, provided seedlings are protected. On a dollar per ton of CO_2-equivalent basis, costs are lowest for the longer project timespans because the trees have more time in their prime growing years, and the initial costs of land preparation, planting, and weed control are amortized over a larger quantity of sequestered carbon. This can be seen in the statewide capacity estimates discussed in next section.

Statewide Capacity Estimates

In Washington, at a levelized cost of \$20 or less per metric ton of CO_2 and a project life of 20 years, almost 289 $MMTCO_2$ could be sequestered on rangelands and croplands on 4.3 million acres. At a project life of 40 years, the aggregate of projects meeting the economic criterion of \$20 per metric ton rises to more than 1,233 $MMTCO_2$ on 10 million acres. Finally, at project life of 80 years, approximately 3,176 $MMTCO_2$ could be stored on 14 million acres (Table 7). Converting this total amount at 40 years to an approximate annual rate results in about 31 $MMTCO_2$/yr.[140]

In Oregon, at a levelized price of \$20 or less per metric ton of CO_2 and a project life of 20 years, almost 280 $MMTCO_2$ could be sequestered on 3.3 million acres. At a project life of 40 years, the aggregate of projects meeting the economic criterion of \$20/metric ton rises to more than 1,813 $MMTCO_2$ on 18

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[140] Dushku, A., S. Brown, S. Petrova, J. Winsten, N. Martin, T. Pearson, and J. Kadyszewski (Winrock International). 2007. *Carbon Sequestration Through Changes in Land Use in Washington: Costs and Opportunities.* California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2007-075.

million acres. Finally, at project life of 80 years, approximately 4,203 $MMTCO_2$ could be stored on 24 million acres (Table 7). Converting this total amount at 40 years to an approximate annual rate results in about 45 $MMTCO_2$/yr.[141]

Table 7. Terrestrial carbon storage capacity estimates for rangelands and croplands in Oregon and Washington

	Quantity of Carbon (MMT CO_2) @ ≤\$20.00 per metric ton			Area Available (million acres)		
	20 years	40 years	80 years	20 years	40 years	80 years
Rangelands WA	279.4	1,178	2,450	4.2	8.8	8.9
Croplands WA	9.8	54.9	725.9	0.1	1.4	5.5
Rangelands OR	117.7	1,336	2,827	1.4	15.6	19.1
Croplands OR	162.0	477.2	1,376	1.91	2.15	5.0

An earlier study for California used different cost thresholds for analysis. For a price of <\$5.50 per metric ton and a project lifespan of 20 years, 345 $MMTCO_2$ could be sequestered on 2.7 million acres of rangeland, 3 billion metric tons CO_2 on 14.8 million acres after 40 years, and 5.5 billion metric tons on 19 million acres after 80 years.[142]

Afforestation project developers are already participating in carbon markets, including the voluntary carbon market. In the United States, the major carbon registries have protocols for conducting afforestation projects, and they are an allowable offset option under California's AB 32 cap and trade program, which commences in 2013.[143] Afforestation/reforestation projects are part of the Clean Development Mechanism (CDM) offset program under the Kyoto Protocol.

Shasta County Reforestation Pilot Tests

WESTCARB conducted reforestation projects in Shasta County, California, in 2007–2010. Criteria for selection required that projects be eligible for carbon registries—should landowners choose to register—and that sites have less than 10% tree canopy cover for at least ten years at the start of the project in order to comply with the Climate Action Reserve's definition of reforestation.

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[141] Dushku, A., S. Brown, S. Petrova, T. Pearson, N. Martin, J. Winsten, and J. Kadyszewski (Winrock International) 2007. *Carbon Sequestration Through Changes in Land Use in Oregon: Costs and Opportunities.* California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-2007-074.

[142] Brown, S., A. Dushku, T. Pearson, D. Shoch, J. Winsten, S. Sweet, and J. Kadyszewski (Winrock International) 2004. *Carbon Supply from Changes in Management of Forest, Range, and Agricultural Lands of California.* California Energy Commission, PIER Energy-Related Environmental Research. 500-04-068F.

[143] California Environmental Protection Agency, Air Resources Board, *Proposed Regulation to Implement the California Cap-and-Trade Program, Part V, Staff Report and Compliance Offset Protocol, U.S. Forest Projects,* Release Date: October 28, 2010.

Twelve sites were selected to include a diversity of land and project types, and reflect a broad geographic distribution across Shasta County, including lands at low, medium, and high elevations; lands suitable for oak, conifer, and oak/conifer; and diverse conditions created by the elevation, slope, climate, and vegetation. Site selection also considered the potential for replication in other areas in the WESTCARB region.

Project size ranged from 7 to 98 acres, with an average of 40 acres. Existing vegetation consisted of a variety of brush species, mostly in dense stands. Baseline carbon stocks ranged from zero for a project that had recently burned in a wildfire to 34 metric tons of carbon per acre on a site with dense old-growth manzanita. Projects were planted with ponderosa pine, mixed conifer stands, or native oaks.

Landowner interest in developing multiple revenue streams, contributing to climate change mitigation, and improving forest health or reducing fire risk led to high interest in the pilot projects and a willingness to share costs.

Projections of net carbon stocks on conifer plantings over 100 years ranged from 53 to 111 metric tons carbon/acre. The native oak planting had projected net carbon stocks of 24 metric tons carbon/acre after 100 years. Survival of planted conifer seedlings was high, despite limited rainfall in the year of planting. Project costs ranged from $354 to $1,880 per acre. Sites with high baseline carbon stocks generally do not yield a net carbon benefit until 30 to 40 years after project implementation.

The variation in costs is based largely on the amount of site preparation needed before seedlings can be planted. Clearing brush, for example, can be costly, whereas sites planted soon after a wildfire can have much lower costs if the fire has destroyed existing vegetation. A second cost consideration is the amount of vegetation control needed after planting to decrease competition from species that would overtake the seedlings during the early years of establishment.

Other considerations such as soil and precipitation, species planted, number of trees per acre planted, and seedling survival have an impact on forest growth rates and carbon stocks. For instance, Douglas fir sequesters more carbon than ponderosa pine, but tends to have a lower survival rate. Oaks grow slowly but are better suited for certain soil types (e.g., gravelly sandy loam), and have traditionally grown on rangelands where dairy farming or cattle ranching provides a primary revenue stream. When seedlings are planted on grazing lands, they require protection for several years from livestock (treeshelters can be used), which adds to project costs.

Two different approaches to disposal of brush were investigated in the Shasta County pilots.

1. Piling and burning. This is the conventional and often the only feasible approach for brush disposal in “brush-conversion” afforestation projects. This approach essentially results in the immediate emission to the atmosphere of all baseline vegetation carbon stocks.

2. Grinding and removal to a biomass energy facility. This alternative still emits as CO_2 the carbon contained in the brush, but offers a better overall GHG balance. Efficient and complete combustion at a biomass plant (where available) would likely release less non-CO_2 GHGs than pile-burning, in addition to which power plants have emissions controls. Further, electricity

generated from biomass power plants may offset generation of electricity using fossil fuels, thus reducing the net emission.

Hybrid Poplars

Hybrid poplar, a short rotation woody crop, is of interest in the west coast states of California, Oregon, and Washington because of its potential as a bioenergy crop or wood products crop in combination with the potential revenue from carbon credits.

A WESTCARB study of hybrid poplars[144] found that most of the land suitable for growing this species (based on soil composition, land slope, and climate) is located on the western side of the Cascade Range in Oregon and Washington. The estimated area where hybrid poplars could be grown without irrigation in these two states totals about 2.5 million acres. Suitable land in California not requiring irrigation totals around 300,000 acres and is located primarily on the north coast.

Of these potential lands, the most suitable could produce an average of 3–4 tons carbon/acre per year. Revenue from a dedicated bioenergy plantation on a 6-year rotation is estimated to be $737–$976/acre, of which $86–$325/acre is earned from carbon credits. Revenue from a wood products plantation on a 20-year rotation is estimated to be $9,396–$10,989/acre, of which $425–$1,592/acre is earned from carbon credits.

Although the overall potential for carbon credits from hybrid poplar crops grown for wood products is expected to be less than for bioenergy crops, any hybrid poplar project would need to be assessed on a site-specific basis, and financial feasibility will vary considerably depending on local markets, the price of goods, and the price of carbon credits.

Hybrid poplar plantations are unlikely to compete successfully against the economic benefits of current crops, and may be precluded from native grasslands to avoid biodiversity losses. The best opportunities may well be found on marginal agricultural lands, degraded areas, or areas where riparian buffers can offer both economic and ecological benefits.

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[144] Netzer, M., Goslee, K., Pearson, T.R.H., and Brown, S. *Opportunity Assessment for Establishing Hybrid Poplars in California, Oregon, and Washington.* California Energy Commission, PIER Energy-Related Environmental Research. Draft report, 2010.

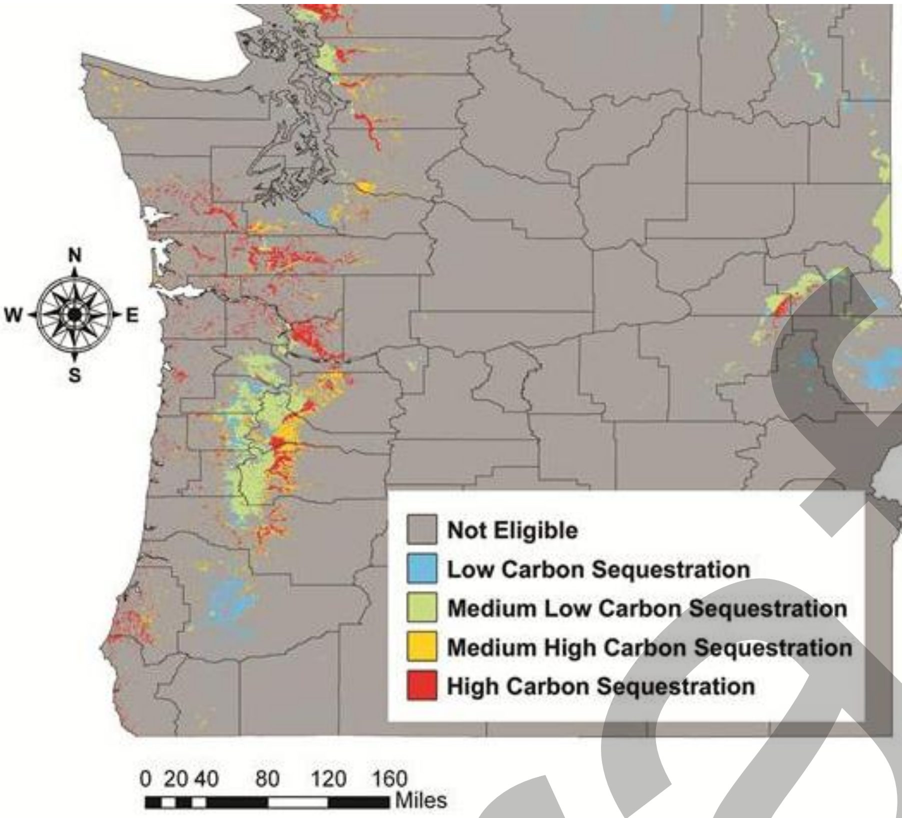

Figure 19. Carbon storage potential with hybrid poplars in Oregon and Washington without irrigation[145]

Forest Conservation Management

Forests in active harvest rotations can be managed to increase overall carbon stocks. WESTCARB researchers examined three approaches: (1) lengthening timber harvest rotations beyond the economic maturity when harvesting would normally occur, (2) widening riparian buffer zones where trees are not harvested by an additional 200 feet (61 meters); and (3) reducing hazardous fuel in forests to reduce catastrophic fires, and subsequently using fuels in biomass power plants.

Statewide Capacity Estimates for Lengthening Timber Harvest and Widening Riparian Buffers

Although Oregon and Washington have substantial forest area, the cost of carbon sequestration from changing forest management practices is relatively high and the quantity of carbon that could be sequestered is relatively small. In Oregon, if all forests on private and nonfederal public land nearing the economically optimal rotation period (790,000 acres) were to adopt management plans to increase rotation ages by up to 15 years, 35.6 MMTCO$_2$ could be sequestered for an average cost of $37 per metric

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[145] *2010 Carbon Sequestration Atlas of the United States and Canada.*

ton. In Washington under the same scenario, acreage would be about 1.5 million acres, and 61.6 $MMTCO_2$ could be sequestered at an average cost of $37 per metric ton.

By widening the riparian buffer by an additional 200 feet, the area of mature forests in Oregon could potentially be increased by an estimated 20,700 acres. The additional carbon that could be stored on these lands if the forests were conserved is 1.25 $MMTCO_2$ at an average cost of $40 per metric ton.

In Washington, the potential area of mature forests where the riparian buffer zone could be widened by an additional 200 feet was estimated at 34,900 acres. The additional carbon that could be stored on these lands if the forests were conserved is 2.2 $MMTCO_2$ at an average cost of $33.30 per metric ton.

In California, the potential for additional carbon storage from lengthening timber harvest rotations by five years on about 300,000 acres could be 2.0 to 3.5 $MMTCO_2$ over a 20-year span, at a cost of less than $13.60 per metric ton. Widening the riparian buffer zone by 200 feet could sequester 3.91 $MMTCO_2$ at a cost between $2.70 and $13.60 per metric ton. This could occur on about 43,730 acres of forestland.[146]

In Arizona, where an arid environment and population growth make conservation of water resources especially important, WESTCARB studied the potential for afforestation of riparian areas with native species. Total acreage of these ecosystems is limited to about 4% of the state. The study cautioned that actual site selection for riparian afforestation would need to take into account all riparian functions such as preserving water quality, maintaining stream integrity, providing wildlife habitat, and controlling flood and storm water runoff.

Table 8 shows estimated carbon storage from afforestation of areas with high to very high geophysical potential. The study cautioned that actual site selection for riparian afforestation would need to take into account all riparian area functions such as preserving water quality, maintaining stream integrity, providing wildlife habitat, and controlling flood and storm water runoff.

Table 8. Potential for carbon accumulation in Arizona's prime riparian areas[147]

Native woody riparian vegetation	Acres with high to very high sequestration potential	Total carbon sequestration (million metric tons CO_2e)		
		20 years	40 years	80 years
Conifer/oak	63 thousand	3	4	4
Cottonwood/ Willow	1.6 million	75	93	97
Mesquite	1.6 million	76	94	98
Mixed broadleaf	1.5 million	69	85	90

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[146] Brown. *Carbon Supply from Changes in Management of Forest.*

[147] Petrova, S., T. Pearson, K. Goslee, and S. Brown. *Regional Characterization for the State of Arizona: Potential of Riparian Areas for Carbon Sequestration.* California Energy Commission, PIER Energy-Related Environmental Research. Draft report, 2009.

Testing Forest Conservation Management in California

WESTCARB's Bascom Pacific Conservation Forestry Project tested project conservation-based management in a commercially productive forestland in northern California in accordance with Version 2.1 of the Forest Project Protocol of the California Climate Action Registry (now the Climate Action Reserve).

Over the life of the project, 447,877 thousand board feet (MBF) of timber are harvested under the baseline activity scenario, whereas 417,563 MBF are harvested under the project activity scenario. Although the baseline scenario exhibits an average harvest rate of about 4,475 MBF per year, as much as 7,413 MBF per year are harvested per year during the initial clearcut phase and up to 14,820 MBF per year in the second clearcut phase, but only between about 1,000 and 3,000 MBF per year during intermediate thinnings, and no harvest during fallow years.

The wood products carbon pool reflects these changes by accumulating rapidly during clearcutting phases, and more slowly during intermediate thinning phases. In periods with no harvesting, decay of existing wood products leads to a slight decrease in the overall stocks in the pool.

Combining the wood products pool with the standing live tree, standing dead tree, and lying dead wood pools increases the amount of carbon stored under both the baseline activity and project activity scenarios (Figure 20). When the baseline values are averaged over the project lifetime, inclusion of wood products increases the baseline average by 179,000 tons of CO_2. Incorporating wood products also increases the cumulative emissions reductions at the end of the project lifetime by 132,000 tons of CO_2. However, cumulative emissions reductions, including wood products, remains lower than emissions reductions without wood products until 2066, at which point emissions reductions including wood products is greater through the remainder of the project lifetime.

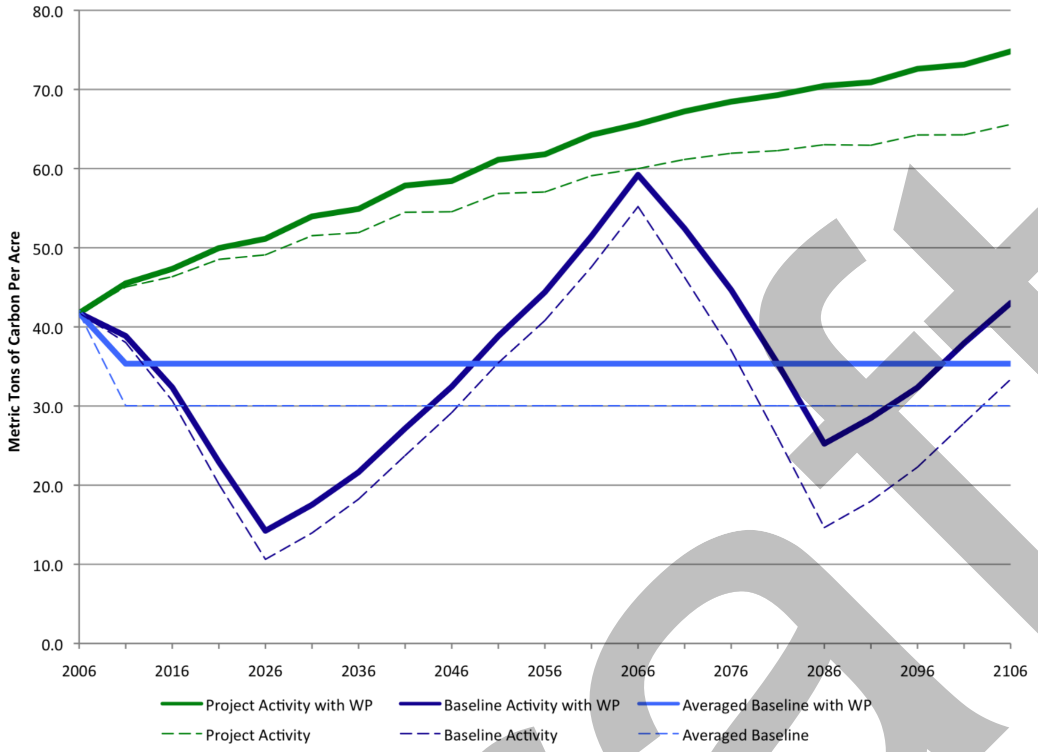

Figure 20. Baseline and project activity carbon stocks, both with and without wood products pool stocks, over the 100-year project lifetime on a per acre basis[148]

[The averaged baseline activity value is also shown. All scenarios have the same initial carbon stocks at the project start date in 2006. The averaged baseline curve begins at this same starting value, but achieves the average value by the end of the first 5-year reporting period by being reduced annually in equal increments.]

After conducting a pro forma analysis for a Bascom Pacific type project, researchers concluded that the potential financial returns from a forest conservation management project provide an incentive for landowner participation, while fostering long-term forest conservation and net gains from long-term reduction of CO_2 emissions.

The baseline inventory, when properly specified, can be cost-effectively undertaken concurrent with a conventional timber inventory, but does add expense, due to the generally higher statistical confidence required in sampling, and the inclusion of additional inventory elements such as dead biomass. Inventory costs vary with the size and heterogeneity of the property, not unlike timber inventories. Larger more homogenous properties will cost less to inventory than the mid-size, relatively diverse Bascom Pacific property.

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[148] Remucal J., C. Best, L.Wayburn, M. Fehrenbacher, and M. Passero. *Demonstration of Conservation-Based Forest Management to Sequester Carbon on the Bascom Pacific Forest.* California Energy Commission, PIER Energy-Related Environmental Research. Draft report, 2010.

Forest Fuels Reduction

Wildfire regimes differ by region and ecosystem due to differences in weather, topography, vegetation type and stand characteristics, which affect the timing, frequency, and behavior of fires. Plant communities may be well adapted to some fire regimes, but not to others. For example, species such as lodgepole, Coulter, knobcone, and Bishop pines have cones that release seed in response to heat and fires; thus the forest is adapted to moderate to high severity fires, even though fire kills individual trees. Ponderosa pine forests and oak woodlands, on the other hand, evolved with, and benefit from, frequent but relatively low intensity understory fires that remove competing vegetation without damaging trees. Seed dispersal is not dependent on fire, so high severity fires can result in extensive tree mortality.[149]

Most of the WESTCARB region experiences large wildfires. In Alaska alone, more acreage burns on average than in all of the other U.S. states combined. Although the amount of CO_2 emitted from wildfires in the United States is estimated to be equivalent to ~5% of anthropogenic emissions, a severe fire season can have a more significant impact on a state's GHG emissions, releasing as much CO_2 as the annual emissions from the entire transportation or energy sector.[150] Some researchers have suggested that wildfires may become more frequent with climate change, and that there is a significant potential for additional net release of carbon from the forests of North America in the coming decades.

A Washington study suggests that most ecosystems in the Pacific Northwest will likely experience an increase in area burned by the 2040s. In the U.S. Columbia Basin, average burn areas are projected to increase from about 425,000 acres annually (1916–2006) to 0.8 million acres in the 2020s, 1.0 million acres in the 2040s, and 2.0 million acres in the 2080s.[151]

In many western forests, the threat of wildfire has been exacerbated by fire suppression activities over the last 100 years. Whereas a fire return interval of every 15 to 20 years would result in low-intensity surface fires that curtail the accumulation of forest fuels, disruption of this fire pattern through suppression has resulted in the build-up of "ladder fuels" at intermediate heights, which can carry surface fires into the crowns of trees and lead to large, catastrophic fires. Such fires generally result in more tree deaths, followed in some cases by arrested succession, whereby a dominant understory species such as Manzanita prevents post-fire tree re-establishment.[152]

Evidence suggests that forest fuel treatments that thin crowded understory vegetation and remove dead biomass appear to have reduced the intensity, spread, or emissions from fires and/or slowed a fire's progress. To study the potential for forest fuels reduction treatments as a terrestrial carbon storage activity, WESTCARB conducted pilot projects in forests in Shasta County, California, and Lake County, Oregon.

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[149] *2009 California Climate Adaptation Strategy,* California Natural Resources Agency: http://resources.ca.gov/climate_adaptation/docs/Statewide_Adaptation_Strategy.pdf

[150] Wiedinmyer, Christine and Jason C. Neff. "Estimates of CO_2 from fires in the United States: implications for carbon management," *Carbon Balance and Management,* 2007, vol. 2-10.

[151] Littell, J.S., M. McGuire Elsner, L.C. Whitely Binder, and A.K. Snover (eds). *The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate,* Executive Summary, Climate Impacts Group, University of Washington, Seattle, Washington, 2009.

[152] *Best Practices for Terrestrial Sequestration of Carbon Dioxide*, NETL.

Net impact calculations for the projects were based on field measurements of carbon stocks before and after fuel treatments, fire modeling, fire risk assessment, growth modeling, and biomass and timber accounting. The study concluded that:

- Fuel treatments resulted in increased net carbon emissions for all projects
- Fuel treatments are unsuitable for generating GHG offsets on a project by project basis
- Biomass-generated electricity from removed forest fuels, which avoids carbon emissions from fossil fuels, did not compensate for the loss of carbon stored as standing timber[153,154]

Although the results of the WESTCARB fuels reduction pilots indicate that such projects are unlikely to function as a carbon offset category, the benefits of managing forest fuels go beyond emissions considerations. In many instances, removing forest fuels can decrease the severity and size of forest fires, and reduced fire severity in one area can lower damages and emissions in surrounding untreated areas. Fuel treatments can lead to increased timber production and reduced firefighting costs, and safeguard nearby communities from life and property loss.

Currently, CO_2 emissions from biomass from forest fuels reduction activities are considered neutral under some GHG emissions regimes, including California's cap and trade program, which specifies that there is no compliance obligation for emissions from wood and wood waste harvested for the purpose of forest fire fuel reduction or forest stand improvement.[155]

EPA, after initially including biomass plants under its December 2010 ruling to regulate GHG emissions from industrial facilities, announced on July 1, 2011**,** that it will defer permitting requirements for CO_2 from the biomass-fired and other biogenic sources plants for three years, pending further scientific research.[156] EPA's decision is being challenged in court by environmental groups that contend biomass energy could reduce carbon sinks by incentivizing deforestation and other harmful practices as forest are "mined' for energy. Some environmental groups also have concerns that the carbon footprint from biomass plants is not well established.

In Lake County, Oregon, forest fuels management has been incorporated into an overall strategy that combines restoration of the region's forests with new opportunities for rural economic development. Multiple public and private parties[157] developed a 20-year Interagency Biomass Supply Memorandum of Understanding, signed in November 2007, which established a framework for planning and implementing forest and rangeland restoration and fuels reduction projects. A contract with the U.S Forest Service

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[153] During Shasta County pilots, a significant portion of the removed fuels were hauled to a local biomass-fired power plant. The emissions from the combustion of these fuels were included in the fuel treatment emissions based on the assumption that the biomass was displacing natural gas, but with higher CO_2 emissions than natural gas.

[154] http://www.nature.com/nclimate/journal/v1/n8/full/nclimate1264.html

[155] Final Regulation Order, California Code of Regulations, Subchapter 10 Climate Change, Article 5, §95852.2. Emissions without a Compliance Obligation.

[156] "EPA to Defer GHG Permitting Requirements for Industries that Use Biomass," U.S. EPA News Release, January 12, 2011.

[157] Lake County Resources Initiative, Lake County, Town of Lakeview, City of Paisley, DG Energy LLC, DG Investors LLC, The Collins Companies, Oregon Department of Forestry, USDA Forest Service Fremont-Winema National Forest, and Bureau of Land Management, Lakeview District.

Pacific Northwest Region provides for a supply of material to support the Collins Companies' new small diameter sawmill (to better handle the smaller timber from restoration projects). A second project, Iberdrola Renewables' new 27 MW Lakeview biomass cogeneration plant, halted construction in October 2011, for lack of a long-term power purchase agreement.[158]

In California, a lawsuit by the Center for Biologic Diversity against the planned 18.5 MW Buena Vista Biomass Power Plant in Calaveras County was settled through mediation when the plant agreed to greater transparency in harvesting by providing feedstock information to an advisory committee, which will ensure the material is renewable and harvested from sustainably managed forest lands.[159]

The projects in Oregon and California suggest that the successful deployment of new biomass power plants in the western region can effectively be undertaken in conjunction with practices for sustainable forest management, including management of forest fuels, and that such projects will benefit from gaining buy-in from a wide range of stakeholders, including environmental and community groups.

Avoided Forestland Conversion

Conversion of agricultural lands, rangelands, forest lands, and wetlands (primarily to accommodate new housing and commercial growth) is a source of GHG emissions in many states, although these are not necessarily counted in GHG inventories. California, for example, saw a population increase of nearly 48% between 1984 and 2008, according to estimates by the state's Department of Finance. In the same timeframe, farm and grazing land decreased by more than 1.3 million acres, or about one square mile per day. Urbanization accounted for the vast majority of this loss, more than 1.04 million acres.[160] California's population is still increasing, albeit more slowly since the recession of 2008, with the continuing need for additional infrastructure. Avoided conversion could become an important strategy for retaining carbon stocks to help achieve the state's GHG emissions reduction goals.[161]

For Washington, urban growth near Seattle has been a source of GHG emissions and a matter of concern to the state legislature and Washington Department of Natural Resources. The risk of conversion is especially high in Puget Sound's watersheds. From 1987–1997, an estimated 246,000 acres were deforested for urban development across the state. Forty-two percent of this area was in in three counties near Seattle, an area that represents just 8% of the state. Estimated net emissions across the three counties were over 6 $MMTCO_2e$/yr, or 45% of the total from development across the whole state.

WESTCARB researchers conducted a study of the residential development being implemented in the Puget Sound region to estimate the emissions associated with conversion of forested lands. Full accounting of emissions from development must include both the emissions from clearing the forest and the sequestration that occurs after development from carbon stock recovery.

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[158] Williams, Christina. "Construction Halted on Lakeview Biomass Plant," Sustainable Business Oregon, October 13, 2011: http://www.sustainablebusinessoregon.com/articles/2011/10/construction-halted-on-lakeview.html

[159] Gibson, Lisa. "Buena Vista Biomass Power project proceeds," *Biomass Power & Thermal Magazine,* June 13, 2011.

[160] http://www.conservation.ca.gov/dlrp/fmmp/trends/Pages/FastFacts.aspx

[161] Avoided conversion projects for forests are a compliance offset option under California's cap and trade program.

The study found a range of net emissions from 65 to 1,285 metric tons CO_2e per development. However, a few subdivisions showed net sequestration, ranging from 7 to 305 metric tons CO_2e. Net sequestration can result when the emissions from forest clearance are low due either to low initial forest cover or to high forest cover retention.

Forest cover cleared during development varied from 57–100% in areas of less than 16 acres, but averaged just 35% for development areas that exceeded 16 acres. This relationship could form the basis of a future performance standard for development projects such that if a developer exceeded the defined area of forest retained by 10% or more, the carbon stocks of the retained forest would be creditable.

An offset project that merely halts development in a forested area would be subject to leakage risk. It is possible that as many or more emissions would result at the alternative site or sites to which the development was displaced. Instead, net emission reductions can result where development is altered without changing the number or category of developed properties. Ultimately the area of forest retained within the full boundary of the development must be increased relative to the proportion that would remain under business-as-usual.

The study observed that it could be possible to mitigate emissions from forest conversion while avoiding leakage through “cluster development,” which allows for the preservation of open space while continuing to provide the same number of lots for residential development. This can be accomplished through density incentives that are applied to reduce the minimum allowable lot size. For example, developers could receive incentives for maintaining a minimum proportion of a development site in open space. County governments could also mitigate emissions from development by directing development away from lands with forest cover to lands with less vegetation. For avoided conversion projects qualifying for offsets under the Climate Action Reserves’ Forest Protocol or California’s cap and trade program, preservation of forest land is achieved through a conservation easement or transfer to public ownership.

Forests in Climate Change Policy Development

The California Air Resources Board’s 2020 Scoping Plan for the Global Solutions Act of 2006 (AB32) calls for maintenance of the current level of 5 $MMTCO_2$e[162] of sequestration in the state’s forests through sustainable management practices, potentially including reducing the risk of catastrophic wildfire and the avoidance or mitigation of land-use changes that reduce carbon storage. The scoping plan notes that California’s forests are expected to play an even greater role in achieving the 2050 GHG emissions reduction targets because trees planted in the near-term will generally maximize their sequestration capacity in 20 to 50 years.[163]

California’s Natural Resources Agency amended the California Environmental Quality Act (CEQA) guidelines, effective March 2010, to include analysis of GHG emissions. A new item in the sample environmental checklist of suggested CEQA thresholds is the assessment of loss of forest land or

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[162] The 5 $MMTCO_2$e emission reduction target is equal to the magnitude of the current estimate of net emissions from California’s forest sector. The target can be recalibrated to reflect new information.

[163] *Climate Change Scoping Plan: A Framework for Change*, California State Air Resources Board, December 2008.

conversion of forest land to non-forest use.[164] This new requirement has triggered the purchase of carbon offsets by some developers, as well as by industrial facility operators with expansion plans.[165]

British Columbia passed the Zero Net Deforestation (ZND) Act on May 6, 2010, setting forth the goal of achieving ZND by 2015 on all lands in the province including First Nations, federal, and private lands. A draft Proposed Implementation Plan was issued in December 2010. In 2007, approximately 6,200 hectares were deforested in BC while 2,000 hectares were afforested. Net GHG emissions attributable to this forest loss accounted for 4.6% of the Province's emissions, about 3.1 MMTCO$_2$e.[166]

British Columbia has also developed protocols to guide the design, development, quantification, and verification of B.C forest carbon offsets from a broad range of forest activities on private and public land within the Province.[167]

Reducing GHG Emissions in the Agricultural Sector

Significant opportunities for decreasing the GHG emissions associated with agricultural activities are found with non-CO$_2$ greenhouse gases. Methane (CH$_4$) emissions, which have approximately 21 times the global warming potential of CO$_2$, come primarily from the enteric fermentation of livestock and from manure. Protocols to capture and destroy methane gas from manure treatment and/or storage facilities on livestock operations are available under several GHG emissions registries and are included as an offset option under California's cap and trade program. In California, methane emissions from manure management were 6.0 MMTCO$_2$e in 2004.[168]

A much smaller methane source in the WESTCARB region is emissions from flooded rice fields. The flooding results in anaerobic conditions in soils, triggering decomposition of organic matter by methanogens, a class of soil bacteria that produce methane during microbial decomposition. In California, methane emissions from flooded rice fields were 0.6 MMTCO$_2$e in 2004.[169] Recently adopted protocols or methodologies for GHG emissions reductions from rice cultivation are available at the Climate Action Reserve[170] and the American Carbon Registry.[171] Methods include reducing the duration and frequency of winter flooding, removal of rice straw from the field after harvest and before winter flooding, and replacing water seeding with dry seeding. As with many land/water use practices, other factors beyond GHG impacts warrant consideration. In the case of rice field management, bird habitat and water quality are also important issues.

Nitrous oxide (N$_2$O) emissions, which have approximately 300 times the global warming potential of CO$_2$, represent a substantial source of GHG emissions from agricultural production, primarily due to

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[164] 2011 CEQA Statutes and Guidelines: http://www.ceres.ca.gov/ceqa/

[165] Per Josh Margolis of CantorCO$_2$e at the California Offsets Workshop, San Francisco, CA, August 8, 2011.

[166] *British Columbia Greenhouse Gas Inventory Report 2008*, Ministry of Environment, Victoria, B.C., September 2010.

[167] *Protocol for the Creation of Forest Carbon Offsets in British Columbia, Version 1.0: http://www.env.gov.bc.ca/cas/mitigation/pdfs/Forest_Carbon_Offset_Protocol_v1_0_Web.pdf*

[168] *Inventory of California Greenhouse Gas Emissions and Sink: 1990 to 2004*, Staff Final Report, California Energy Commission, December 2006, CEC-600-2006-013-SF.

[169] Ibid.

[170] http://www.climateactionreserve.org/how/protocols/agriculture/rice-cultivation/

[171] http://www.americancarbonregistry.org/carbon-accounting/emission-reductions-in-rice-management-systems

fertilizer application. The California Energy Commission reported N_2O emissions from the state's soil management to be about 19 $MMTCO_2e$ in 2004.[172] In November 2010, the American Carbon Registry issued a GHG offset methodology to quantify agriculture sector emissions reductions through changes in fertilizer management. The methodology allows for quantification of direct N_2O emissions as well as indirect emissions from leaching and ammonia volatilization. The approach is applicable not only to changes in fertilizer quantity (rate), but also fertilizer type, placement, timing, use of timed-release fertilizers, use of nitrification inhibitors and other practice changes. Aggregation is permitted, enabling farmers to participate in groupings of multiple farms, which lowers transactions costs, improves modeling results, and diversifies risk.[173]

Another source of agricultural CO_2 emissions is from land clearing, draining, sod breaking, cultivating, and over-fertilization, all of which have served to reduce the store of carbon in soils. Through improved or alternative management practices, many agricultural lands have the potential to become a significant carbon sinks relative to current levels. Among the practices that can improve the carbon balance in soils is conservation tillage (CT), a term that represents reduced-tillage field practices for crop production that are designed to minimize soil erosion and enhance soil tilth. As opposed to conventional tillage, which buries and mixes crop residue into the soil to prepare a seedbed for crop planting, CT systems plant directly into crop residues (no-till, or direct seeding) or only till part of the soil area (strip-till).

In California, based on carbon sequestration rates of 0.35–0.61 metric ton per hectare per year, it is estimated that agricultural land could store up to 3.9 $MMTCO_2$ /year through CT. The cost to sequester this amount of carbon in California has not been calculated, however, data from other regions of the United States suggest costs will be relatively low. The most likely crops for which CT will be adopted are tomatoes, cotton, beans, and corn, which represent a large area of California agricultural land.[174]

A study of Yolo County, California,[175] found that by adopting CT practices at carbon payments of $3 to $8 per ton per year, Yolo County could sequester as much as 33,000 to 39,000 tons of carbon, approximately 3% of the county's total carbon release. The study noted that relatively low carbon payments would likely induce the adoption of sequestering technologies by farmers. It further noted that while the carbon reduction from this single sequestration practice is relatively small, other ecosystem benefits such as reduced water runoff and dust (with associated pollution) could also be realized.

For some Yolo County's crops, however, tillage reduction presents production constraints, such as seed establishment or efficient movement of irrigation water. Also, alternative tillage practices can increase nitrous oxide emissions due to higher moisture content and increased activity of anaerobic microorganisms.[176]

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[172] *Inventory of California Greenhouse Gas Emissions and Sinks: 1990 to 2004.*

[173] American Carbon Registry (2010), *American Carbon Registry Methodology for N_2O Emission Reductions through Changes in Fertilizer Management.* Winrock International, Little Rock, Arkansas.

[174] Brown. *Carbon Supply from Changes in Management of Forest, Range, and Agricultural Lands of California.*

[175] Howitt, R.E. et al. (2009). "Realistic payments could encourage farmers to adopt practices that sequester carbon," *California Agriculture:* Vol. 63: No. 2, Page 91.

[176] Jackson, L.E. *Potential for Adaptation to Climate Change in an Agricultural Landscape in the Central Valley of California,* California Climate Change Center, August 2009, CEC-500-2009-044-F.

One challenge faced in CT is weed control, which is frequently cited as a reason for failure of CT systems and also for limited adoption by organic growers, who rely on conventional tillage to eradicate weeds and incorporate cover crops and compost. However, CT and organic farming need not be mutually exclusive, and the use of cover crops, mulching, and other techniques for non-chemical weed control is gaining recognition. Alternatively, a concern has been expressed that soil carbon storage projects using conservation tillage could be conducted with genetically modified crops grown in conjunction with chemical eradication of weeds.

Conservation tillage has been most widely adopted for agronomic crop production. The overall potential for carbon storage through CT in the WESTCARB states may be curtailed by crop types, which are more heavily weighted toward higher value vegetable and specialty crops. Most vegetable growers continue to use intensive tillage for seedbed preparation.

A major consideration with systems to increase soil carbon is the need to maintain crop yields. A study that tested the transition to CT practices for cotton and tomato crops in the San Joaquin Valley of California[177] found that tomato harvest yields were increased by CT, while cotton harvest yields were decreased. During the four years of the study, tractor trips across the fields were reduced by about 50% for tomatoes and 40% for cotton in the CT systems relative to standard tillage, and dust was also reduced.

Wetlands as Carbon Sinks

The loss of coastal wetlands and marine ecosystems such as peat lands, forested tidal wetlands, tidal freshwater wetlands, and salt marshes leads to decreased carbon storage and can contribute to CO_2 emissions. In contrast to terrestrial forests, wetlands store most of the carbon below ground in an organic soil layer, which can run several feet deep.

Although some researchers contend that wetlands are more efficient than forests at carbon storage on a per acre basis, an overall accounting of GHGs needs to factor in methane and N_2O emissions from these ecosystems. In breaking down plant matter, microbes in wetlands release methane, which partly counteracts the positive climatic effects of CO_2 storage. The extent to which this happens varies from site to site, but is found to be more significant in freshwater wetlands. Methane release in tidal salt marshes is deemed negligible.

At a 14-acre pilot project on Twitchell Island in the western Sacramento-San Joaquin River Delta of California served to test “carbon farming” in conjunction with reducing land subsidence and protecting levees. Twitchell Island is about 15 feet below sea level. Researchers flooded the land shallowly and planted clumps of tules and cattails. As the plants matured, researchers raised the water level. After ten years, this experiment built two feet of peat soils, an accrual of 10 metric tons of carbon per hectare per year.[178]

This type of project could significantly reduce the risk of levee failure and the cost of levee maintenance, while providing greater security to water supplies. However, the potential for such projects to furnish

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[177] Mitchell, Jeffrey P. et al. (2008), “Transition to conservation tillage evaluated in San Joaquin Valley cotton and tomato rotations,” *California Agriculture*, Vol. 62: No. 2, Page 74.

[178] http://soilcarboncoalition.org/twitchell

carbon offsets has yet to be determined. Preliminary measurements of methane during the Twitchell project varied widely, and N_2O was not measured. Further research is needed to establish the overall GHG balance in wetlands restoration projects.

Co-benefits from sustainable management of coastal wetlands and marine ecosystems can include shoreline protection, water quality maintenance, flood control, habitat for birds and other wildlife, harvestable resources such as fish, as well as opportunities for recreation. Maintenance and restoration of coastal wetlands could factor in mitigating the impact of sea level rise. Coastal wetlands can attenuate wave energy and provide enhanced protection against increasingly frequent storms and rising sea levels.

Project Financing and Support Mechanisms

Although terrestrial carbon storage projects can provide a relatively inexpensive way of reducing atmospheric CO_2, they can also entail high transaction costs that reduce their competitive advantage. Costs can be expected to accrue most heavily during the early phases, which can entail feasibility studies, insurance, baseline assessments, project registration, and implementation of land change practices (i.e., thinning, planting, weed control). Analyses of transaction costs found a range between $0.50–$4.50 metric ton/carbon for forestry projects sequestering between 10,000,000 and 10,000 metric tons of carbon, respectively. Economies of scale play a large role in transaction costs, which rise steeply for projects storing less than 100,000 metric tons of carbon.[179]

Transaction costs and methodological requirements vary according to the standards used. In some instances, a small project may be able to recover transaction costs under standards that are less stringent; however, the market of potential buyers and funders will also shift and most likely shrink significantly.[180]

Funding for terrestrial carbon storage projects can come from a variety of sources including publicly traded funds, conservation non-profits, foundations, private equity, commercial banks, governments, companies, and development finance institutions. Since the advent of carbon markets, funds specifically targeted at investments in offset credits have been formed. Project developers and offset retailers will typically fund a carbon offset project and forward sell the promised credits. This mechanism generates funds to start new offset projects, although future offsets are generally worth less than existing offsets because of the risk of non-delivery. Most project developers/funders seek to place their investments in larger projects where economies of scale can improve the rate of return.

Reducing Project Costs Through Aggregation

Aggregation can facilitate participation in carbon markets for small landowners. By pooling credits from multiple projects, an aggregator is able to offer blocks of credits in a carbon market. This reduces transaction and monitoring and verification costs for project owners through economies of scale, as well as reducing transactions costs for purchasers, who can buy more credits through fewer transactions.

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[179] Miller, Cheryl and Dean Current. *Terrestrial Carbon Sequestration: A Survey of Policies and Programs* University of Minnesota, 2006.

[180] Olander, Jacob and Johannes Ebeling. “Building Forest Carbon Projects: Step-by-Step Overview and Guide,” *Building Forest Carbon Projects*, Johannes Ebeling and Jacob Olander (eds.). Washington, D.C.: Forest Trends, 2011.

Aggregators can also play a role in developing carbon markets by providing information to landowners on how they can participate in a carbon market.

The now-closed Chicago Climate Exchange (CCX) required landowners to work through an aggregator if their project sequestered less than 12,500 metric tons of carbon per year. The National Farmers Union defined its role as an aggregator to include:

- Arrange for third-party verification
- Register individual acreages into blocks
- Maintain a database of credits
- Send annual certifications to CCX and provide other data as needed
- Manage sales of blocks of credits
- Distribute sale proceeds to participants

The Farmers Union collected a 10% service fee from annual sale proceeds to cover administrative expenses associated with these activities.

The Climate Action Reserve's approach to aggregation in Version 3.2 of the Forest Project Protocol stipulates that only projects of less than 5,000 acres may enroll in an aggregate.[181] The Reserve's policy allows for fewer sample plots per project to generate a forest carbon inventory on the grounds that greater statistical uncertainty per individual project will be compensated through aggregation with other projects. Each project in an aggregate also requires less frequent verification than is required for standalone projects. Forest owners still register individually with the Reserve and maintain a separate account, and liability for reversals lies with each individual owner. The Reserve requires that aggregators be responsible for selecting a verifier, coordinating verification schedules, and maintaining a Reserve account to receive credits transferred from the accounts of participating forest owners and from which credits must be transacted. Other services that may be provided by an aggregator, such as project development, are subject to negotiation between forest owners and the aggregator.

Under California's cap and trade program, CARB did not include project aggregation in the Offset Protocol for U.S. Forest Projects, reasoning that the aggregation rules were a recent addition to CAR's protocol on which the California protocol is based, and that further work is needed to ensure compatibility within the compliance offset program.[182]

Funding Terrestrial Carbon Storage Through Allowance Auctions

Auctioning of GHG allowances creates revenues that can be expected to grow under programs that scale back the number of free allowances in later years, provided the price of carbon is not undermined. Most

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[181] *Guidelines for Aggregating Forest Projects*, Climate Action Reserve, Version 1.0, August 31, 2010.

[182] *Proposed Regulation to Implement the California Cap-and-Trade Program, Part V, Staff Report and Compliance Offset Protocol for U.S. Forest Projects,* California Environmental Protection Agency Air Resources Board, October 28, 2010.

climate change regimes allocate a portion of their allowance revenues to financing technologies and programs to reduce GHG emissions. This mechanism could be used to fund terrestrial carbon storage, and may be especially suited for projects on public lands.

The Climate Trust Funding Model

In 1997 with the passage of HB 3283, the Oregon legislature created the Oregon Carbon Standard for baseload gas power plants, non-baseload power plants, and non-generating energy facilities that emit CO_2. These entities must reduce their net CO_2 emissions 17% below the most efficient baseload gas plant in the United States. Excess CO_2 emissions beyond what can be reduced through power plant design or cogeneration may be addressed through offsets. Facilities may implement CO_2 offset projects either directly or through a third party, subject to approval by the state's Energy Facility Siting Council (EFSC). Alternatively, they may provide funds (corresponding to their CO_2 emissions at a rate determined by the EFSC) to The Climate Trust, a non-profit organization established to implement projects that reduce or sequester CO_2 emissions.

Over the history of the Oregon Standard, the overwhelming majority of facilities have chosen to offset their emissions via The Climate Trust. Every two years, EFSC may adjust the offset rate by 50%. The last rate change was in May 2007, when EFSC enacted a full 50% increase, which resulted in an offset price of $1.27 per short ton (about $1.40 per metric ton).

As of year-end 2009, The Climate Trust had 18 projects listed for a projected 2,654,855 metric tons $CO_{2.}$[183] Three forestry projects—one in Oregon, one in Washington, and one in Ecuador—account for 555,382 metric tons CO_2. In June 2011, with the passage of HB 3538, Oregon expanded the scope of offsets to allow projects for non-CO_2 GHGs to be included in compliance options.

Terrestrial Carbon Storage Projects in Carbon Markets

The shaping of terrestrial carbon storage as a GHG mitigation strategy is predominantly determined by the policies that define participation in carbon markets. For example, the inclusion of Reducing Emissions from Deforestation and Forest Degradation (REDD and REDD+) in the post-2012 United Nations Framework Convention on Climate Change process is expected to provide an incentive for undertaking forest carbon storage projects, provided the a post-2012 agreement is reached. California's inclusion an offset protocol for U.S. Forests under the state's cap and trade program is also expected to act as a driver for forest carbon projects.

Thus far, participation in the primary CDM market by forestry projects appears to have been hampered by the risk management mechanism of issuing credits that have to be replaced upon expiration, and which therefore command lower prices than credits from other offset activities. The EU-ETS, the world's biggest carbon market, does not accept these temporary credits, which presents a further barrier. Other limiting factors under CDM are the lengthy process of obtaining project approval, due primarily to the use of non-standardized protocols that require a more extensive project review, and the restriction of reforestation projects to lands that were not forested on December 31, 1989.

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[183] *The Climate Trust 2009 Annual Report:* http://www.climatetrust.org/documents/CT_FINAL_web.pdf

Criteria for Qualifying Offsets

The quality of offsets—the degree to which they represent GHG emissions reductions or avoidances that are real, additional, quantifiable, permanent, verifiable, and enforceable—is based on the stringency of the protocols or standards under which they enter the market. Offsets that are verified under more exacting standards can command higher prices because buyers have faith in their value. "Higher-priced standards (>$8/tCO2e) are primarily focused on pure voluntary buyers, especially those who pay premiums for the co-benefits associated with the Gold Standard and SOCIALCARBON certification."[184] However, the requirements for meeting higher standards can be prohibitive for smaller projects.

Designing offset standards requires balancing different policy goals. If standards are too strict or narrow, good offset projects can be excluded and overall compliance costs can increase. However, if standards are too lenient, they are less likely to result in real GHG reductions and can undermine the integrity of a carbon regime.

Many standards are still evolving through a process of stakeholder input, testing, and refinement, and new protocols for different types of projects are being developed. In 2010, the Verified Carbon Standard[185] (VCS) accounted for over half the transactions for forest carbon in the voluntary market and was the dominant standard for projects in developing countries.[186] Ninety-five percent of the VCS transactions were also certified under the Climate, Community & Biodiversity Alliance (CCBA) Standards, one of the most prominent standards for ensuring social and biodiversity co-benefits. The widespread use of CCBA certification suggests that this standard offers a market access premium (if not a price premium as well), particularly for projects also seeking VCS certification.[187]

Additionality

A project must result in GHG emission reductions that are above and beyond what would occur under a "business as usual" scenario, including any GHG reductions or removals that would occur through compliance with laws or regulations or that would occur because the activity is economically viable without income earned from offsets credits.

Concerns have been raised about the difficulty in determining additionality, and critics charge that some offset projects would have been undertaken on the basis of their own merits without the existence of a carbon market. According to one organization with experience monitoring the development of the Kyoto Protocol's CDM offset program, "project developers have strong incentives to make claims on additionality and baselines that are skewed in their own favor. Meanwhile regulators and third-party certifiers have strong incentives to give developers' claims the benefit of the doubt for a number of reasons, including that they are under financial and/or political pressure for the system to "work" and therefore generate large amounts of offsets."[188]

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[184] Peters-Stanley, M. et al. *Back to the Future: State of the Voluntary Carbon Markets 2011*, Ecosystem Marketplace and Bloomberg New Energy Finance, June 2, 2011.

[185] Formerly the Voluntary Carbon Standard.

[186] Olander. "Building Forest Carbon Projects."

[187] Ibid.

[188] "Quality Criteria for Offsets Under AB32: Comments by International Rivers," 21 May 2009, to the California Air Resources Board: http://www.arb.ca.gov/cc/capandtrade/meetings/042809am/apr281pcintlriver.pdf

Within existing carbon offset programs, there are two basic approaches to determining additionality: project-specific and standardized.[189]

1. *Project-specific* approaches seek to assess whether a project differs from a hypothetical baseline scenario in which there is no carbon offset market. Generally, a project and its possible alternatives are subjected to a comparative analysis of their implementation barriers and/or expected benefits (e.g., financial returns). If an option other than the project itself is identified as the most likely alternative for the business as usual (or baseline) scenario, the project is considered additional. A project-specific approach has the capability to allow unique projects to qualify for carbon credits, however, the time needed to evaluate and register each project can be substantial.

2. *Standardized* approaches evaluate projects against a consistent set of criteria on a sector-wide basis. Standardized tests can involve determinations that a project:

    - Is not mandated by law
    - Exceeds common practice
    - Is not a least-cost option (as defined by regulators)
    - Involves a particular type of high-performing technology
    - Has an emission rate lower than most others in its class (e.g., relative to a performance standard)

From a regulatory perspective, standardized methodologies are advantageous because they avoid subjective evaluations at the project level and are easier to administer than project-specific standards. Additionally, they can reduce transaction costs and shorten registration periods for project developers, alleviate uncertainties for investors, and increase the transparency and consistency of regulatory decisions.

According to CAR, developing standardized methods requires significant research and analysis to establish credible benchmarks and emission factors that can be applied to similar projects throughout an entire industry or sector. Furthermore, because business-as-usual activities can vary significantly across different geographic areas, standardized benchmarks and factors for one region will not necessarily be appropriate for other regions. CAR's standardized protocols generally apply to a limited geographic area.

Permanence – Guarding Against Reversals

Permanence is an issue for terrestrial storage projects because their effects can be reversed over time. A reversal occurs when the stored carbon associated with a project is released to the atmosphere. A distinction is made between reversals that result from human activities and are considered avoidable—such as land conversion, over-harvesting, or harm due to negligence—and unavoidable reversals such as those caused by fire, pest infestation, or disease.

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[189] Broekhoff, D. and K. Zyla. "Outside the Cap: Opportunities and Limitations of Greenhouse Gas Offsets," *Climate and Energy Policy Series*, World Resources Institute, December 2008.

Buffer pools of credits from projects are a common mechanism for insuring against unavoidable reversals. A risk analysis and rating is used to determine the number of credits each project is required to contribute to the buffer pool account, which then covers all at-risk projects in the registry or program. In the event of an unavoidable reversal, credits from the buffer pool must be retired in the amount equal to the carbon that was lost. Projects are terminated when a reversal reduces carbon stocks below baseline levels. Contributions to the buffer pool are adjusted over time to reflect updated risk ratings, which are conducted as part of project verification.

In the event of an avoidable reversal, project owners must surrender offsets or compliance instruments out of their own accounts to cover the amount of the reversal. CAR's protocol stipulates that forest credits must be replaced with other forest offset credits to recognize the co-benefits of forest projects and the preferences of offset buyers in the voluntary market to ensure their investments remain in forest projects.

Under the California cap and trade program, intentional reversals can be compensated for with any CARB-issued or approved allowances or offset credits. This allows for fungibility across all compliance instruments in the program, and guards against a potential shortfall in forest offset credits in the case of a large intentional reversal. Unintentional reversals are insured against by contributing a percentage of CARB-issued offset credits to a forest buffer account.

Another approach to guarding against impermanence is to issue temporary or expiring credits. Credits for reversible reductions can be made to expire at a predefined date, or canceled if verification indicates that a reversal has occurred. In both cases, the holder of the credits (rather than the project developer) must procure replacement credits or allowances in order to remain in compliance with the cap-and-trade system. This approach has been adopted by the CDM for afforestation/reforestation (A/R) projects,[190] and has resulted in a lower credit price for forest carbon than for other CDM sectors, placing A/R projects at a disadvantage.[191]

Impermanence could also be addressed by issuing credits on a "discounted" basis. With this approach, less than a full credit is awarded for each ton of GHG reduction. The amount of the discount would be based on a risk assessment of expected future losses of sequestered carbon over a certain time period. Discounting has been proposed as a means of managing other risks and uncertainties pertaining to offset credit issuance, such as additionality. Currently, some CDM and CAR protocols use discounting to account for uncertainty in measurement methods.[192]

Widespread use of discounting could have adverse effects on the efficiency and integrity of carbon markets by reducing the emissions-equivalent value of offsets and the revenue flowing to offset projects. In turn, this could lead to a decrease in the supply of offsets.[193]

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[190] Ibid.
[191] *BioCarbon Fund Experience: Insights from Afforestation and Reforestation Clean Development Mechanisms Projects – Summary,* World Bank Carbon Finance Unit, Washington, D.C., 2011.
[192] Kollmuss, Anja, Michael Lazarus, and Gordon Smith. *Discounting Offsets: Issues and Options,* Stockholm Environment Institute Working Paper WP-US-1005, July 2010.
[193] Ibid.

Leakage

Leakage is an increase in GHG emissions or decrease in sequestration outside the project boundaries that occurs as a result of project activities. Leakage can lessen or nullify gains from an offset project, as when a forest conservation project shifts logging activities to other forest land. Under some protocols/standards, project developers are required to assess and mitigate certain types of leakage and even deduct leakage that "significantly reduces the GHG emissions reduction and/or removal benefit of a project."[194]

Enforceability

Carbon offsets should be backed by regulations and tracking systems that define their creation and ownership and provide for transparency. Clear definitions of ownership are essential for enforceability and to avoid double counting. For example, a forest owner and a mill owner might both want to claim the emissions sequestered in forest products—as might the owners of the products themselves. Regulatory rules must establish who may claim the emission reductions, who is ultimately responsible for ensuring project performance, who is responsible for project verification, and who is liable in the case of reversals.[195]

Voluntary Carbon Markets

The voluntary market is not part of any compliance or regulatory system, and almost all the carbon credits offered in this market originate from project-based transactions. Historically, 73% of forestry offsets transactions have occurred in the voluntary carbon market.[196] Buyer motivations include the desire to offset their GHG emissions, an interest in innovative philanthropy, public relations benefits, anticipation of GHG regulation, and plans to re-sell credits for a profit.

In 2010, suppliers reported a total volume of 131 MMTCO$_2$e transacted in the global voluntary carbon markets, as compared to the 98 MMTCO$_2$e transacted in 2009, a growth of 34%. The volume of carbon credits transacted voluntarily in 2010 represents less than a 0.1% share of the global carbon markets.[197]

This relatively small volume is nonetheless of critical importance because the voluntary market has served as an incubator of innovative protocols, registries, alliances, and project types, which inform the development of regulatory carbon markets.[198] This can be seen in California's adaptation of some of CAR's offset protocols for its cap and trade program.

Terrestrial Carbon Sequestration Under the California Cap and Trade Program

California's cap and trade program requires reductions of approximately 273 MMTCO$_2$e through 2020 as compared to business as usual, representing a reduction in emissions to 15% below 2012 levels. The

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[194] *The American Carbon Registry Standard, Version 2.1,* October 2010: http://www.americancarbonregistry.org/carbon-accounting/ACR%20Standard%20v2.1%20Oct%202010.pdf

[195] Broekhoff. "Outside the Cap."

[196] Hamilton, K. et al. *State of the Forest Carbon Markets 2009: Taking Root and Branching Out,* Ecosystem Marketplace, January 14, 2010.

[197] Peters-Stanley. *Back to the Future.*

[198] Hamilton, K. et al. *Building Bridges: State of the Voluntary Carbon Markets 2010,* Ecosystem Marketplace and Bloomberg New Energy Finance, June 14, 2010.

program, which allows regulated businesses to meet up to 8% of their compliance obligation with offsets, stands to become a significant driver for forest carbon storage in the WESTCARB region and elsewhere. According to one analysis, regulated businesses are expected to make full use of offsets as one of the least-cost emissions reduction opportunities available. Estimates of offset demand range from approximately 214–232 $MMTCO_2e$ through 2020. As of December 2010, current offset supply eligible for use in the California market is approximately 8.3 $MMTCO_2e$.[199]

At present, there are four offset project types that are eligible in the California market: domestic forestry, urban forestry, livestock (manure/methane) management, and the destruction of ozone depleting substances. It is expected that the market will likely rely extensively on forest carbon offset supply.

California's offset protocols were adapted from CAR protocols. CARB staff modified the protocol to include a crediting period of 25 years for forest projects, without any explicit limitation on the number of potential renewals. Monitoring, verification, and replacement of all carbon lost through reversals is required for 100 years following the last issuance of any offset credits, consistent with the CAR's current protocol.

Projects are required to move to the latest version of CARB's protocol at the end of the crediting period as a condition of renewal. This ensures that all projects use the latest factors, and reduces the number of versions of the protocol that could potentially be in use after a period of time to assist with project verification. For example, Forest Buffer Account contribution factors, and emissions leakage factors will likely be updated in the future as better information becomes available. Transitioning projects to the most recent approved protocol will help ensure that offset credits in CARB's program are quantified using the best available science, and reduce the administrative burden of having projects operating under many different versions of the Forest Offset Protocol as it is updated over the years.

California will "grandfather" 2005-2014 vintage offsets issued under the voluntary CAR protocols for projects registered with CAR before January 1, 2012. After that date, all offset projects must be developed according to protocols adopted by CARB. California is also developing a pathway for the admission of offset credits from sector-wide emissions reductions in developing countries, beginning with Reduced Emissions from Deforestation and Degradation (REDD). California entered into a memorandum of understanding with the states of Acre, Brazil, and Chiapas, Mexico, to establish subnational REDD programs to supply credits to the California cap-and-trade market. CARB envisions a fully developed REDD market in operation by 2015 that will include activities both at the project and state level, involving government-led and private sector investment.[200] Final rules for REDD interface have yet to be worked out, however it is anticipated that within the 8% limit on offsets, REDD credits will be restricted to 25%/50%/50% for 1st/2nd/3rd compliance periods, respectively, which would translate in to a maximum of 105 $MMTCO_2$ from 2012 to 2020.[201]

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[199] Shillinglaw, Brian, MaryKate Hanlon, and Marisa Meizlish. "The California Carbon Market: Implications for Forest Carbon Offset Investment," *NewForests Market Outlook,* December 2010.

[200] Ibid.

[201] Ibid.

Expanding the Role of Terrestrial Storage Projects

Opportunities for terrestrial carbon storage increase as carbon markets develop and link and as protocols for more types of projects are developed and adopted. The scope of terrestrial carbon storage under the California cap and trade could be increased beyond current parameters by extending the program to cover additional project types (CARB intends to evaluate more protocols in the future). Allowing aggregation could prove beneficial in encouraging participation by smaller landowners. A further inclusion, which could be forthcoming after further review by CARB, would be to allow for projects on federal lands.

Increasing the limit on offsets that may be purchased by regulated sources would increase the demand for offsets and lead to more terrestrial carbon storage projects, as well as other offset-generating activities, but would disincentivize emissions cuts from the regulated sector.

Balancing Terrestrial Carbon Storage with Other Land Uses and Values

Terrestrial carbon storage can add a further interest to an already complex patchwork of land uses and cultural values. Under favorable circumstances, projects have the potential to complement a range of existing activities. Examples include:

- Preserving greenbelts in housing and commercial developments
- Providing an additional revenue stream for farmers, ranchers, and forest owners
- Improving wildlife habitat and recreational activities
- Creating jobs in biomass energy and sustainable forestry and wood products

However, measures are needed to ensure that carbon storage is not pursued to the detriment of the environment or local communities. This has been a matter of particular concern for projects in developing countries. Although some environmental NGOs are involved in international forest carbon projects, others have pointed out the risks of conducting projects in situations where tenure and property rights are weak or uncertain and the national governance and policy framework is unsupportive.[202] Under such circumstances, standards for additionality and permanence are less likely to be observed, and leakage can result when local communities are impacted negatively, marginalized, or even excluded from project opportunities.[203]

The memorandum of understanding between California and Chiapas, Mexico, to allow REDD offset credits into the California cap and trade market has raised concerns that REDD projects could negatively impact the wellbeing of some of the indigenous communities in the jungles of Chiapas. The Climate Action Reserve, which is developing protocols for forest carbon projects in Mexico, is planning to incorporate environmental and social safeguards into the requirements for these projects.

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[202] Blomley, Tom and Michael Richards. “Community Engagement Guidance: Good Practice for Forest Carbon Projects,” *Building Forest Carbon Projects*, Johannes Ebeling and Jacob Olander (eds.). Washington, D.C.: Forest Trends, 2011.

[203] Ibid.

Within the WESTCARB region, local community interests will likely factor in the development of some projects and can help ensure that the terrestrial carbon storage does not occur at the expense of other beneficial or traditional land uses.

Adapting Terrestrial Carbon Storage During Climate Change

Climate change impacts in the WESTCARB region will benefit some species of plants over others and will vary depending on locale. Flexibility will be needed to ensure that terrestrial carbon storage projects can continue to mitigate climate change by withstanding impacts triggered by increased concentrations of CO_2, temperature change, water availability, and shifts in insect habitats and disease patterns. Land management practices, including species substitution and crop switching, will likely evolve to maintain economic viability for a range of land uses. In natural habits, using native species for conservation and restoration may need to be carefully assessed to ascertain if these species can remain viable as conditions change.

A California study of agriculture in the Central Valley concluded that climate change will lead to a northern migration of weeds, and that disease and pest pressure will increase with earlier spring arrival and warmer winters, allowing greater proliferation and survival of pathogens and parasites. Higher temperatures during the summer season will likely reduce rangeland livestock production and the supply of irrigated forage crops. The study noted that significant crop switching can be anticipated but that investments in technology, plant breeding, and cropping system research will result in less yield loss, higher yield reliability, and greater agricultural sustainability.[204]

According to the Intergovernmental Panel on Climate Change, the effects of climate change on forests can be found in decreased growth of white spruce on dry south-facing slopes in Alaska, which has declined over the last 90 years due to increased drought stress, and in semi-arid forests of the southwestern United States, where growth rates have decreased since 1895, again correlated with drought linked to warming temperatures. A combination of warmer temperatures and insect infestations has resulted in economically significant losses of the forest resource base to spruce bark beetle in both Alaska and the Yukon.[205]

However, warmer temperatures are expected to lead to increased growth rates for some forested areas. A study of the economic valuation of private timberland in California (9.2 million acres) indicated that if warming trends increase productivity in high latitude timberlands, increases in global timber prices would be curtailed based on supply. This relative decline in value for California’ timber could predispose the state’s timberlands to conversion to higher value uses, further exacerbating a trend that has already resulted in the loss of timberlands to residential development and vineyards.[206]

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[204] Jackson. *Potential for Adaptation to Climate Change in an Agricultural Landscape in the Central Valley*.

[205] Chapter 14.2.4, *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007,* M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[206] Hannah, L. et al. *The Impact of Climate Change on California Timberlands*, California Energy Commission, CEC-500-2009-045-F, August 2009.

The study found that adaptation programs such as altering species composition can help reduce the impact of climate change on timber values, and that participation in carbon markets can generate income in areas experiencing the greatest timber value declines, thereby providing an incentive to keep lands in forest.

Adaptation strategies for managing water resources will be critical in areas where changes in the timing and amount of water available for human use and natural habitats will lead to increased competition.[207] Approaches to sustaining water conditions in forests include managing tree densities and the use of artificial or live vegetation snow-fences to increase snowpack retention and infiltration. Watershed management approaches to improve hydrologic conditions within headwater and riparian areas include seasonal return of water to the environment from reservoirs and agriculture, and construction of wetland complexes to help maintain base flows, groundwater recharge, and timing of peak flows in headwater areas. Riparian management techniques such as reducing grazing along riparian areas and using beavers to improve stream management could help sustain flows and moderate the effects of warming air and stream temperatures.[208]

Adaptive approaches to forest regeneration can increase resilience in the short and long-term by adjusting silvicultural practices to establish forests that are more tolerant of future climate conditions. This includes planting genetically appropriate species that will be better adapted to changed climate conditions than the genotypes currently on site.

Some western state climate adaptation assessments have recognized the potential for urban forestry to mitigate local effects of rising temperature and precipitation runoff events. A 10% increase in vegetation cover can reduce ambient temperatures by 1 to 2 degrees. Increased street tree cover provides shade relief, absorbs pollutants including ozone and CO_2, which may increase with climate change, and reduces stormwater pollution and flooding.

Knowledge and Infrastructure Needs for Terrestrial Carbon Storage Projects in the WESTCARB Region

Maintaining the viability of terrestrial carbon storage projects during climate change will require new tools and techniques by which landowners, ranchers, farmers, and other land management decision-makers can access and analyze information to determine the best course of action to take in response to altering conditions.

Several western state climate adaptation plans have called for improved scientific knowledge base through additional research. As one plan observed, "much more needs to be known about how to downscale regional climate to local conditions and whether such downscaling will decrease the uncertainty forest managers face. Current data resources and future scenarios are generally inadequate to assess impacts at scales useful for managers."[209]

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[207] Robles, M.D. and C. Enquist. *Managing Changing Landscapes in the Southwestern United States.* The Nature Conservancy. Tucson, Arizona, 2010.

[208] Ibid.

[209] "Interim Recommendations from Topic Advisory Group 3, Species, Habitats and Ecosystems," *Washington State Integrated Climate Change Response Strategy,* February 2011.

Terrestrial carbon storage will also benefit from increased coordination and collaboration between agencies at all levels, private and public land managers, conservation organizations, tribes, and other stakeholders. Such partnerships can increase knowledge exchange and prevent the duplication of effort when it comes to climate modeling, response modeling, or gathering and analyzing data, and facilitate development, transfer, and assimilation of effective adaptation approaches.[210]

Planning should include short and long term strategies, monitoring for unanticipated climate effects and for effectiveness of adaptation strategies, and flexibility to manage adaptively and make adjustments.

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[210] Ibid.

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CERTIFICATION FRAMEWORK: LEAKAGE RISK ASSESSMENT FOR CO2 INJECTION AT THE MONTEZUMA HILLS SITE, SOLANO COUNTY, CALIFORNIA

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DOE Contract No.: DE-FC26-05NT42593

Contract Period: October 1, 2005 - May 11, 2011

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1 Introduction

WESTCARB and C6 Resources are partners in a CO_2 injection project in the Montezuma Hills, 80 km (50 mi) northeast of San Francisco, CA. Through a phased process that involves drilling an appraisal well and injecting CO_2 on a small-scale, along with thorough analysis of data and modeling of the system, the goal of the project is to assess the deep geologic formations in the area for Geologic Carbon Sequestration (GCS), and if favorable, inject CO_2 currently emitted to the atmosphere from nearby refinery facilities at industrial scales on the order of 1 million tons of CO_2 per year. The deep geology at the site is considered very favorable for GCS by virtue of the numerous sandstone formations which are potentially capable of storing large amounts of CO_2 and which are vertically separated by thick shale formations that prevent CO_2 from migrating upward. This general geologic environment is a proven trap for natural gas over geologic time as evidenced by the nearby Rio Vista Gas Field. Assuming step-by-step progress through the various stages, the Montezuma Hills project will involve drilling an appraisal well to over 3 km (10,000 ft) depth, carrying out a small-scale evaluation injection of 6,000 tons of CO_2, and evaluation of the feasibility of developing the site for a large-scale injection (e.g., 1 million tons of CO_2), and further consideration of the site for an industrial-scale GCS operation (e.g., 0.75 million tons CO_2/yr for 25 years).

Because GCS is not widely carried out either in the U.S. or abroad, there is very little experience upon which to base estimates of performance of GCS systems. In the absence of a long track record, leakage risk assessment methods are needed to address concerns by the various stakeholders about the effectiveness of CO_2 trapping and the environmental impacts resulting from CO_2 injection. For the last two years, investigators at the Lawrence Berkeley National Laboratory (LBNL), The University of Texas at Austin (UT), and the Texas Bureau of Economic Geology (TBEG) have been developing a framework called the Certification Framework (CF) for estimating CO_2-leakage risk for GCS sites (Oldenburg et al., 2009). Risk assessment methods such as the CF rely on site characterization, predictive models, and various methods of addressing the uncertainty inherent in subsurface systems. A brief outline of the methods used in the CF is provided in Appendix A. This report presents a discussion of leakage risk issues for the Montezuma Hills project and an outline of the research that needs to be done to carry out a leakage risk assessment by the CF approach.

C6 Resources has already gathered and synthesized a large amount of data and information on the Montezuma Hills site to examine the feasibility of injecting CO_2 at the site. In this case study discussion and research outline, we focus on public data and information that are important from the perspective of CO_2 and brine leakage risk assessment. For understandability, inevitably some overlap with information already collected will occur, but our emphasis is on data and interpretations relevant to leakage risk assessment that apparently have not previously been considered in detail by C6 or WESTCARB related to vulnerable entities and potential risk mitigation. For example, we discuss the shallow aquifers, surface water, potential for pressure impact on natural gas resources, and the significance of historical natural gas seepage. As for risk mitigation, winds in the area are a favorable mitigating factor relative to surface leakage due to their ability to disperse CO_2 ground plumes. Note that some of the information and text presented here is taken directly from an LBNL report two of us (Oldenburg and Jordan) contributed to several years ago (Oldenburg et al., 2003), and will be indicated as such.

2 Site Description

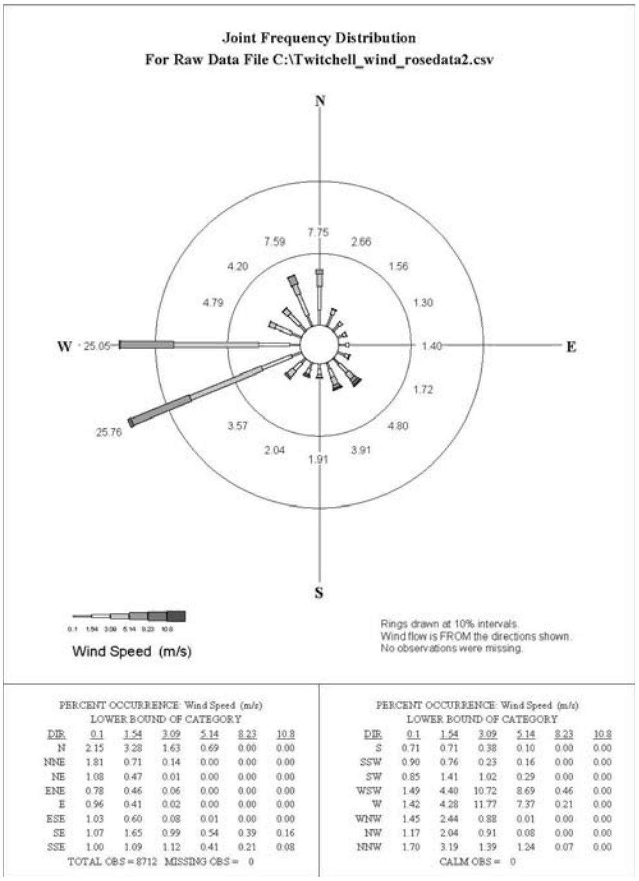
2.1 Surface and Climate

The Montezuma Hills are immediately north and west of the Sacramento River in the southwestern part of the Sacramento Valley, CA (Figure 1). Shown in Figure 1 is the location of the proposed appraisal well site 5 km (3 mi) north of the Sacramento River. The Montezuma Hills cover an area of approximately 120 km^2 (45 mi^2) and consist of grassy rounded hills separated by numerous ephemeral and some perennial stream valleys with relief averaging 45-60 m (150-200 ft). The Montezuma Hills are bordered on the west by low-lying tidal wetlands and sloughs, to the north by grassland plains, and to the east and south by the Sacramento River. South and east of the Sacramento River are sub-sea level islands that have been drained and diked off from water channels for agriculture. The Rio Vista Gas Field spans either side of the Sacramento River near the town of Rio Vista, which lies along the Sacramento River along the eastern boundary of the Montezuma Hills. The Montezuma Hills are mostly used for grazing lands and agriculture, rural and semi-rural residential use, and wind power generation. Climate in the area is Mediterranean with warm and dry summers and cool winters. The most significant aspect of the climate for CO_2 leakage risk is the winds, which are relatively strong and steady at this location as discussed next.

Figure 1. Proposed appraisal well site (N 38^{o}06’59.12”, W 121^{o}50’18.28”), elev. approx. 80 m (250 ft), in the Montezuma Hills north of the Sacramento River.

2.2 Winds

Winds in the area are favorable for power generation, and the Montezuma Hills is the location of hundreds of large wind turbines. Because winds are a mitigating factor for surface CO_2 release through their ability to disperse surface leakage of CO_2, we present in Figure 2 a quantitative assessment of winds from nearby Twitchell Island. This figure, from Oldenburg et al. (2003), shows a five-year time series (06-11-97 to 06-12-03) of hourly wind speed and direction measurements at the DWR meteorological station on Twitchell Island in the form of a wind rose. In Figure 2, the radial spokes indicate the direction the wind is coming from, the concentric circles are contours of the percentage of time (in 10% intervals) that the wind blows from the given direction, the thickness of the bar on the spokes indicates the wind speed, and the numbers at the end of the spokes are the total percentage time that the wind blows from the given direction. Over the measurement averaging time of 1 hour, there were no calms recorded. Figure 2 shows that the dominant wind direction is from the west to west-southwest (i.e., percent occurrence = 29.44 + 24.53 = 54%). The mean and standard deviation of the corresponding wind speed time series were 3.4 and 2.0 m s^{-1} (7.5 and 6.6 mph), respectively. The dominant wind directions during the spring (March-May), summer (June-August) and a portion of the fall (September-October) are from the west to west-southwest. However, from November to February, dominant wind directions are highly variable. The highest (4.8 m s^{-1} (10.6 mph)) and lowest (2.6 m s^{-1} (5.7 mph)) mean wind speeds were observed during summer and winter months, respectively, while intermediate mean wind speeds were observed during spring and fall months (3.7 and 2.9 m s^{-1} (8.1 and 6.4 mph), respectively).


Joint Frequency Distribution
For Raw Data File C:\Twitchell_wind_rosedata2.csv

Rings drawn at 10% intervals.
Wind flow is FROM the directions shown.
No observations were missing.

PERCENT OCCURRENCE: Wind Speed (m/s)
LOWER BOUND OF CATEGORY

DIR	0.1	1.54	3.09	5.14	8.23	10.8
N	2.15	3.28	1.63	0.69	0.00	0.00
NNE	1.81	0.71	0.14	0.00	0.00	0.00
NE	1.08	0.47	0.01	0.00	0.00	0.00
ENE	0.78	0.46	0.06	0.00	0.00	0.00
E	0.96	0.41	0.02	0.00	0.00	0.00
ESE	1.03	0.60	0.08	0.01	0.00	0.00
SE	1.07	1.65	0.99	0.54	0.39	0.16
SSE	1.00	1.09	1.12	0.41	0.21	0.08

TOTAL OBS = 8712 MISSING OBS = 0

PERCENT OCCURRENCE: Wind Speed (m/s)
LOWER BOUND OF CATEGORY

DIR	0.1	1.54	3.09	5.14	8.23	10.8
S	0.71	0.71	0.38	0.10	0.00	0.00
SSW	0.90	0.76	0.23	0.16	0.00	0.00
SW	0.85	1.41	1.02	0.29	0.00	0.00
WSW	1.49	4.40	10.72	8.69	0.46	0.00
W	1.42	4.28	11.77	7.37	0.21	0.00
WNW	1.45	2.44	0.88	0.01	0.00	0.00
NW	1.17	2.04	0.91	0.08	0.00	0.00
NNW	1.70	3.19	1.39	1.24	0.07	0.00

CALM OBS = 0

Figure 2. Wind rose for Twitchell Island, CA, located just across the Sacramento River from the Montezuma Hills, south of Rio Vista, CA.

2.3 Natural Gas Seepage

Historical surface natural gas seepage is well documented in California with numerous seeps located in Solano County (e.g., http://geomaps.wr.usgs.gov/seeps/). Early discovery wells at the Rio Vista Gas Field were located near natural gas seeps (Johnson, 1990). The main source of information for hydrocarbon seepage in the area is the public report TR26 by the California Division of Oil & Gas (1987). Chapter 3 of TR26 consists of a long table that identifies and locates 543 onshore oil and gas seeps in California, with several in Solano County in the lands north and northwest of the Montezuma Hills as shown in Figure 3.

The closest mapped historical seeps to the Montezuma Hills are numbered in the TR26 report and shown by the red triangles in Figure. 3. These historical mapped seeps are located in fenced, low-lying agricultural (alfalfa) and/or grazing lands (goats and cattle) with minimal topography. Based on a reconnaissance field trip by three LBNL investigators on March 18, 2009, there does not appear to be any natural gas seepage or associated springs or plant stress in these areas. We concluded from our field reconnaissance and discussions with local landowners that the historical seeps are no longer active. We did observe an abandoned exploration well (locally known as the artesian well) that continuously bubbles water and natural gas in the Denverton, Calif., 7.5 minute quadrangle, in Section 12, along Nurse Slough Rd. (Figure 4). We do not know the depth and other information about this well.

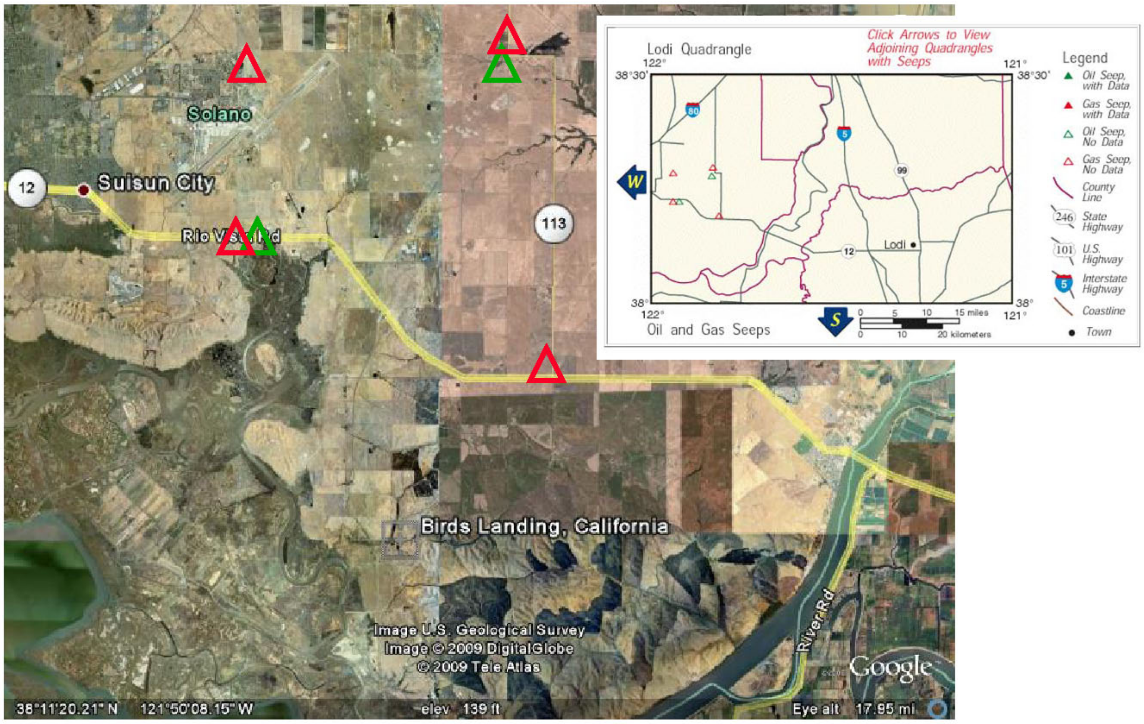


Figure 3. Location map of Solano County seeps from the USGS Seeps webpage (http://geomaps.wr.usgs.gov/seeps/) and transcribed onto a GoogleEarth image.

Figure 4. Photograph of the Nurse Slough Rd. abandoned artesian well with natural gas bubbles and foam at the open well head.

2.4 Surface water

The Montezuma Hills drain predominantly to the southeast to the Sacramento River. The perennial streams in the Montezuma Hills occupy some of these drainages. Minor seasonal streams drain the margins of the hills to the north and west. Extensive wetlands and slough channels cover much of the area between diked-off islands developed for agriculture. The Sacramento River is a major river in California with average flow rate estimated from November 1983 to November 1984 to be 1000 $m^3\ s^{-1}$ (35000 $ft^3\ s^{-1}$) (Ota et al., 1986). The mean winter (December-February), spring (March-May), summer (June-August), and fall (September-November) flow rates were estimated to be 2180, 629, 519, and 481 $m^3\ s^{-1}$, respectively. While there is a great deal of surface water to the west, south, and east of the Montezuma Hills appraisal well site, the Montezuma Hills themselves do not contain extensive lakes or wetlands.

2.5 Subsurface

2.5.1 Introduction

A block stratigraphic column of the subsurface beneath the proposed appraisal well is shown in Figure 5. As shown, the geology appears favorable for GCS by virtue of the numerous sandstone reservoirs capped by low-permeability shale units. Critical aspects of the system relevant to leakage risk assessment discussed in this section include the properties of the ground water present, nearby natural gas resources, wells and faults as potential conduits for leakage, and the trapping that occurs in a dipping monocline absent structural closure.

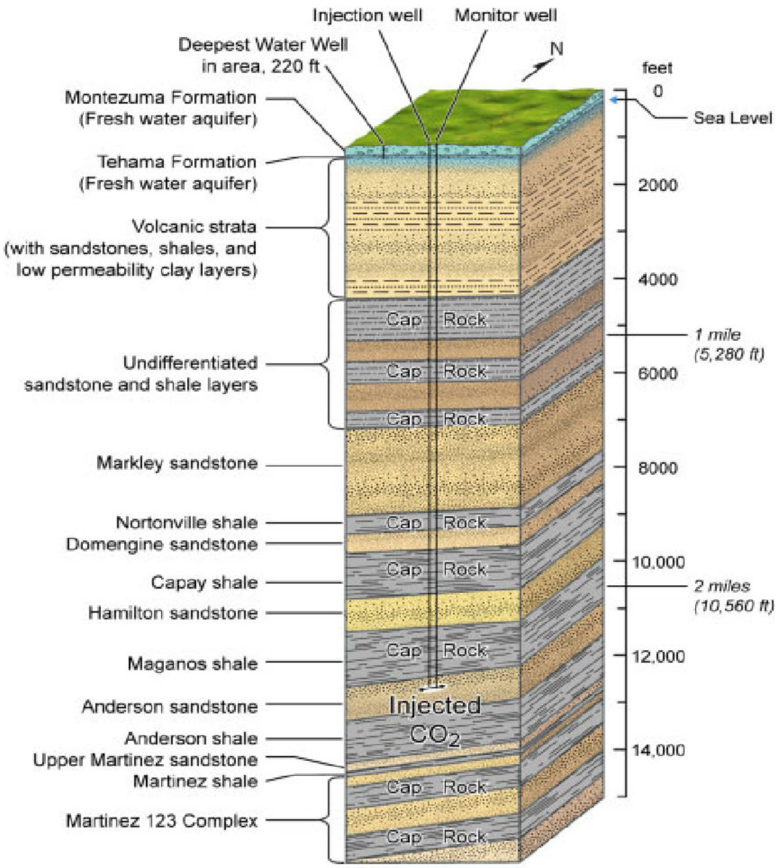


Figure 5. Block stratigraphic column of the geologic units at the appraisal well site in the Montezuma Hills.

2.5.2 Hydrology

2.5.2.1 Shallow Aquifers

Oldenburg et al. (2003) presented data on water-table elevations along with descriptions of the shallow aquifers as repeated here. As shown in Figure 6, depth to the water table varies from less than 2 m (7 ft) at lower elevations, to greater than 13 m (42 ft) around the margins of the Montezuma Hills. The greatest observed water-table depths are likely near the producing wells on the northern flanks of the Montezuma Hills.

Based on available data, the water table elevation near the center of the Montezuma Hills is about 49 m (160 ft) and decreases to about 1 m (4 ft) at the eastern edge of the hills, over a distance of about 13,700 m (45,000 ft). These values yield a maximum horizontal gradient of about 0.003. Maximum horizontal gradients from high elevations near the center of the hills to low elevations at the edges could be up to 0.01. Horizontal gradients are much less in the lowlands characterized by flat topography and perennial water channels. Water pressures are hydrostatic from the water table through the Eocene reservoirs.

The average hydraulic conductivity in the Sacramento Valley aquifer is 0.9 m d^{-1} (3 ft d^{-1}) (Williamson et al., 1989), corresponding to a permeability of approximately 10^{-12} m^2. Combining this with an estimated maximum gradient of 0.01 and an estimated effective porosity of 25% yields an estimated maximum linear groundwater velocity of 15 m yr^{-1} (50 ft yr^{-1}).

The shallow groundwater in the vicinity of the Rio Vista Gas Field has a total dissolved solids (TDS) content of 250 to 500 ppm and therefore can be characterized as fresh. Groundwater to the northwest of the Sacramento River is classified as sodium bicarbonate (Evenson, 1985; Johnson, 1985). To the southeast, the dominant chemical constituents in groundwater are sodium or calcium and chloride or sulfate (Bertoldi et al., 1991).

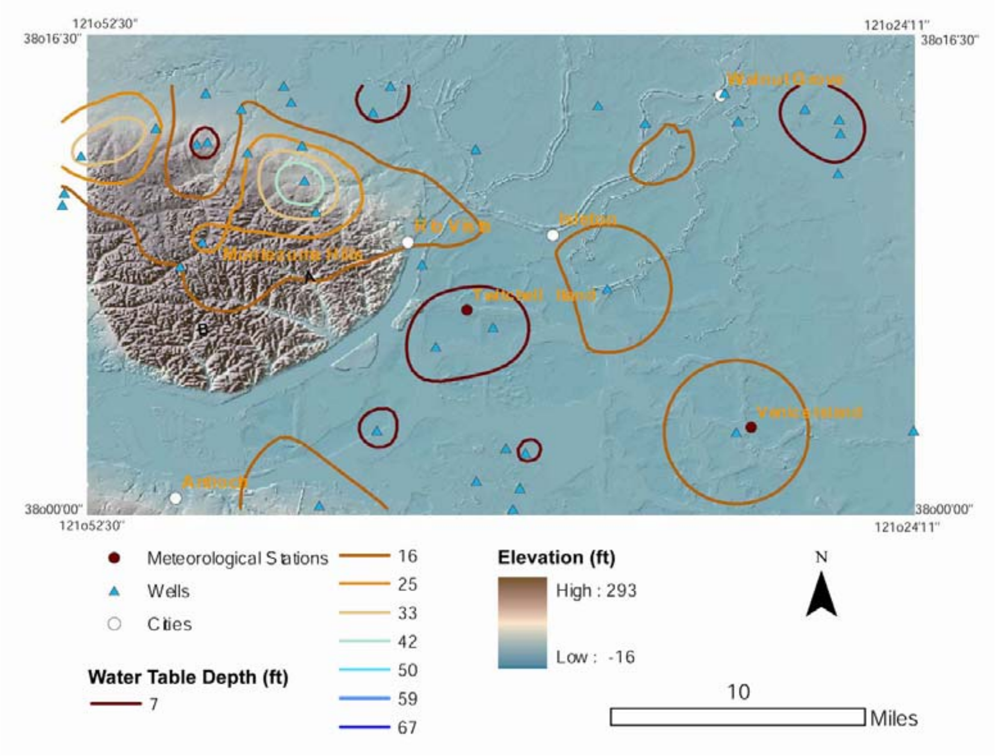


Figure 6. Water table depth and topographic elevation around the Rio Vista area.

2.5.2.2 Deep Groundwater

As described in Oldenburg et al. (2003), the base of the fresh groundwater (TDS < 2000 ppm) in the Rio Vista area generally occurs at or just below the lower contact of the Tehama Formation (Figure 5), or at a depth of 300 to 550 m (1000 to 1800 ft) below sea level (Page, 1986). The TDS of groundwater in the Markley sand at 240 m (800 ft) below sea level in the Rio Vista field is approximately 5000 ppm and the anion and cation contents are dominantly sodium and chloride, respectively, making the salinity nearly equal to the TDS. The sodium chloride content increases with depth to about 17,000 ppm in the Hamilton Sand and then decreases with depth to approximately 8000 ppm in the Peterson Sand (Johnson, 1990). This reversal in salinity (TDS) with depth was analyzed further in the preparation of this CF outline and discussion as presented further below.

The significance of TDS relates mostly to UIC regulations under the Safe Drinking Water Act, which requires non-degradation of ground water having a TDS less than 10,000 ppm. However, increasing TDS with depth (positive TDS gradient) also provides resistance to brine leakage up conduits such as wells and faults due to the higher density of the uplifted brine (e.g., Nicot et al. 2008). The TDS distribution is therefore a critical element of leakage risk assessment.

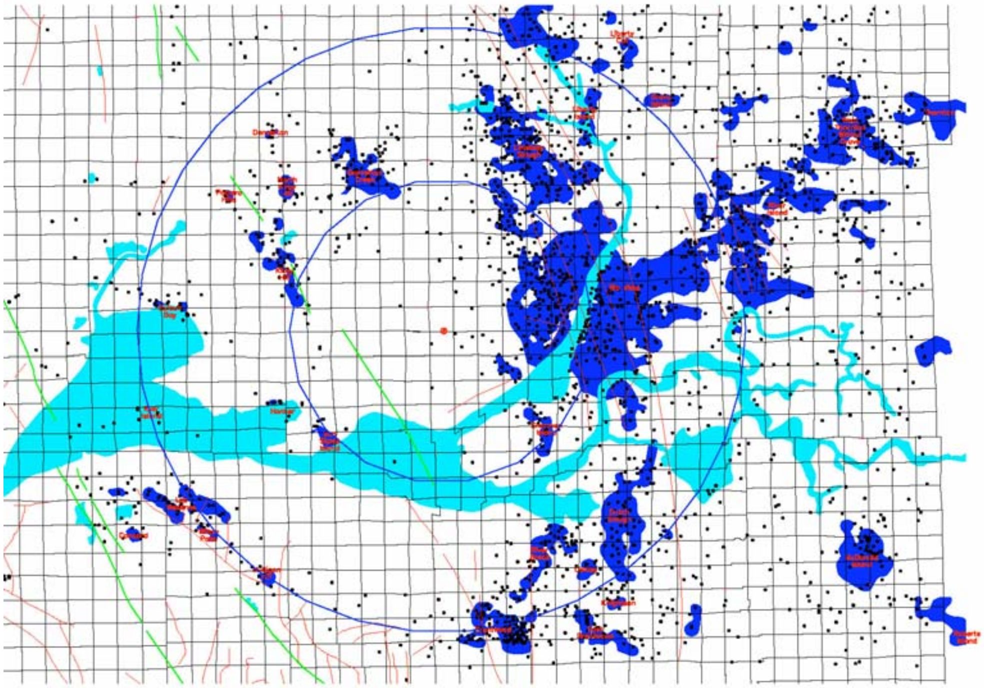


Figure 7. Gas fields surrounding the Montezuma Hills along with wells and faults.

Salinities (NaCl concentration) are shown for 36 of the 55 pools in the fields shown in Figure 7 and described in the DOGGR database (DOGGR, 19xx), while TDS values are reported for only two pools. Salinities are plotted against depth in Figure 8 with ranges shown for some of the pools. As there is no information about the distribution of the data yielding these ranges, Figure 8 plots the center of the given range within the range bars.

The two TDS (*sensu stricto*) values are also shown on Figure 8. One of these values is given for a pool along with salinity which shows that the TDS value is only slightly higher than the salinity value suggesting salinity is a reasonable proxy for TDS.

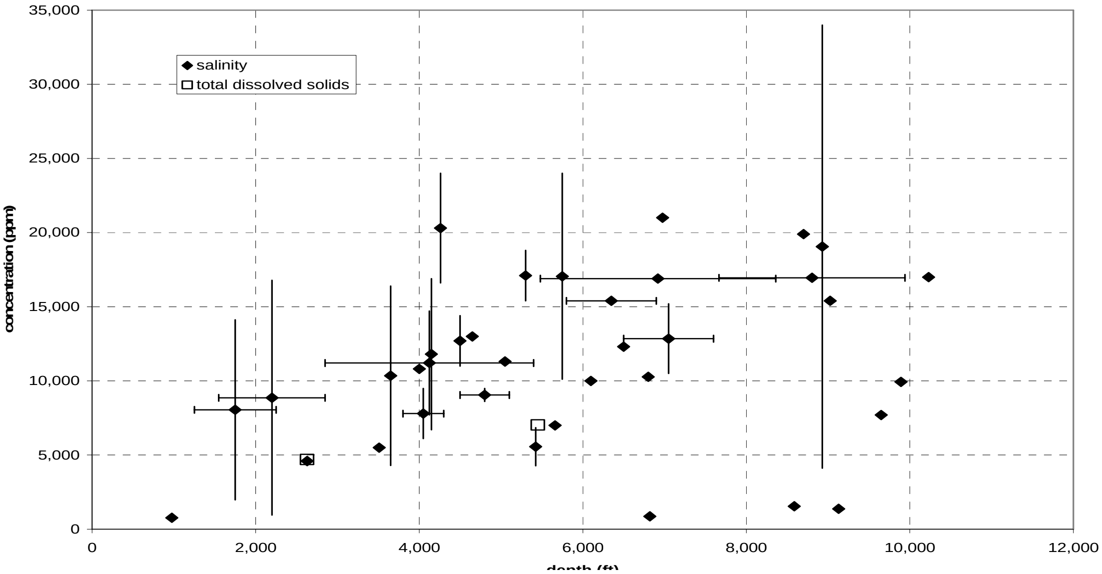


Figure 8. Total dissolved solids and salinity with depth in the natural gas pools around the FOA 15 site. Data from DOGGR ().

Salinity generally increases with depth as shown on Figure 8. A closer examination suggests the salinity gradient decreases with depth, potentially to zero or even becoming negative, below a depth of 7,000 ft (2100 m). Figure 9 shows the salinity data for each separate natural gas field. The fields are organized in the legend clockwise from north of the appraisal well site. All of the low values relative to the main trend at depths greater than 7,000 ft (2100 m) occur in fields centered generally from north to east of the site. This suggests relatively low salinities at depth are focused in this quadrant, with attendant concern for UIC non-degradation regulations, and for brine upwelling in response to storage-induced pressure rises in this area. However, there may be more widespread low-salinity water around the appraisal well site as the existing data are all for the deep pools that tend to exist only in this quadrant.

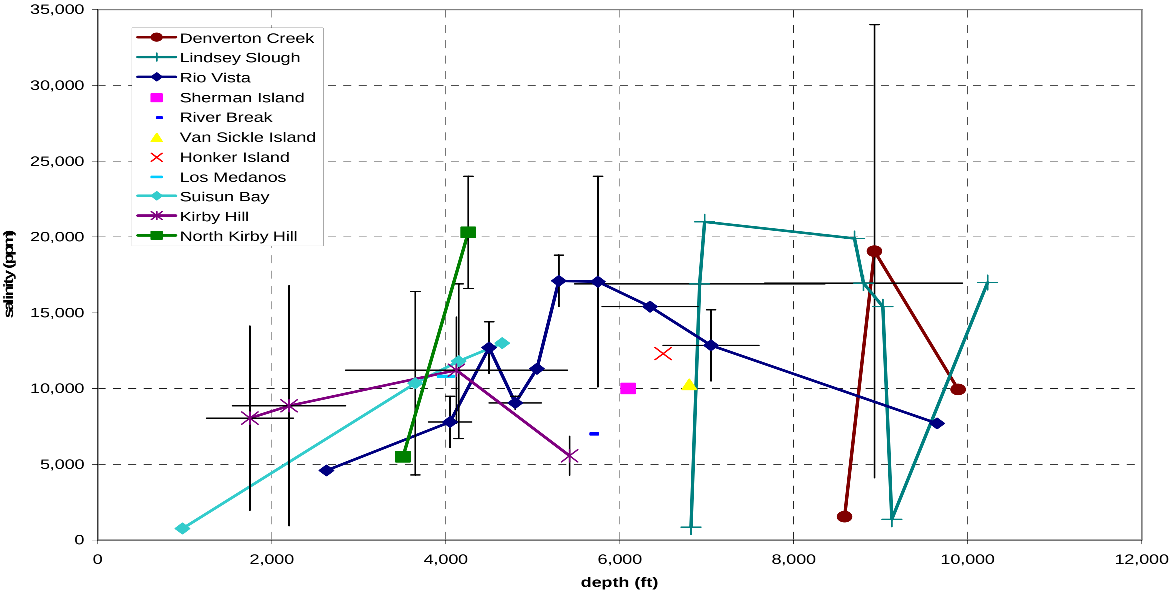


Figure 9. Salinities in natural gas pools around the FOA 15 site indicated by field.

Another perspective on salinity distribution is presented in Figure 10, which plots salinity by geologic unit. The units are listed in stratigraphic order from youngest to oldest in the legend. Salinities are available for most of the units over only limited depth ranges, although the depth range for the Domengine and Martinez is greater than 4,000 ft (1200 m). There appears to be only a slight increase in salinity with depth for the Domengine, and no increase for the Martinez. Perhaps crucially, though, the two deepest salinities for the Domengine, at about 7,000 ft (2100 m), are both slightly greater than 10,000 ppm. This, along with the slight salinity gradient in the Domengine, suggests that salinity at depths greater than 10,000 ft (3000 m) will exceed 10,000 ppm.

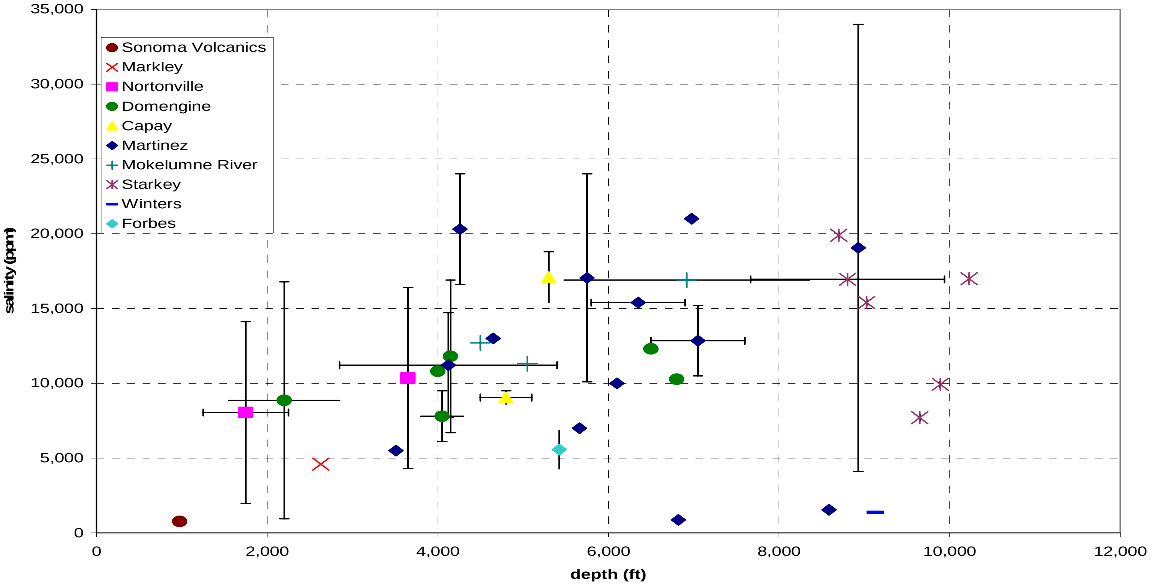


Figure 10. Salinities in natural gas pools around the FOA 15 site indicated by field.

The relative depth invariance of salinity in each geologic unit suggests aggregating the salinities in each unit. Figure 11 shows the salinity for each unit averaged from the single and range mid-point values given in Figure 10, with the range bars indicating the distribution of these points. Note the distributions for sets with more than three points (Domengine, Martinez, and Starkey) are typically platykurtic (flat relative to a normal distribution) and left skewed (more high than low values relative to a normal distribution). This indicates more probability in the tails than a normal distribution, but less probability toward the bottom of the range. Taken together, these tend to suggest somewhat normal probability at the lower end of the distribution toward the 10,000 ppm cutoff.

Figure 11 indicates increasing salinity with depth down through the section to the mid Cretaceous Forbes. There is also a fairly constant salinity gradient from the Nortonville to the Starkey, which contains the potential storage targets. Average salinities by unit are above 10,000 ppm throughout this storage section, but the bottom of the salinity distribution is below 10,000 ppm. While it is tempting to conclude from this salinity gradient, particularly as extrapolated to the deeper storage targets, that salinity will be greater than 10,000 ppm, this would be misleading. The lack of a salinity gradient or only weak salinity gradient per unit shown in Figure 10 suggests salinities in the storage targets will not be much greater than those shown on Figure 11. For instance, even though salinities at 7,700 ft (2300 m) are about 14,000 ppm using the linear trend of Nortonville to Starkey salinities, the linear trend from Domengine salinities on

Figure 10 suggests a salinity in that unit of 12,000 ppm at this depth, albeit with a distribution that likely extends below 10,000 ppm.

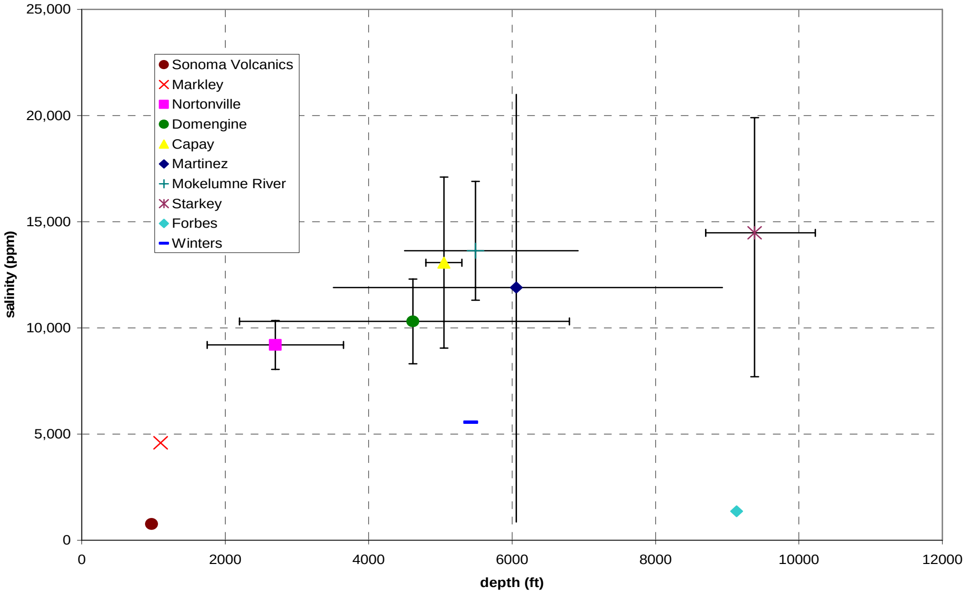


Figure 11. Salinities by geologic unit versus depth in the vicinity of the FOA 15 site.

The Mokelumne River data, at a depth shallower than the Martinez data despite the former being deeper in the section than the latter, suggests plotting the data by unit age. Figure 12 presents this perspective using approximate central ages for each unit. The salinities down through the Forbes lie on linear trend with a relatively high correlation coefficient (0.87). All of the salinities shown are below the salinity of sea water (~30,000 ppm) despite marine deposition of most of these units. This suggests deep freshwater fluid circulation at a rate higher than dissolution of cations and anions from the host rocks. Consideration should be given to the timing and possible significance of this fluid circulation relative to long term carbon storage at the site.

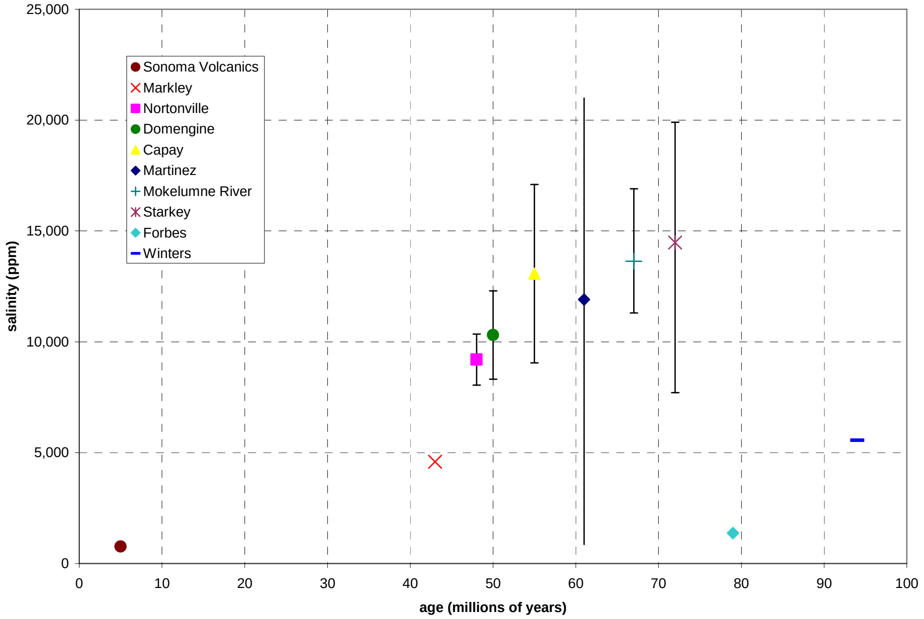


Figure 12. Salinities by geologic unit in the vicinity of the FOA 15 site.

The analysis of salinity suggests the probability that TDS in the storage targets are above the 10,000 ppm threshold is significantly greater than 50%, but less than 95%, at the storage target depths. Salinities also generally increase with depth and geologic age, but field-specific data suggest localized gradient inversion occur. The hydrostratigraphic column shown in Figure 13 represents the current understanding based on our preliminary analysis of the DOGGR data. The significance of the low TDS ground water at depth is that the system would not be at hydrostatic conditions, and that if open conduits are present there would presumably already be upwelling. Even with the general slight increase in salinity with depth, upwelling may currently be sustained over a broad area due to an overall density decrease with depth due to the geothermal gradient. Whether this is occurring or not, the low salinity gradient overall suggests pressure increases due to storage could readily induce upwelling in any leakage pathways present.

Despite the lack of a sufficient salinity gradient to significantly resist brine upwelling along potential leakage pathways in response to storage reservoir pressurization, the impact of such leakage would be significantly moderated by the low salinities involved. Because the storage target salinities are potentially very close to the 10,000 ppm threshold, significant upwelling would have to occur to significantly increase the TDS of overlying waters.

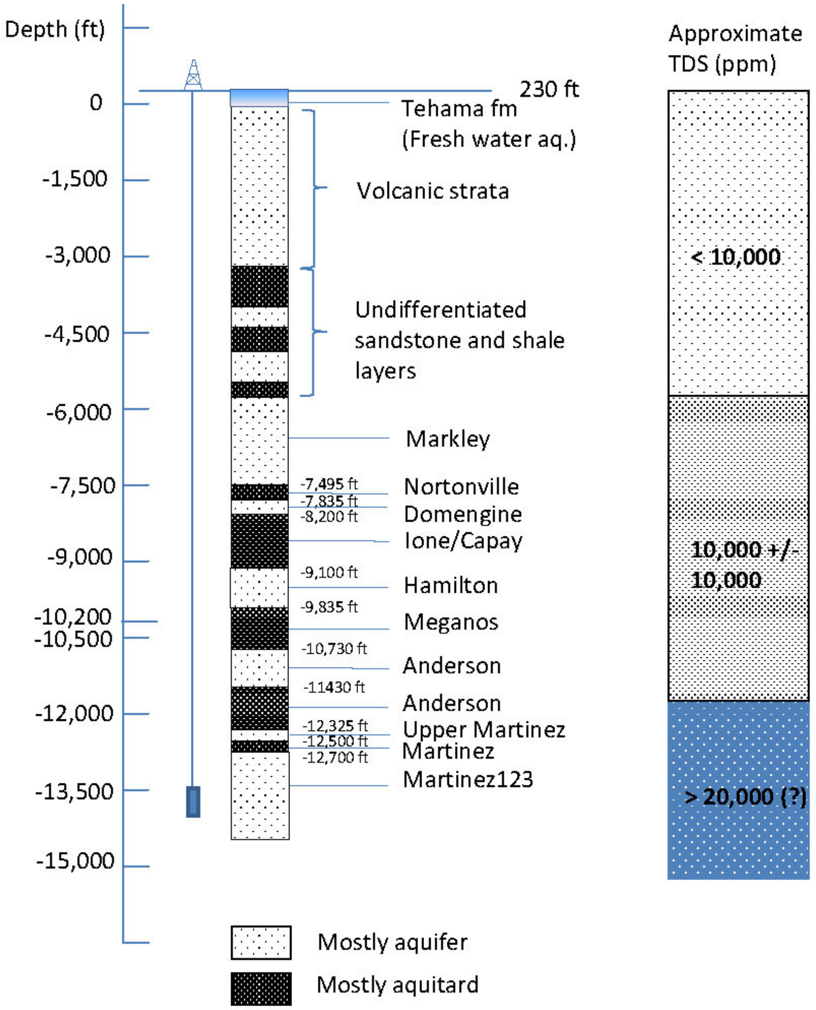


Figure 13. Expected hydrostratigraphy and water quality at the Montezuma Hills appraisal well.

2.5.3 Natural Gas Resources

Natural gas in economic quantities has not been found in the synclinal structure present at the proposed site of the Montezuma Hills appraisal well, and no gas production is noted from the Anderson or Hamilton in the DOGGR database (DOGGR, 19xx). This suggests CO_2 storage in these targets has reduced risk of impacting natural gas resources as compared to the other potential targets. However, this may be a matter of stratigraphic nomenclature, and so should be further checked and confirmed. Approximately 5 km (3 mi) to the east of the appraisal well site is the western edge of the Rio Vista Gas Field. The description below of the Rio Vista gas resource, geology, and structure repeats that given in Oldenburg et al. (2003).

The Rio Vista Gas Field is the largest onshore gas field in California (Burroughs, 1967) and has been in production since 1936. Natural gas production from the Rio Vista Gas Field peaked in 1951 with annual production of 4.4×10^9 m^3, and has declined steadily since then (Cummings, 1999). Production decline is caused by decreasing reservoir pressures and increased water production, particularly on the western boundary of the field. Cumulative production of CH_4 is in excess of 3 Tcf (9.3×10^{10} m^3) (at standard conditions of 1 bar, 15.5 ˚C [14.7 psi, 60 ˚F]).

The primary gas reservoir in the Rio Vista Gas Field is the Eocene Domengine sand, predominately a marine sandstone with shale interbeds. The Domengine resides approximately 1200 m (4000 ft) below sea level in the field area. In Figure 13, we show a highly schematic cross section (not to scale in the vertical direction) that shows the general structure of the reservoir and overlying formations. Natural gas plays have been encountered in all of the predominantly sandy formations, and in sand stringers within almost all of the predominantly shaly formations (including the Nortonville), in the Paleocene and upper Cretaceous section. Most notably, gas plays were encountered in the Markley sand above the Domengine-capping Nortonville shale. The gas traps in the Rio Vista Gas Field are described variously as faulted-dome or up-dip fault traps created by offset of reservoir sands against shales with lateral structural closure due to folding (Burroughs, 1967; Johnson, 1990).

The west-dipping Midland fault strikes northwest through the eastern portion of the Rio Vista Gas Field (Figures 7 and 13). Stratigraphic units at the reservoir level exhibit normal (down to the west) displacement, and thicken across this fault from east to west indicating syndepositional faulting. These characteristics, along with the apparent rapid accumulation of sediment and overpressuring of deeper shales led Johnson (1990) to characterize the Midland fault and associated faults as both growth and tectonic faults. Units above the Domengine sand reservoir typically exhibit reverse offset with thickening to the east indicating this fault has been tectonically reactivated in compression since the Miocene (Weber-Band, 1998). Based on regional structural analysis, Weber-Band (1998) concluded that the Midland fault and associated faults were likely due primarily to extensional tectonics during deposition of the reservoir units. West of the Midland fault, the geologic structure in the gas field consists of an elongated, faulted dome. The trend of the dome’s axis and the strikes of faults cutting the dome are north to northwest. The faults appear to be sympathetic and antithetic to the Midland fault. Displacement on these faults does not appear to be greater than the thickness of the Nortonville shale, which caps the Domengine sand (see schematic cross-section Figure 13) (Burroughs, 1967; Johnson, 1990). East of the Midland fault, the gas field consists of the unfaulted half of a north- to northwest-trending elongated dome that is faulted through its eastern limb.

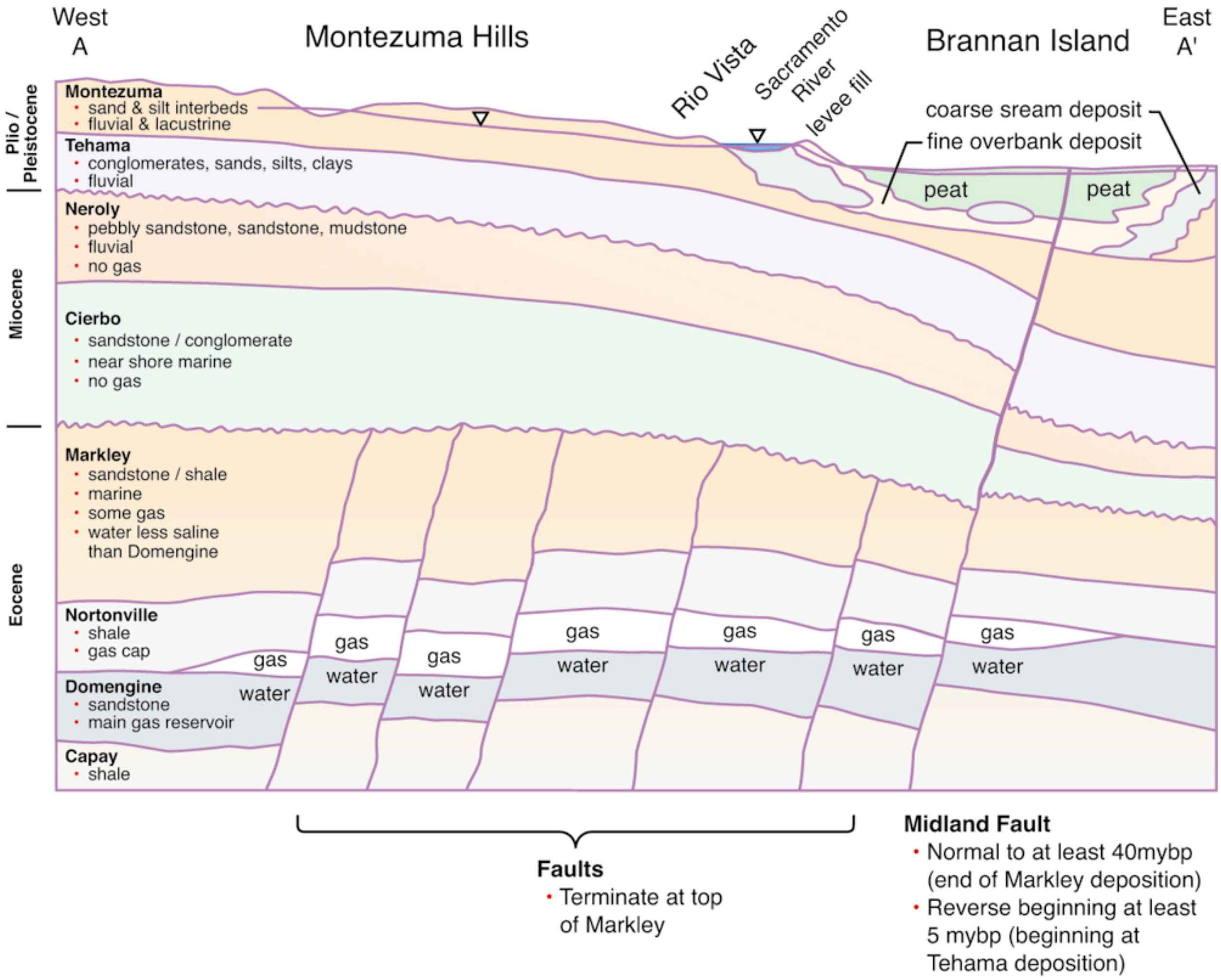


Figure 13. Cross section A-A' of the Rio Vista area from Oldenburg et al. (2003). Note that gas reservoir thickness is exaggerated relative to total formation thicknesses.

2.5.4 Geology

2.5.4.1 Montezuma Model

A three-dimensional geologic framework model needs to be developed to evaluate lithology, structure, well penetrations, and faults. Absent this model, no further discussion of the geology or structure will be presented here.

2.5.5 Boreholes

Hundreds of deep hydrocarbon (gas) exploration and production wells exist within a 20 km (12 mi) radius of the appraisal well site. Figure 14 shows existing hydrocarbon wells within and just outside of a 10 km (0.62 mi) radius of the site. Some of these wells were constructed approximately 80 years ago. Because wells are potential conduits for leakage of CO_2 and brine, the depth, current use, and integrity with respect to how well they were plugged and abandoned are critical properties for leakage risk assessment.

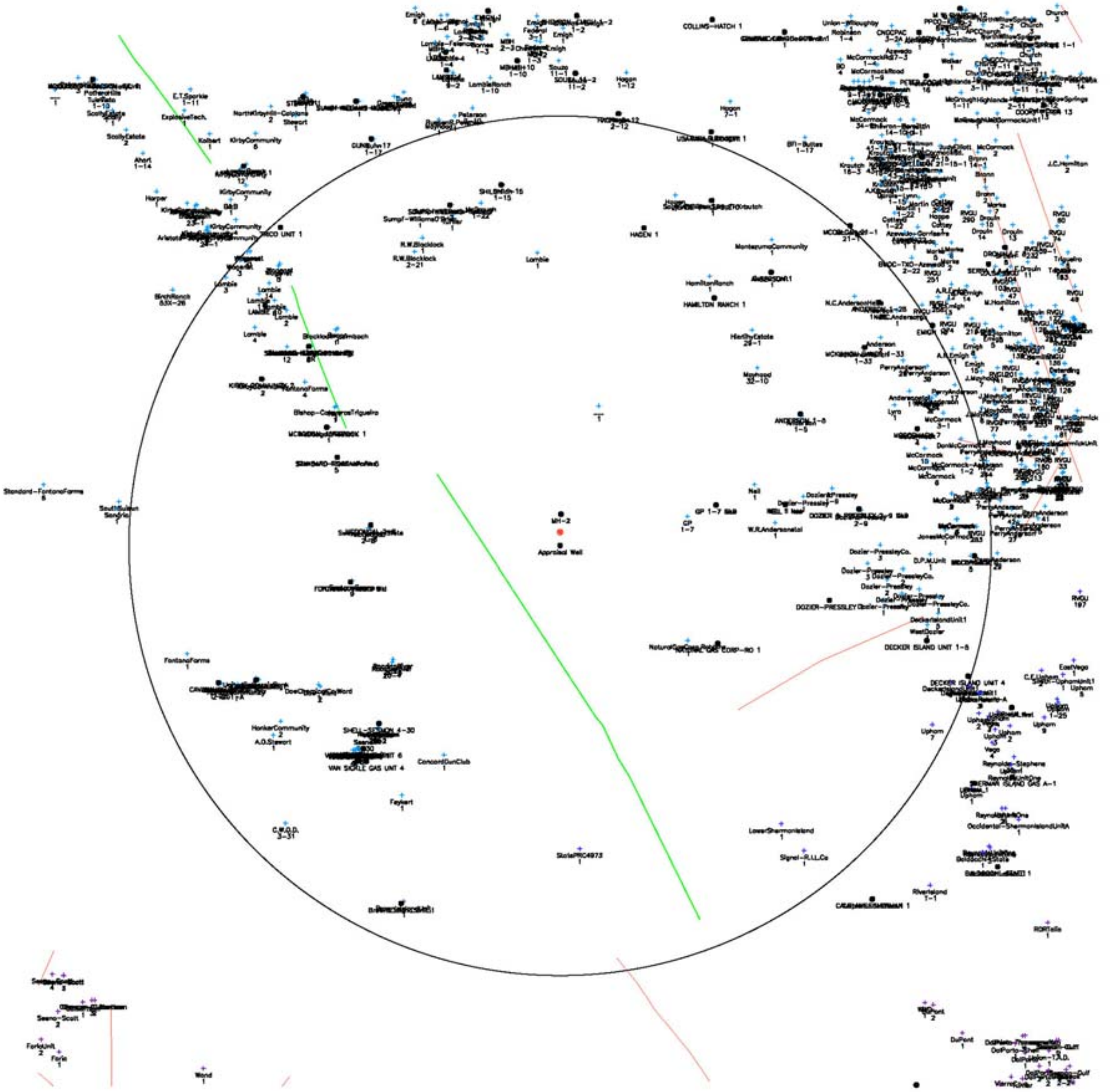


Figure 14. Approximate location of Appraisal well and possible monitoring well to the north along with 10 km (6.2 mi) circle with exploration and production wells indicated. The green line trending northwest-southeast is the Kirby Hills Fault.

2.5.6 Faults

Faults are also critical features for GCS risk assessment due to their potential for producing earthquakes and due in some cases to their potential for providing leakage pathways for CO_2 or brine. The main known faults in the area of the appraisal well are the Kirby Hills Fault (KHF) to the west and two lesser faults to the east referred to as Fault A and Fault B. The Midland Fault is a major feature to the east, just beyond the 10 km (6.2 mi) radius. A major component of ongoing research related to leakage risk will be focused on characterizing faults and their potential role as permeable pathways for CO_2 and brine. Induced seismicity and earthquake hazard is being handled by a different group working on the project.

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SEISMICITY CHARACTERIZATION AND MONITORING AT WESTCARB'S PROPOSED MONTEZUMA HILLS GEOLOGIC SEQUESTRATION SITE

T.M. Daley, R. Haught, J.E. Peterson, K. Boyle, J.H. Beyer and L.R. Hutchings

Lawrence Berkeley National Laboratory

DOE Contract No.: DE-FC26-05NT42593

Contract Period: October 1, 2005 - May 11, 2011

Seismicity Characterization and Monitoring at WESTCARB's Proposed Montezuma Hills Geologic Sequestration Site

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October 14, 2010

Introduction

The West Coast Regional Carbon Sequestration Partnership (WESTCARB), in collaboration with Shell Oil Co. performed site characterization for a potential small-scale pilot test of geologic sequestration of carbon dioxide (CO2). The site area, know as Montezuma Hills, is near the town of Rio Vista in northern California. During the process of injection at a CO_2 storage site, there is a potential for seismic events due to slippage upon pre-existing discontinuities or due to creation of new fractures. Observations from many injection projects have shown that the energy from these events can be used for monitoring of processes in the reservoir. Typically, the events are of relatively high frequency and very low amplitude. However, there are also well documented (non-CO2-related) cases in which subsurface injection operations have resulted in ground motion felt by near-by communities. Because of the active tectonics in California (in particular the San Andreas Fault system), and the potential for public concern, WESTCARB developed and followed an induced seismicity protocol (Myer and Daley, 2010). This protocol called for assessing the natural seismicity in the area and deploying a monitoring array if necessary. In this report, we present the results of the natural seismicity assessment and the results of an initial temporary deployment of two seismometers at the Montezuma Hills site. Following the temporary array deployment, the project was suspended and the array removed in August of 2010.

Natural seismicity characterization

We reviewed currently available public information including 25 years of recorded seismic events, location of mapped faults and estimates of the stress state of the region. We have also reviewed proprietary geological information collected by Shell, including seismic reflection imaging in the area, this information was reported in Myer, et al, 2010. There are known faults in this area, the one closest to the proposed injection site is the Kirby Hills Fault. The Kirby Hills fault is associated with earthquakes which are deep (9-17 miles below the surface) with magnitudes up to 3.7 (in 30+ year study period). The Shell data also indicates two unnamed faults in the area. The seismic events (earthquakes) we reviewed were not well located because of lack of nearby seismic stations, especially to the north and east. Therefore, attributing the recorded earthquakes to any single fault is inexact. This was somewhat unexpected given the relatively dense monitoring in California, but the Montezuma Hills site is on the very ~~e~~eastern edge of local networks, which are focused on the San Francisco Bay Area and the San Andreas Fault System. Figure 1 shows the seismic monitoring stations of the Northern California and Berkeley monitoring networks. Because of the relatively poor coverage, we revisited the historical events including visually inspecting seismograms and re-picking arrival times of seismic waves.

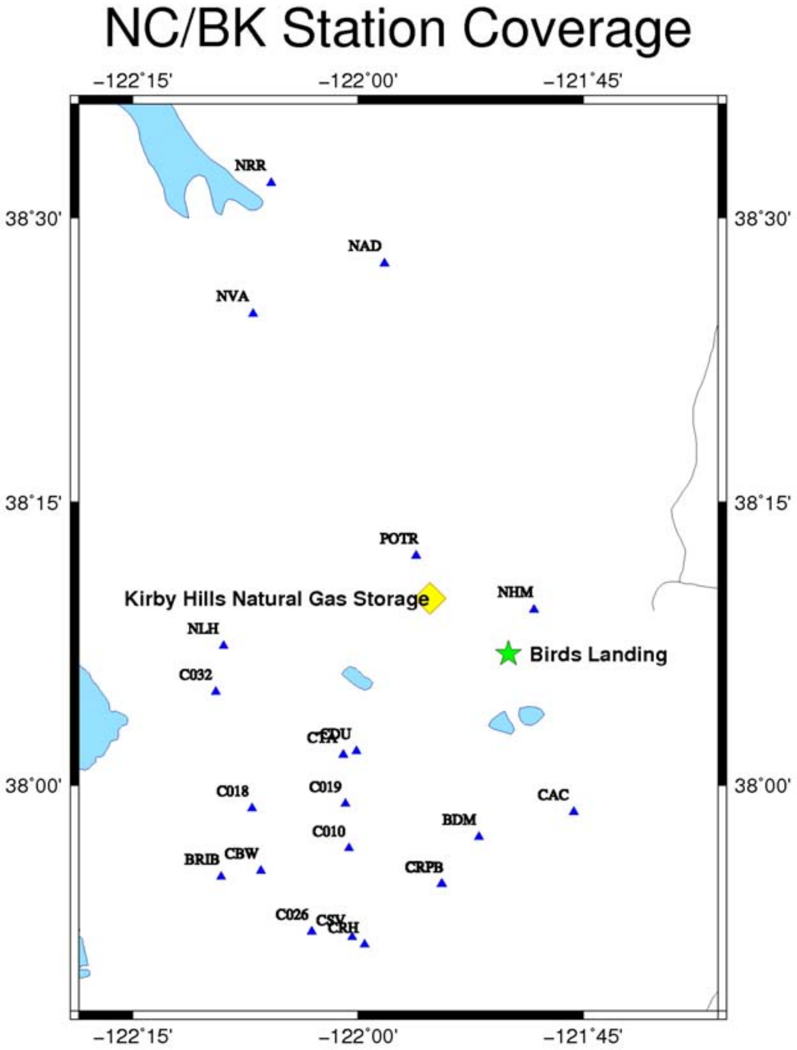

Figure 1. Station locations near the Montezuma Hills (Birds Landing) site for the Northern California Seismic Network (NCSN) and the Berkeley Digital Seismic Network. These stations were used for the event relocation.

We attempted to re-relocate all 111 earthquakes that were listed in the NCSN catalog to have occurred within a 11km x 14 km rectangular area around Birds Landing from 1978 to the present. We also modified the general NCEDC northern California velocity model to a published velocity model specific to the area (Rhie and Dreger). We used HYPOINVERSE to re-locate the earthquake (Klein, 1985). The area and original locations obtained by the NCEDC (red dots) are shown in Figure 2.

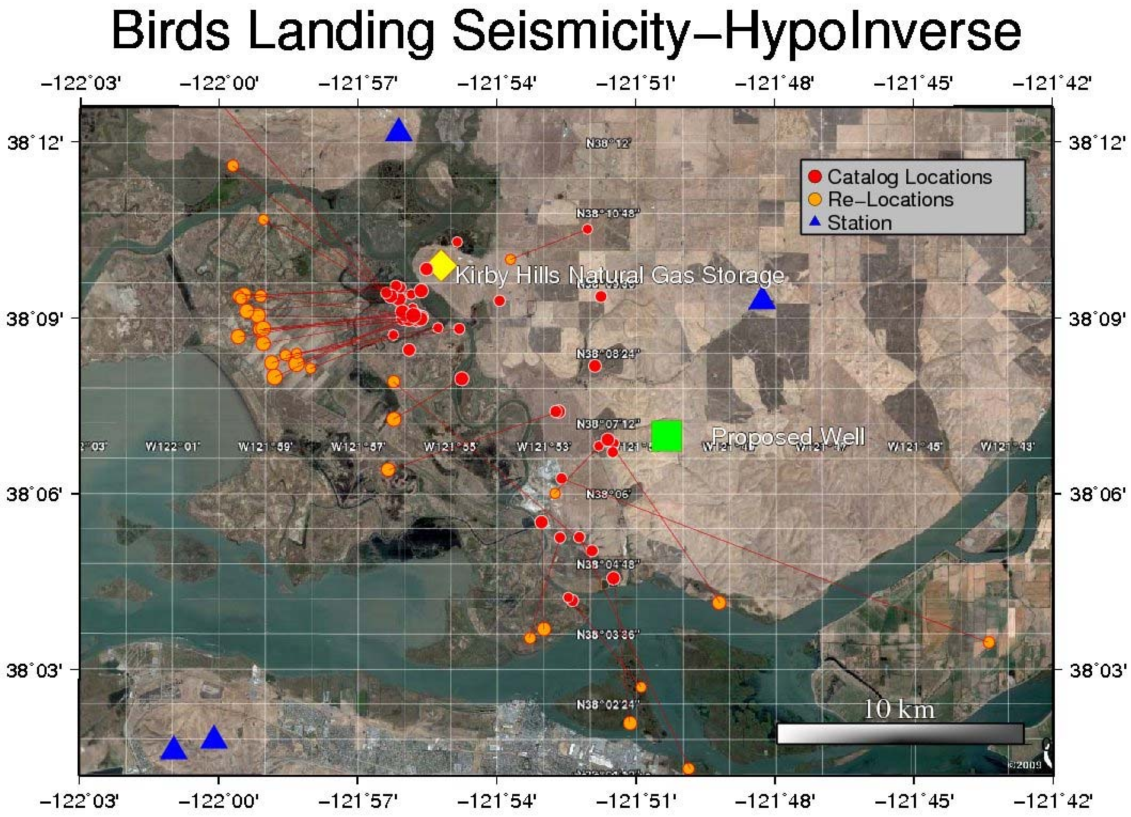

Figure 2. The original NCSN and Berkeley locations for events in the Montezuma Hills area (red) with lines connecting them to the new locations (orange). The green square is the proposed injection well location. Also shown are seismic stations (blue triangle) and the Kirby Hills underground injection facility for natural gas storage.

We obtained waveforms for 80 events for re-location. Of the 80 events, only 56 had sufficient waveform data for us to re-locate. We hand picked these data. We found that many phases were not identified by the auto-picker, but those that were auto-picked appeared to be fairly accurate. When we re-located the events using hand picks, the events moved considerably (up to 10 km), and most moved outside the box. Re-located events are shown as orange dots in Figure 2. One consideration is that if all the events in the region were re-located, many that originally fell outside the box would move into the box.

Temporary monitoring array design and deployment

Because of the number and size of events in the area, we decided to deploy a monitoring network in advance of any subsurface injection. The initial step in the network deployment was installation of two temporary stations to assess data quality. The initial array design was considering both spatial sampling and a focus on the Kirby Hills fault west of the injection site. Figure 3 shows the location of the two temporary sites (MH-1 and MH-2) along with potential locations for the 5 semi-permanent stations. The temporary site locations were put on property with ease of access and permitting, rather than by scientific design. Because the project was suspended, no further work on array design has been undertaken.

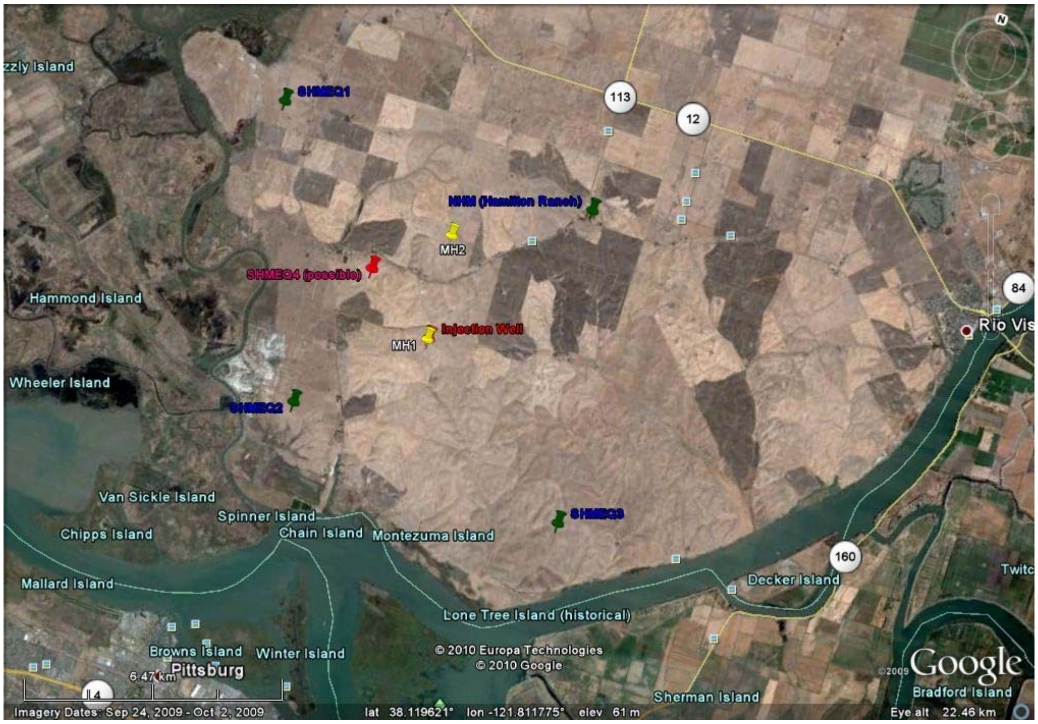

Figure 3. Locations of the temporary seismic stations (yellow markers) and potential stations (green and red markers), along with the injection well location. The town of Rio Vista is on the Eastern edge of the map and Pittsburgh, CA, is to the Southwest.

Observations of the temporary microseismic array at Montezuma Hills

Both temporary stations were deployed close to gravel access roads due to the agricultural use of the area. The station MH-1, accessed using Gate 1, operated from Day 138 to Day 230 (May 18 to August 18). In addition to the continuous acquisition, it also acquired triggered data starting on Day 173 (June 22). The station MH-2, accessed using Gate 3, was also deployed on Day 138 (May 18) but began have problems on Day 182 (July 2). Limited data are available after that. Figure 4 shows a photograph of a site.

Figure 4. (left) A temporary seismic site with solar panel and recording system (inside grey box). (right) A three-component seismometer, placed about 3 m from the station in shallow hole, before being covered with dirt, along with compass used for alignment.

The data was acquired by a seismic recorder manufactured by Refraction Technology (REF TEK) which includes a global positioning system (GPS) clock for accurate time keeping. We recorded data from each station continuously. The REFTEK format data had a sample rate of 500 samples/second. Each file contained one hour of data (3600 seconds), and therefore 1,800, 000 samples. The data was converted to SEG-Y format (defined by the Society of Exploration Geophysicists). Each station had three components, so the SEG-Y file has three traces each 1,800,000 samples long. Standard SEG-Y format limits the data to 32767 samples, so the data needed to be parsed to one minute trace lengths (30,000 samples). These seismograms are scanned manually for events. There were very few discrete events. Noise events were observed, many of which we interpret as being related to traffic on the gravel road. There were also smaller events that did not have characteristics of microseisms, but at 2-4 seconds length, seem to be too short for road traffic. An example of these is shown in Figures 5. These events are characterized by no impulsive onset and a relatively slow ramp up of energy, with an equally slow drop in energy. Figure 6 is another event which has an impulsive onset, but still does not look like a microseism. None of these ‘noise’ events were correlated between the two stations, meaning that even if they were true earth seismic events, they were very small and localized. The background noise at this site was expected to be influenced by commercial windmills which were operating near both stations. However no records of on/off times for the windmills were available, so we can not characterize the windmill noise specifically. Figure 7 show examples of background noise in the frequency domain (spectral content).

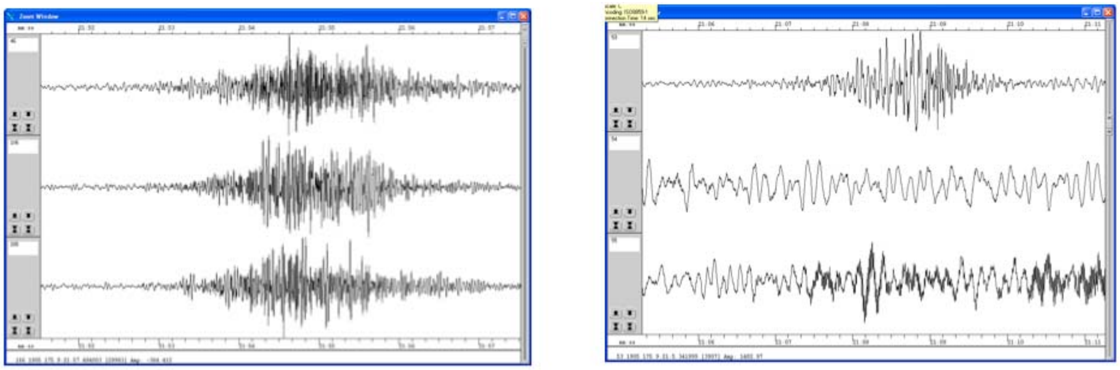

Figure 5. Two typical noise events which are not interpreted as earthquake events because of the lack of clear P- and S-wave arrivals and the non-impulsive onset.

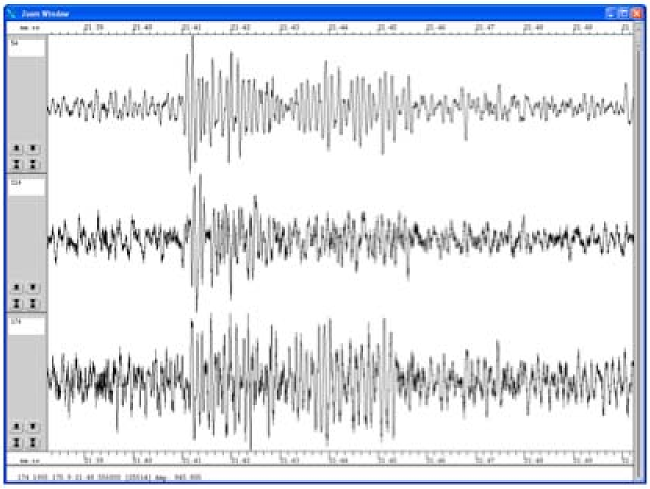

Figure 6. An impulsive event which is not interpreted as earthquake event because of the lack of clear S- wave arrival and the sudden end of high amplitudes.

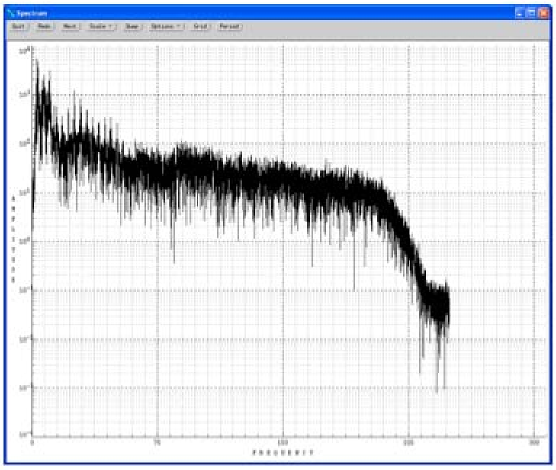

Figure 7. Spectral analysis of a noise recording showing the amplitude as a function of frequency.

One question addressed by the temporary stations was the ability of the REF TEK units to operate on ‘triggered’ event mode versus the continuous recording described previously. The triggered data worked very well. All of the triggered data were scanned and we found that every observable noise event was in the triggered data. This gives confidence that nothing would be missed if only the triggered data was recorded, which makes the identifying of events much more efficient. Also, any noise event was entirely recorded, no matter how long it was. The data for each day took about 5 minutes to manually scan, with some possibility of missing an event. There were between 0 and 10 triggers a day, with an average of 3 triggers, which means a month worth of triggers can be scanned in a few minutes. However, only one component of the data was recorded in triggered mode, so the continuous data is used in this report.

We searched the NCEDC catalog for events within 10 miles during the time of our temporary array deployment, and found 3 in the catalog (Table 1). There did not appear to be any observable events in our data at the time the first two catalog events. However, there was a clear event at the time of the third EQ (2010/06/21 22:29:06.80) shown in Figure 8.

Table 1. Events from the NCEDC data base during our deployment

Date	Time	Lat	Lon	Depth	Mag	Magt	Nst
2010/06/08	16:55:52.90	38.0920	-121.9330	22.93	1.78	Md	13
2010/06/09	11:05:13.10	38.1117	-121.8777	18.97	1.59	Md	10
2010/06/21	22:29:06.80	38.0785	-121.8705	20.63	2.13	Md	45

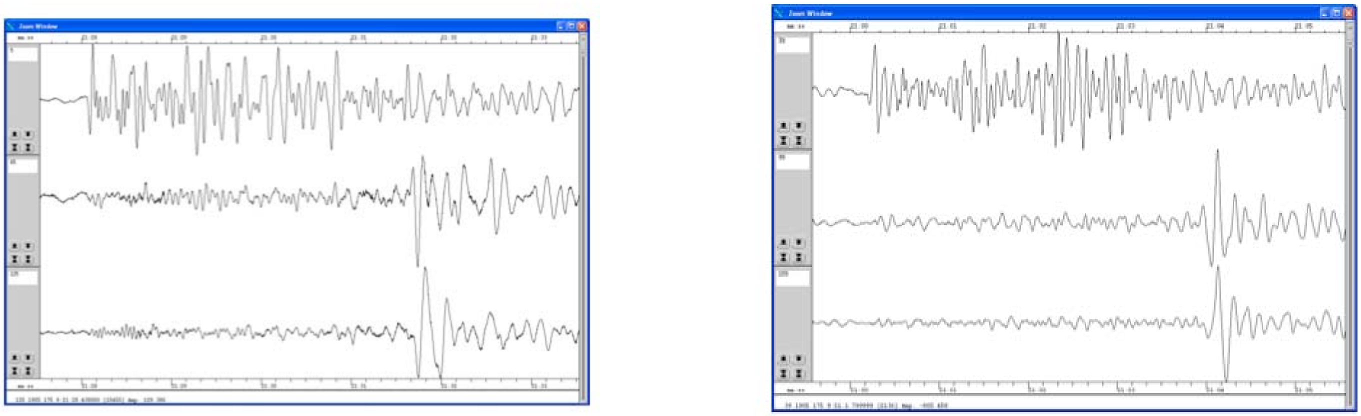

Figure 8. An earthquake event, identified as magnitude 2.1 from the NCEDC database, shown for station MH-1 (left) and MH-2 (right). The three seismograms are vertical, North and East (top, middle, and bottom, respectively).

Conclusions

Initial investigation of natural seismicity in the Montezuma Hills area found that the publicly available data sets were useful in characterizing historical seismicity, but that the locations of events in those databases were not very good for the study area. Our relocation of events showed a significant shift in locations. This highlights the need for dedicated monitoring stations designed for accurate locations in the area of study. The temporary array at Montezuma Hills was successful in characterizing noise sources, sensitivity and data recording parameters. At this point the study is suspended, however future work in the area will benefit from initial investigations.

Acknowledgement

This work was supported by the Office of Fossil Energy through the National Energy Technology Laboratory under Cooperative Agreement DE-FC26-05NT42593 with the California Energy Commission, and Lawrence Berkeley National Laboratory under U.S. Department of Energy Contract No. DE-AC02-05CH11231.

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Appendix 1.

Relocated Events

Date	Time	Lat	Lon	Depth	Mag	Magt	Nst	Gap	Clo	RMS	SRC	Event ID
1980/01/24	05:18:47.49	38.0708	-121.8657	18.12	2.63	Md	41	108	11	0.16	NCSN	1050025
1983/06/09	04:05:51.24	38.1365	-121.8647	17.69	3.10	Md	109	47	6	0.27	NCSN	1096431
1983/09/20	00:35:11.24	38.1585	-121.9360	19.40	2.59	Md	25	91	12	0.19	NCSN	1103125
1984/10/28	11:35:46.61	38.0698	-121.8727	18.27	2.84	Md	46	103	11	0.16	NCSN	30821
1986/04/05	17:32:42.90	38.1717	-121.9142	17.55	2.52	Md	33	64	10	0.19	NCSN	69554
1987/11/17	14:52:18.25	38.1562	-121.8625	17.14	2.86	Md	62	39	5	0.25	NCSN	108533
1988/06/20	01:15:58.30	38.1235	-121.8777	21.05	3.20	Md	50	60	7	0.15	NCSN	119328
1988/06/20	20:06:00.51	38.1235	-121.8787	21.01	2.94	Md	42	85	8	0.14	NCSN	119319
1989/09/11	16:20:35.74	38.0840	-121.8657	19.64	2.87	Md	55	60	10	0.14	NCSN	143902
1989/10/01	12:21:37.36	38.1550	-121.8990	16.62	2.70	Md	78	58	27	0.25	NCSN	144828
1989/10/01	13:10:24.28	38.1410	-121.9315	17.64	3.00	ML	121	35	25	0.28	NCSN	144913
1989/10/01	13:19:27.50	38.1640	-121.9252	15.59	3.20	ML	149	24	28	0.37	NCSN	144978
1989/10/01	21:41:58.64	38.1453	-121.9372	17.84	2.54	Md	36	89	12	0.14	NCSN	144940
1989/10/02	11:20:19.54	38.1470	-121.9135	21.56	2.70	Md	40	61	10	0.13	NCSN	144873
1990/04/18	14:03:04.30	38.1137	-121.8632	20.93	2.52	Md	19	122	7	0.15	NCSN	156402
1992/08/20	02:31:06.64	38.1328	-121.9125	20.18	3.34	Md	52	81	10	0.08	NCSN	311727
1992/11/23	20:59:55.56	38.0762	-121.8580	17.91	3.26	Md	54	61	10	0.10	NCSN	326667
1994/05/10	18:26:35.80	38.1045	-121.8767	20.94	2.68	Md	43	97	9	0.10	NCSN	401972
1994/07/11	18:25:48.81	38.0878	-121.8703	18.74	2.71	Md	37	108	9	0.06	NCSN	30052630
1996/07/15	19:39:47.35	38.1145	-121.8577	21.64	2.62	Md	37	101	7	0.11	NCSN	30113343
1996/07/15	21:44:36.35	38.1155	-121.8600	21.14	3.22	Md	67	90	7	0.12	NCSN	30113368
1996/07/17	11:06:30.65	38.1120	-121.8583	21.56	2.79	Md	53	61	7	0.12	NCSN	30113545
1997/03/26	14:06:24.53	38.1568	-121.9307	22.74	2.58	Md	45	96	11	0.12	NCSN	499512
1997/03/26	15:34:59.51	38.1517	-121.9300	21.67	2.81	Md	48	65	11	0.06	NCSN	499523
1997/03/27	10:10:45.14	38.1507	-121.9287	21.55	3.35	Md	57	86	11	0.06	NCSN	499604
1997/03/27	10:26:35.30	38.1492	-121.9287	21.88	2.92	Md	48	85	11	0.07	NCSN	499607
1997/03/27	11:11:24.51	38.1505	-121.9268	22.02	2.91	Md	51	86	11	0.06	NCSN	499624
1997/03/27	11:30:06.99	38.1500	-121.9335	21.52	3.57	Md	60	65	12	0.09	NCSN	499625
1997/03/27	13:38:08.84	38.1498	-121.9273	21.33	3.33	Md	61	65	11	0.10	NCSN	499649
1997/03/27	14:01:24.23	38.1498	-121.9315	21.64	3.48	Md	60	86	11	0.08	NCSN	499650
1997/03/27	15:39:49.00	38.1510	-121.9307	21.61	3.70	Mw	63	57	11	0.08	NCSN	499656
1997/03/27	17:07:37.80	38.1528	-121.9302	21.68	2.51	Md	51	88	11	0.06	NCSN	499679
1997/03/27	17:16:42.79	38.1578	-121.9272	21.79	3.41	Md	54	90	11	0.08	NCSN	499680
1997/03/27	18:01:43.17	38.1555	-121.9352	21.83	3.38	Md	60	89	12	0.08	NCSN	499681
1997/03/27	22:16:18.77	38.1587	-121.9347	21.68	2.65	Md	59	66	12	0.07	NCSN	499719
1997/03/27	22:47:53.01	38.1510	-121.9328	21.86	3.60	Md	61	65	11	0.08	NCSN	499729
1997/03/27	22:53:07.62	38.1518	-121.9340	21.65	3.46	Md	64	57	12	0.08	NCSN	499730
1997/04/01	01:36:54.86	38.1508	-121.9300	21.57	3.65	Md	63	72	11	0.07	NCSN	500112
1997/04/01	11:25:54.45	38.1592	-121.9363	21.95	2.73	Md	55	91	12	0.06	NCSN	500135
1997/04/01	18:37:18.59	38.1563	-121.9382	21.56	3.38	Md	64	54	12	0.10	NCSN	500154
1997/04/02	12:14:12.37	38.1473	-121.9212	21.90	2.51	Md	35	92	10	0.06	NCSN	500201
1997/04/02	22:27:08.94	38.1572	-121.9397	21.55	2.70	Md	43	67	12	0.10	NCSN	500230
1999/04/04	18:12:15.38	38.0920	-121.8838	20.30	3.19	Md	62	58	10	0.13	NCSN	21006629
2002/08/16	06:06:43.99	38.0877	-121.8772	20.41	2.63	Md	49	60	10	0.09	NCSN	21240822
2007/03/05	21:26:56.29	38.0707	-121.8743	15.99	2.52	Md	43	59	11	0.25	NCSN	40194201
2009/06/04	12:49:48.96	38.1753	-121.8673	21.21	2.57	Md	78	94	6	0.25	NCSN	40237628

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POTENTIAL FOR INDUCED SEISMICITY RELATED TO THE NORTHERN CALIFORNIA CO_2 REDUCTION PROJECT PILOT TEST, SOLANO COUNTY, CALIFORNIA

Larry Myer[1], Laura Chiaramonte[2], Thomas M. Daley[1],
Daniel Wilson[3], William Foxall[2], and John Henry Beyer[1]

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DOE Contract No.: DE-FC26-05NT42593
Contract Period: October 1, 2005 - May 11, 2011

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June 15, 2010

LBNL Report # LBNL-3720E

LLNL Report # LLNL-TR-435831

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Executive Summary

The objective of this technical report is to analyze the potential for induced seismicity due to a proposed small-scale CO_2 injection project in the Montezuma Hills. We reviewed currently available public information, including 32 years of recorded seismic events, locations of mapped faults, and estimates of the stress state of the region. We also reviewed proprietary geological information acquired by Shell, including seismic reflection imaging in the area, and found that the data and interpretations used by Shell are appropriate and satisfactory for the purpose of this report.

The closest known fault to the proposed injection site is the Kirby Hills Fault. It appears to be active, and microearthquakes as large as magnitude 3.7 have been associated with the fault near the site over the past 32 years. Most of these small events occurred 9-17 miles (15-28 km) below the surface, which is deep for this part of California. However, the geographic locations of the many events in the standard seismicity catalog for the area are subject to considerable uncertainty because of the lack of nearby seismic stations; so attributing the recorded earthquakes to motion along any specific fault is also uncertain. Nonetheless, the Kirby Hills Fault is the closest to the proposed injection site and is therefore our primary consideration for evaluating the potential seismic impacts, if any, from injection. Our planned installation of seismic monitoring stations near the site will greatly improve earthquake location accuracy.

Shell seismic data also indicate two unnamed faults more than 3 miles east of the project site. These faults do not reach the surface as they are truncated by an unconformity at a depth of about 2,000 feet (610 m). The unconformity is identified as occurring during the Oligocene Epoch, 33.9–23.03 million years ago, which indicates that these faults are not currently active. Farther east are the Rio Vista Fault and Midland Fault at distances of about 6 miles (10 km) and 10 miles (16 km), respectively. These faults have been identified as active during the Quaternary (last 1.6 million years), but without evidence of displacement during the Holocene (the last 11,700 years).

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[*] Short biographies of authors are provided in Appendix 1.

The stress state (both magnitude and direction) in the region is an important parameter in assessing earthquake potential. Although the available information regarding the stress state is limited in the area surrounding the injection well, the azimuth of the mean maximum horizontal stress is estimated at 41° and it is consistent with strike-slip faulting on the Kirby Hills Fault, unnamed fault segments to the south, and the Rio Vista Fault. However, there are large variations (uncertainty) in stress estimates, leading to low confidence in these conclusions regarding which fault segments are optimally oriented for potential slip induced by pressure changes. Uncertainty in the stress state can be substantially reduced by measurements planned when wells are drilled at the site.

Injection of CO_2 at about two miles depth will result in a reservoir fluid pressure increase, which is greatest at the well and decreases with distance from the well. After the injection stops, reservoir fluid pressures will decrease rapidly. Pressure changes have been predicted quantitatively by numerical simulation models of the injection. Based on these models, the pressure increase on the Kirby Hills Fault at its closest approach to the well due to the injection of 6,000 metric tons of CO_2 would be a few pounds per square inch (psi), which is a tiny fraction of the natural pressure of approximately 5,000 psi at that depth. The likelihood of such a small pressure increase triggering a slip event is very small. It is even more unlikely that events would be induced at the significantly greater depths where most of the recorded earthquakes are concentrated, because it is unlikely that such a small pressure pulse would propagate downwards any appreciable distance.

Therefore, in response to the specific question of the likelihood of the CO_2 injection causing a magnitude 3.0 (or larger) event, this preliminary analysis suggests that no such induced or triggered events would be expected. However, it is possible that a fault, too small to be detected by the existing seismic data, yet sufficiently large to cause a magnitude 3 event, could exist in close proximity to the injection point where the pressure increase could cause slippage. However, the existence of such a fault would be detectable in the data planned for collection from the well prior to injection. We do note that natural earthquake events of up to 3.7 in magnitude have occurred in this area and would be expected to occur again regardless of the proposed CO_2 injection.

To reduce the uncertainties discussed above, we recommend (1) installing a seismic monitoring network to record natural and possible induced seismic activity before, during, and after CO_2 injection; (2) collecting well log data and core samples from the wells to assess the in-situ stress state and fracturing near the wells; (3) using this information to refine operating procedures to minimize the risk of significant induced seismicity and develop a protocol for mitigation should it occur; (4) conducting geomechanical analyses and developing a probabilistic seismic hazard analysis (PSHA) during and after injection; (5) as the project progresses, relocating microearthquakes in the Northern California Seismic Network catalog, calculating focal mechanisms where possible, and improving characterization of the Kirby Hills Fault; and (6) evaluating PSHA results for the Montezuma Hills area.

Introduction

The objective of this report is to analyze the potential for induced seismicity due to a proposed small-scale CO_2 injection project in the Montezuma Hills.

To address this question, it is necessary to understand the present-day stress state, its relationship with the preexisting faults in the area, and the effects of pressure changes resulting from injection activities. Therefore, currently available information on faults and the stress state in this region has been assembled and used in conjunction with preliminary simulation data to assess the potential for slip on the preexisting faults. Finally, recommendations are made for specific actions to address the potential for induced seismicity due to injection operations.

Faults in the Vicinity of the Montezuma Hills

Figure 1 shows mapped faults in the vicinity of the proposed small-scale injection project. Information is reproduced from the California fault map compiled by the California Geological Survey (CGS) (Jennings and Bryant, 2010; http://www.consrv.ca.gov/cgs/cgs_history/Pages/2010_faultmap.aspx), which is the state agency responsible for assessing the natural seismic hazard potential throughout California. Also shown are a small subsurface fault, the Sherman Island Fault, and the blind Midland fault, both identified in a report on the probabilistic seismic hazard analysis (PSHA) supporting the California Department of Water Resources Delta Risk Management Strategy (DRMS) (URS Corporation/Jack R. Benjamin & Associates, 2007).

Kirby Hills Fault

The trace of the Kirby Hills Fault (KHF) on the CGS fault map is located approximately 3 miles (5 km) west of the proposed injection site (Figure 1). The CGS map characterizes the KHF as active during the Quaternary (last 1.6 million years), but finds no evidence of surface displacement along the fault trace since the early Quaternary period (at least 700,000 years ago) (Jennings and Bryant, 2010). (The Vaca fault immediately to the north is shown as active during the last 700,000 years.) However, based on seismic reflection data along the Sacramento River and on microseismicity, Parsons et al. (2002) concluded that the KHF zone has been recently active at depth, predominantly in a strike-slip (SS) direction, and along a fault plane that dips 80º–85º east. The DRMS report characterizes the KHF as active in the Holocene (last 11,700 years). Figure 2 shows the earthquakes recorded by the USGS/UC Berkeley Northern California Seismic Network (NCSN) between 1974 and 2001, relocated by Parsons et al. and assumed to be associated with the KHF zone. Microearthquake focal mechanisms presented by Parsons et al. (2002) reveal both strike-slip and reverse components of fault slip, with the reverse component increasing to the north of the proposed injection well location. The majority of the earthquake hypocenters located by Parsons et al. lie between 9 and 17 miles (15 and 28 km) in depth, which is unusually deep for this region of California.

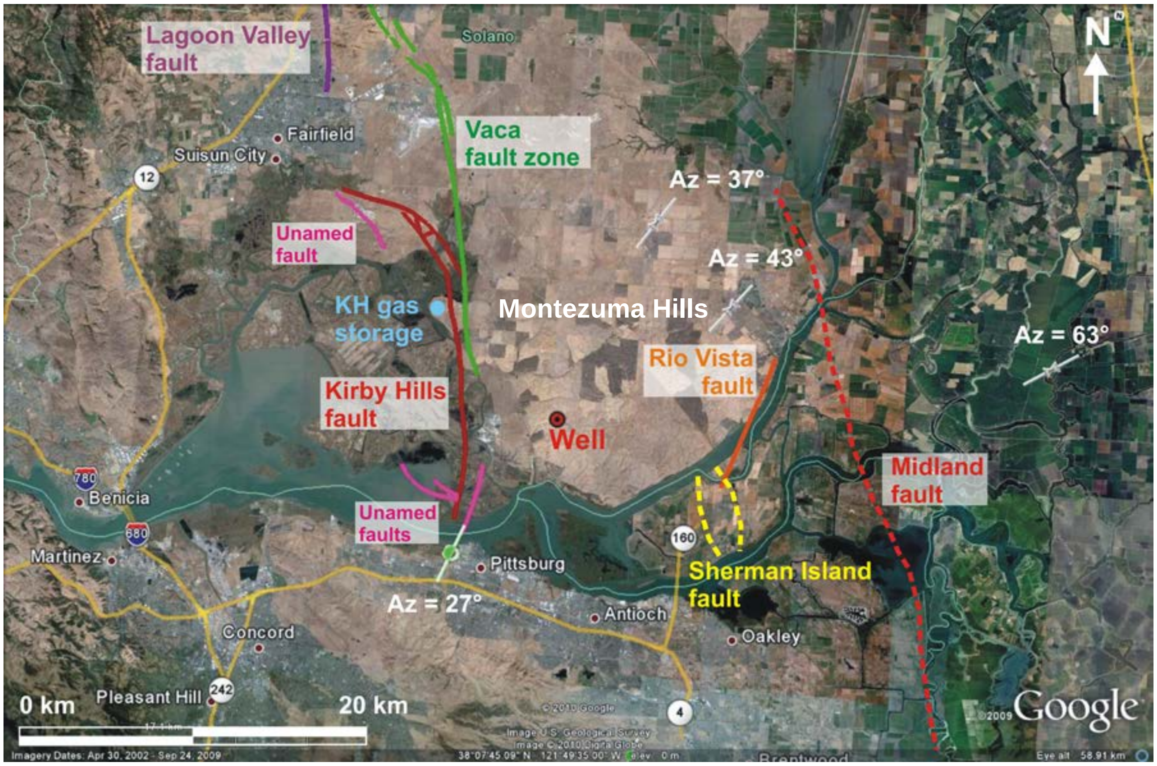

Figure 1 Faults and maximum horizontal stress (S_{Hmax}) direction in the area under study. Solid lines correspond to faults with surface expression taken from the CGS fault map (Jennings and Bryant, 2010); dashed lines are subsurface faults from the DRMS report (URS Corporation/Jack R. Benjamin & Associates, 2007). S_{Hmax} directions are plotted as short gray lines (Heidbach et al., 2008). S_{Hmax} symbols with a green dot are determined from single earthquake focal mechanisms (FMS). The lines without a green dot come from borehole breakout observations. The proposed injection site is indicated with a red dot labeled "Well."

Midland Fault

The Midland Fault (Figure 1) is located about 10 miles (16 km) east of the proposed injection site. It is described in the DRMS report as an approximately 37-mile (60-km) long, north-striking and west-dipping blind fault underlying the central Delta region. It is interpreted as an early Tertiary, normal fault that was reactivated in the late Cenozoic as a reverse fault, and it is shown on the CGS fault map as active during the Quaternary, but without evidence of Holocene movement (last 11,700 years). The Midland fault has been characterized primarily from natural gas exploration well data and analysis of overlying folding. The fault breaks into a series of northwest-striking splays associated with a series of active and abandoned gas fields in the Sacramento Valley between the towns of Rio Vista and Woodland (URS Corporation/ Jack R. Benjamin& Associates, 2007).

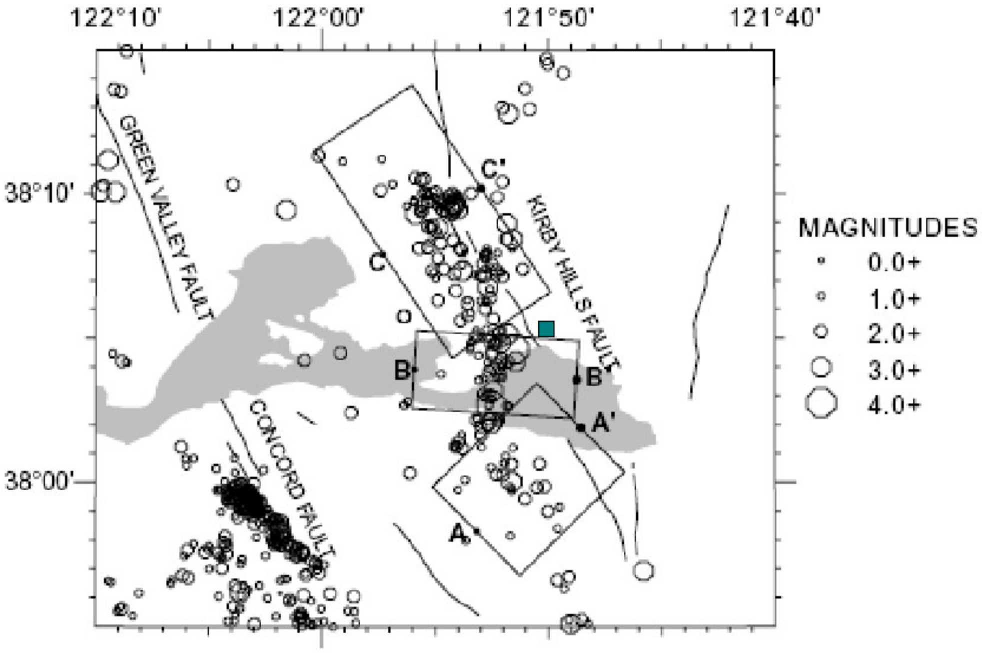

Figure 2: Kirby Hills Fault zone and associated seismicity from 1974–2001, recorded by the Northern California Seismic Network and relocated by Parsons et al. (2002). The proposed well site is shown by a green square.

Sherman Island/Rio Vista Fault Zone

The Sherman Island fault zone, at its closest point, is located approximately 5 miles (8 km) southeast of the proposed injection site (Figure 1). According to the DRMS report, this fault has been identified only in the subsurface and was active in late Cretaceous-early Tertiary time. To date, the fault has not been studied for evidence of Quaternary reactivation. The CGS fault map shows the Rio Vista fault at the same location as the Sherman Island fault, but the Rio Vista fault appears to have a different strike than that of the Sherman Island fault. CGS identifies the Rio Vista fault as active during the Quaternary, but without evidence of Holocene movement (last 11,700 years).

Montezuma Hills Fault

A geomorphic feature trending NNW-SSE along the southwestern edge of the Montezuma Hills is identified as the “Montezuma Hills Fault” in a California Division of Mines and Geology (DMG) report (1983). However, DMG Fault Evaluation Report FER-136 (1982) cites evidence from geophysical surveys, boreholes, and trench excavations that the feature is likely erosional, resulting from a meander of the Sacramento River. As a result of this evidence, William A. Bryant, a lead author of both reports, said that the feature is not shown on subsequent CGS fault maps. Upon seeing the seismic profile shown in Figure 4 below, Bryant said that this corroborates the interpretation that the Montezuma Hills “Fault” is, in fact, an erosional feature (Bryant, 2010).

Unnamed Buried Faults

As discussed in the Seismic Data Interpretation section below, two faults were detected at least 3 miles east of the project area by Shell's east-west trending 2D seismic line. They are not shown on geologic maps because they do not reach the surface.

Natural Seismicity in the Project Area

The microearthquakes relocated by Parsons et al. (2002) and assumed to be associated with the KHF zone (Figure 2) were discussed above. Figure 3 shows the NCSN catalog locations of magnitude 2.5 and greater earthquakes within the area immediately surrounding the project site for the period January 1, 1978, through January 28, 2010. The largest event recorded within the area during this period has a catalog magnitude of 3.7 and depth of 22 km (14 miles). Preliminary examination of the recorded NCSN data indicates that the uncertainties in many of the catalog locations may be relatively large, due primarily to the scarcity of recording stations in the surrounding area, particularly to the east of the injection site (Figure 3). Therefore, a focused study of the locations and mechanisms of the better recorded events should be carried out to better define the relationship of the microearthquakes to the KHF in the immediate vicinity of the site. The largest earthquake recorded in the larger area considered by Parsons et al. (Figure 2) was M 4.3. This event was located at a depth of 20 km (12 miles) below the confluence of the San Joaquin and Sacramento Rivers.

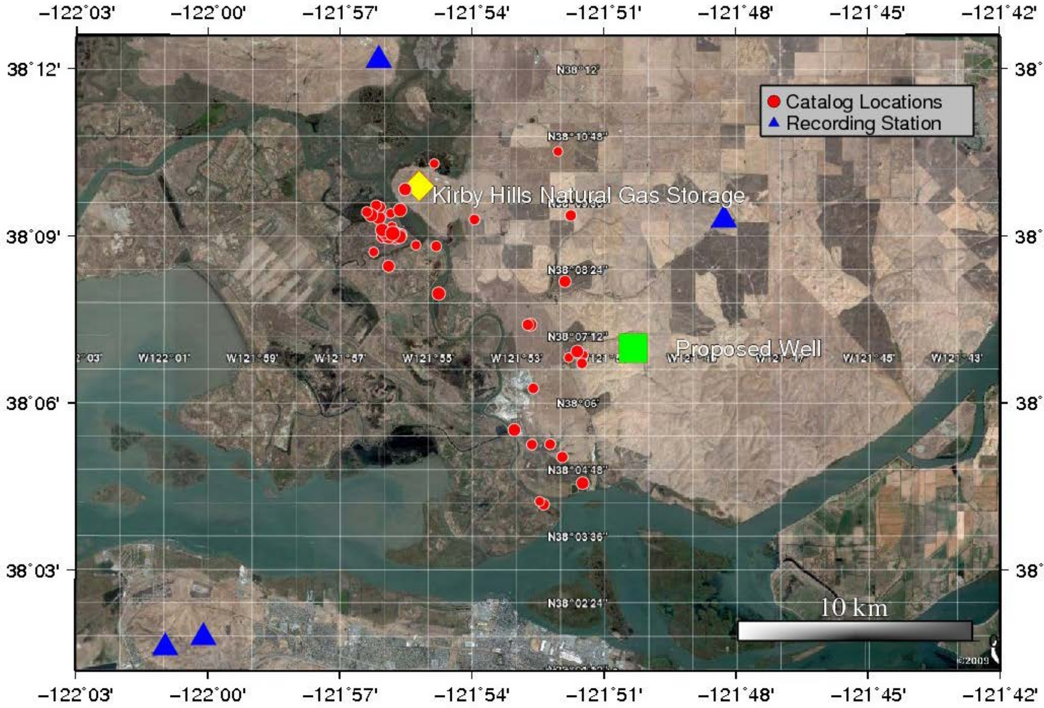

Figure 3. Seismicity with magnitude of at least 2.5 for the period 1/1/78-1/28/10 (red dots) in the area surrounding the injection site (green square) from the NCSN catalog. The largest event had a magnitude of 3.7. Blue triangles are NCSN recording stations.

Seismic Data Interpretation

Shell developed an initial model of the subsurface geologic structure in the vicinity of the project based in part on an internal interpretation of twenty 2D seismic lines. LBNL has carried out an independent analysis of the seismic data and concurs with the Shell interpretation. As shown in Figure 4, the seismic data indicate that the structures closest to the proposed injection well are two unnamed faults (labeled Fault A and Fault B), and the Kirby Hills Fault.

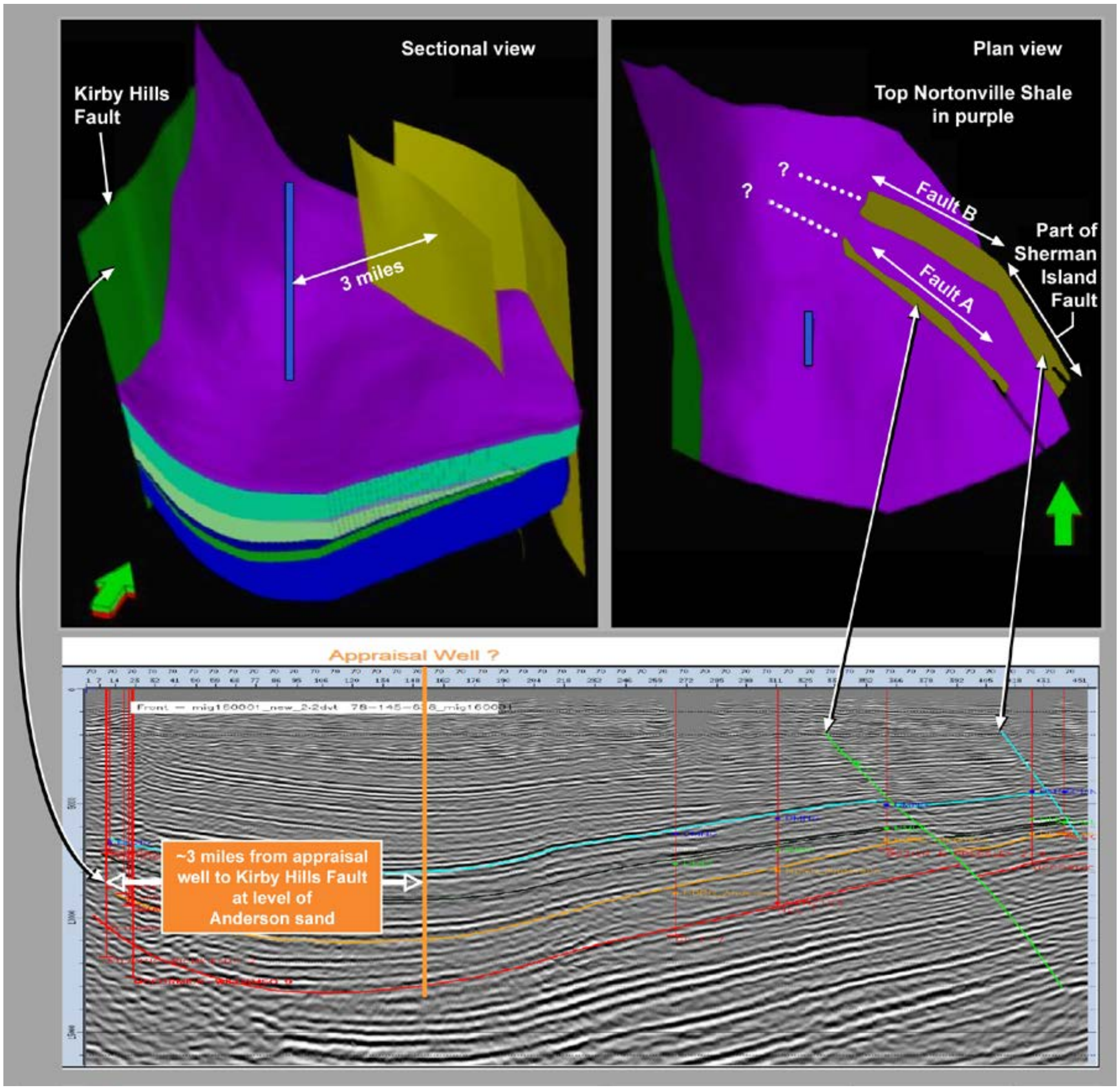

Figure 4: *Top*: Views of Shell's 3-D geologic model based on offset well log data and twenty 2-D seismic lines showing the Kirby Hills Fault, buried Fault A and Fault B, and site of proposed well. *Bottom*: Shell's east-west 2D seismic line, which passes about 1,700 feet (520 m) south of the proposed well location, showing interpreted Kirby Hills Fault Zone and buried Faults A and B. This model and all the seismic data were reviewed by Daniel Wilson, one of the report authors; he concurs with Shell's analysis and interpretation of the data.

Fault A is more than 3 miles (5 km) from the proposed injection well at reservoir depth. Neither Fault A nor Fault B reach the surface as they are truncated by an unconformity at a depth of about 2,000 feet (610 m). The unconformity is identified as occurring during the Oligocene Epoch, 33.9–23.03 million years ago. Since the faults do not extend into the formations overlying the unconformity, it indicates that these faults have not been active since the Oligocene. Both faults trend toward the Sherman Island fault, but further work is required to evaluate their possible relationship to the Sherman Island Fault. The seismic data also show that the Kirby Hills Fault is about 3 miles (5 km) from the proposed injection well at reservoir depth. The primary indicator of the Kirby Hills Fault in the seismic data is a "wash-out" of the seismic signals (similar to the expression of the fault in the seismic data along the Sacramento River presented by Parsons et al. [2002]). Improved delineation would require acquisition of additional seismic data.

Stress State

Limited information on the present day stress state was found for this area. Orientations of the maximum horizontal stress were compiled from the World Stress Map (Heidbach et al., 2008). The mean maximum horizontal stress (S_{Hmax}) azimuth is 41°. Measured values (Figure 1) near the proposed pilot well are 20°, 27°, 37°, 43°, 54° and 63°. These orientations were estimated from single focal mechanisms (FMS) (short gray lines with green dot in Figure 1) and borehole breakouts (short gray lines). The FMS analyses also indicated a strike slip (SS) stress regime.

Dr. Haibin Xu from Shell performed a Fracture Pressure Prediction study and found indications from leak-off tests and seismic observations of offsets on the faults that the stress state could accommodate reverse faulting (RF regime) at the surface and strike slip (SS regime) at depth (Xu, 2010). The limited available information regarding the stress state indicates that the area surrounding the injection well could be an oblique faulting SS/RF environment, consistent with the focal mechanism solutions reported by Parsons et al. (2002). Uncertainty in the stress state can be substantially reduced by measurements made when the proposed well is drilled.

Relationship Between Faults and *In situ* Stress

Knowledge of the orientation of the *in situ* stresses enables identification of faults that are most prone to movement under that stress regime. This is the first step in evaluating the likelihood of fault movement, which also requires an analysis of the magnitude of stress change required to cause movement on a fault. Under a strike slip (SS) stress state, faults oriented approximately ±30° from the S_{Hmax} direction are most prone to slip. Under a reverse faulting (RF) environment, the optimal fault orientation for movement is sub-perpendicular to the S_{Hmax} direction (Zoback, 2007). However, there are certain values of the *in situ* stress tensor that correspond to both SS and RF regimes. If a region is characterized by an SS/RF state of stress, then faults having multiple orientations could be prone to movement at the same time.

Figure 5 shows the faults and stress orientation near the proposed injection well based on currently available data. It also shows the mean S_{Hmax} direction (red line in lower right circle), the optimal direction for movement in a SS regime (dotted green lines), and the optimal direction for movement in a RF regime (blue line).

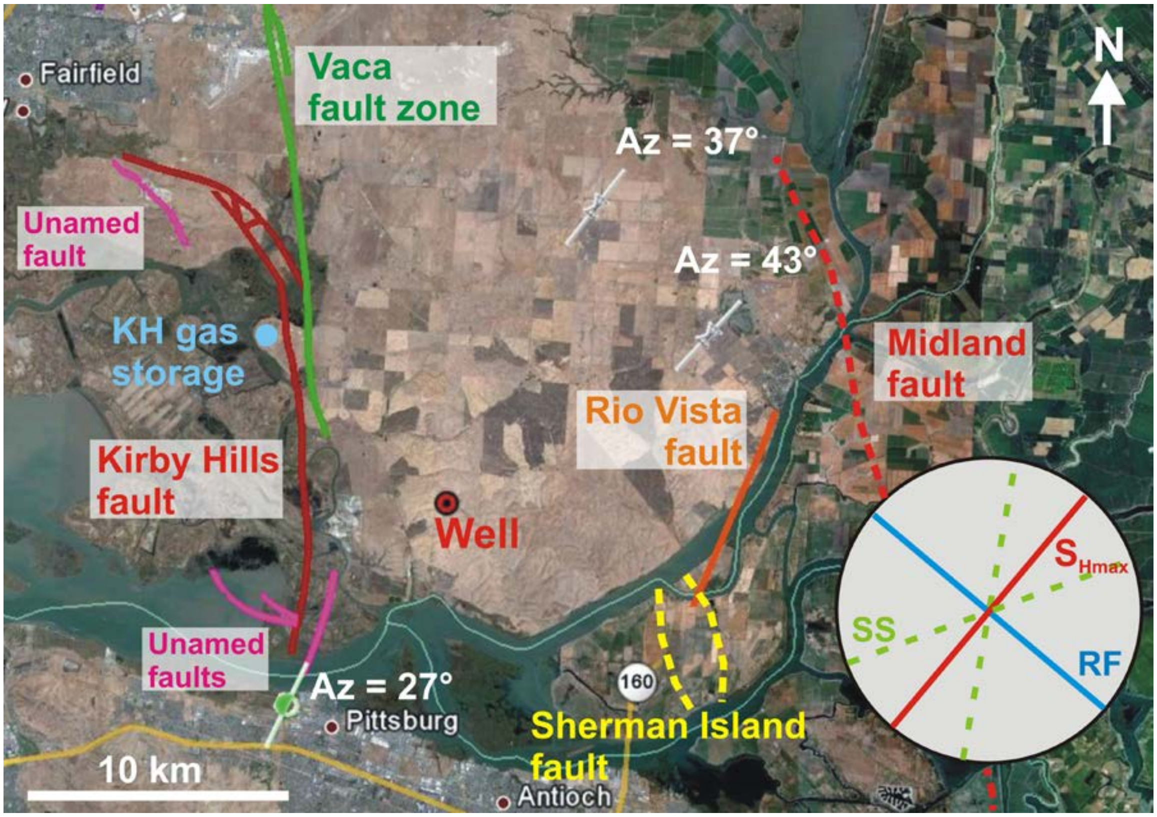

Figure 5: Faults and maximum horizontal stress direction near the proposed injection well (red dot). The circle in the lower right corner shows the mean S_{Hmax} direction (red), the optimal directions for fault movement for SS (green) and for RF (blue).

Comparison of the SS and RF directions with the fault traces shown in Figure 5 suggests that segments of the KHF, the unnamed faults south of the KHF, and the Rio Vista Fault, are oriented in directions most favorable for movement. The level of confidence in this conclusion is low, however, due to the large scatter in the stress observations near the injection well, which results in uncertainty in the orientation of the stress field, and due to uncertainty in the geometry of the fault planes at depth. Since the KHF is active, it is assumed that its fault plane is favorably oriented for slip at least in the depth range within which microearthquakes have occurred. It is possible that the *in situ* stress orientations change with depth, but additional data are required to support such a hypothesis.

Relationship Between Faults and Reservoir Pressures

Injection of CO_2 will result in a reservoir fluid pressure increase, which is greatest at the well and decreases with distance from the well. After the injection stops, reservoir fluid pressures will decrease rapidly, approaching pre-injection values for situations in which the storage reservoir is very large in comparison to the volume of injected fluid. It is well known that injection operations can induce fault movement if pressures in a fault zone are increased to a level where the resistance to slip on the fault is exceeded. Faults with optimum orientation with respect to the natural stress direction, as described in the previous section, will in general require relatively smaller pressure increases than those having other orientations.

Since the Kirby Hills Fault is the active fault closest to the injection test site, we made a preliminary assessment of the potential for slip on this fault due to the pressure increase expected from the proposed volume of injection. As the basis for this assessment, we used the results of a preliminary reservoir simulation performed by Shell to predict pressure increases due to the planned 6,000 metric ton CO_2 injection. The values for subsurface parameters used for this simulation are shown in Table 1. After the first well is drilled and data are collected, simulations will be recalculated.

Table 1: Parameter values used in pressure increase simulation

Parameter	Assigned Value
Depth of injection	11,200 feet TVDss*
Pore pressure	4,800 psi
Temperature	228^{o}F
Net-to-Gross Ratio	1
Porosity	20%
Permeability	20 millidarcies
Vertical/horizontal permeability ratio	0.1
Dip angle	3 degrees

* True vertical depth sub sea

The western boundary of this model was placed at about 10,000 feet (1.8 miles, 3 km) from the injection well in the form of a “no-flow” hydrologic boundary condition (equivalent to the assumption of a sealing fault). The simulated increase in pressure at the western boundary of the model is less than 0.08 MPa (12 psi), which corresponds to 0.2% of the hydrostatic pore pressure of about 5,000 psi (34.5 MPa) at the Anderson Formation depth of 2.1 miles (3.4 km). This maximum pressure increase occurred 150 days after injection stopped, with pressures declining thereafter. The Kirby Hills Fault is about 1.2 miles (2 km) farther to the west from the western boundary of the model, and so the pressure increase extrapolated from the model to the fault at a depth of about 2.1 miles (3.4 km) would be considerably less than 12 psi. Even if the fault is optimally oriented for movement at the injection depth, the likelihood of such a small pressure increase triggering a slip event is very small. It is even more unlikely that events would be induced at the significantly greater depths where most of the recorded microearthquakes are concentrated, because it is unlikely that such a small pressure pulse would propagate downwards over any appreciable distance (e.g., Segall, 1985).

Discussion

To understand what size of fault can produce a magnitude 3 earthquake, we can use one of the numerous scaling relationships for the magnitude of an earthquake versus the area of slip (e.g., Shaw, 2009; Kanamori, 1977). Using Kanamori (1977), a 250-m (820-ft) radius fault is needed to produce a magnitude 3 earthquake, which would correspond to a circular fault area of ~0.2 km^2 (~0.08 mi^2). This could easily be accommodated by any of the faults discussed above. However, as discussed in previous sections, multiple factors influence the potential for slip on any particular fault. Based on Shell's preliminary reservoir modeling, the faults near the injection well would experience, at most, a very small increase in fluid pressure. Therefore, this preliminary analysis suggests that no slip events would be expected due to the proposed injection.

In general, the greatest increase in storage reservoir fluid pressure occurs in a limited volume around the injection well; for example, Shell's reservoir simulations showed that the region of pressure increase in excess of 30 psi (0.21 MPa) will extend for about 0.6 mile (1 km) in all lateral directions from the well. Review of the seismic reflection data did not reveal any faults within this area. However, if a fault or fracture with a radius of 820 feet (250 m) does exist this close to the CO_2 injection point, the resolution of the existing seismic data is probably not sufficient to detect it. Therefore, based on currently available data, it is not possible to say whether or not a fault or fracture of 250-m radius is present near the proposed well. However, a stress increase of even 30 psi is relatively insignificant compared to the estimated natural pressure of about 5,000 psi at the injection depth, so the likelihood of triggering an event is also relatively small. Once the well is drilled, information will be available to reduce this uncertainty significantly.

As discussed above, the injection operation is not expected to cause slip on the Kirby Hills Fault. However, review of the natural seismicity reveals several naturally occurring earthquakes having magnitudes greater than 3 since the late 1970s. A recurrence analysis has not yet been carried out, but a natural earthquake greater than magnitude 3 will certainly occur eventually in the area, independent of any possible effects of the injection project.

If future injection projects involving larger volumes are considered for this site, a site-specific probabilistic seismic hazard analysis (PSHA) is recommended. PSHA is the calculation of the probability that a particular ground-motion measure (acceleration or velocity) will exceed given amplitude thresholds at one or more places of interest during a specified time period (e.g., Hanks and Cornell, 2008). The first step would be to refine the PSHA for the naturally-occurring seismicity in the area published by CGS/USGS by carrying out more detailed characterization of the local active faults. The second step would be to assess the influence on the seismic hazard of potential induced seismicity associated with a large-scale injection project.

At present, definitive, quantitative statements about the likelihood of induced seismicity are difficult to make because of the present lack of data and uncertainty in the subsurface structure. To improve risk assessment and to begin acquiring the data necessary for analysis, a high-resolution microseismic monitoring network should be installed to detect and locate seismic events that might occur in the site region. This local network would be capable of detecting smaller events than the USGS regional network and provide improved event location accuracy. The network should be integrated into the regional seismic network and installed as soon as possible, in order to record the maximum number of naturally occurring events as a baseline before injection of CO_2 begins.

Conclusions and Recommendations

Initial geologic characterization studies performed to date have identified mapped and unmapped faults and other structural features in the area surrounding the proposed injection well. From an analysis of the available data on *in situ* stresses and preliminary reservoir simulations, the likelihood of slip on these faults resulting from the proposed 6,000 metric ton injection is judged to be very low. Examination of the local seismicity shows that natural earthquakes having magnitudes greater than 3 have occurred in the past and consequently are likely to recur in the area regardless of injection operations.

To reduce the uncertainties discussed above (including uncertainties about fault locations and *in situ* stress directions), we recommend several actions:

1. Prior to well drilling and injection: Install a microseismic network as soon as possible to begin to compile a high-resolution baseline of natural seismicity and seismicity induced by human activities in the area. The network will remain in place to monitor for natural seismicity and any induced seismicity that may occur during injection operations.[†]
2. Once wells are drilled: Collect information on the *in situ* stress state and natural faulting or fracturing near the wells.
3. After drilling and prior to injection: Reassess the potential for operating conditions during injection to induce significant seismicity and develop a protocol for responding to any significant natural or induced events recorded by the network.
4. During and after injection: Carry out additional geomechanical analyses using information obtained during the small scale injection, and develop a PSHA which includes potential induced seismicity at the site.
5. Simultaneously with field work: Carry out focused studies to relocate the better recorded microearthquakes listed in the NCSN catalog for the site area and to calculate focal mechanism solutions for selected events. Evaluate the relationship of the relocated earthquakes to the KHF to improve characterization of the fault.
6. Simultaneously with field work: Evaluate PSHA results for the Montezuma Hills area in the DRMS report (URS Corporation/Jack R. Benjamin & Associates, 2007).

[†] Two temporary seismic stations have been installed to collect initial data. Additional details are provided in Appendix 2.

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Appendix 1

Biographies of Authors

Larry Myer is a retired Staff Scientist at Lawrence Berkeley National Laboratory, Earth Sciences Division (ESD), where he has conducted research in geophysics and geomechanics since 1981. He has a Ph.D. in Geological Engineering from the University of California, Berkeley. Dr. Myer's research experience spans a wide range from basic theoretical and laboratory investigations of rock properties and processes to field measurements of rock behavior and instrumentation development. Basic research activities have been directed at understanding the microprocesses associated with deformation and failure of rock, seismic wave propagation, and fluid flow in fractured porous media. A particular focus has been the mechanical, hydrologic and seismic properties of single fractures and faults with the development of new theoretical concepts accompanied by laboratory and field validation experiments. Dr. Myer has been leading research activities in geologic sequestration since 1999. He co-directed the DOE funded QEO-SEQ project, an applied R&D effort focused on monitoring and verification, and subsurface flow and transport in geologic sequestration. As part of the GEO-SEQ project, he led the development of the monitoring program for the Frio CO_2 injection pilot. The Frio pilot was the first saline formation CO_2 pilot in the United States. As Geologic Sequestration Program Head, he was responsible for programmatic leadership of the ESD geologic sequestration research program, a multidisciplinary effort focused on monitoring, risk, and reservoir performance of sequestration projects. The ESD Geologic Sequestration Program includes research conducted as part of major international sequestration projects, including Weyburn, Canada, Otway, Australia, and In Salah, Algeria. Most recently, until his retirement, Dr. Myer was Technical Director of the West Coast Regional Carbon Sequestration Partnership (WESTCARB), which is evaluating CO_2 sequestration options and opportunities for the west coast of North America.

Laura Chiaramonte is in the Computational Geosciences Group at Lawrence Livermore National Laboratory (LLNL). She holds a Ph.D. in Geophysics from Stanford University (2008), an M.S. in Structural Geology and Geomechanics from Stanford University (2003) and a B.S. in Geological Sciences from the Universidad de Buenos Aires (1996). Prior to joining LLNL in 2010, she was a postdoctoral fellow at Lawrence Berkeley National Laboratory (LBNL). From 1997-2001, she worked for REPSOL-YPF in Argentina as a structural and reservoir geologist.

Tom Daley works as a research scientist in the Earth Sciences Division of Lawrence Berkeley National Laboratory. He has been with Berkeley Lab since 1987. He received a Bachelors degree in Geophysics from the University of California, Berkeley in 1980 and a Masters degree in Engineering Geoscience from UC Berkeley in 1987. He worked from 1980 to 1985 with Seismograph Service Corporation performing borehole seismic surveys and managing a district office in Ventura, CA. Tom's research work is focused on the acquisition and analysis of borehole seismic data from field scale experiments. Problems addressed have included continuous travel time monitoring to detect stress changes, monitoring of geologic sequestration of CO_2, characterization of fracture content and dominant fracture orientation in geothermal and oil fields, high resolution imaging of shallow surface materials, imaging fracture flow zones in contaminated aquifers, and geophysical characterization of volcanic tuff flows for nuclear waste isolation at Yucca Mountain. Tom is a member of AGU since 1987 and has been a member of SEG since 1980, and is currently on the SEG CO_2 research subcommittee.

Daniel Wilson is the principal at Daniel Wilson & Associates, Inc., a geophysical consultancy near Houston, Texas. Mr. Wilson has 40 years of experience interpreting seismic data for the evaluation and development of oil and gas prospects. From 2003-2009 he consulted for Davis Petroleum Corp. and Stephen Production Co. analyzing and reprocessing 3D seismic data for several prospects in Louisiana and Oklahoma. From 1992-2003 he worked as a Geophysical Advisor for Anadarko Petroleum interpreting 2D and 3D seismic data, evaluating oil and gas prospects, and/or overseeing geophysical activities on domestic projects in Texas, Louisiana, Mississippi, Kansas, Oklahoma, and Alaska; and international projects in Venezuela, Brazil, Jordan, and near the South Caspian Sea. In prior years Mr. Wilson held positions of Senior Staff Geophysicist at Anadarko Petroleum Corporation in Oklahoma City; Project Leader/Division Geophysicist at Tenneco Oil in Oklahoma City; and Geophysicist at Texaco in New Orleans. He earned a B.S. in Geology from Lamar University in Beaumont, Texas, in 1969.

William Foxall is a seismologist with over 30 years of experience in seismic hazard analysis. He earned an M.S. in geophysics from the University of Washington in 1976 and his Ph.D. in geophysics from the University of California, Berkeley, in 1992. He has been employed at the Lawrence Livermore National Laboratory since 1996, and was at the Lawrence Berkeley Laboratory from 1992 to 1996. His work at the Laboratories has included probabilistic seismic hazard analysis, seismic source physics, nuclear forensics, and interferometric synthetic aperture radar analysis of ground deformation related to CO_2 sequestration, enhanced oil recovery and geothermal. Prior to attending UC Berkeley, Dr. Foxall was a Senior Project Seismologist at Woodward-Clyde Consultants in San Francisco.

John Henry Beyer is a Geophysicist in the Earth Sciences Division at Lawrence Berkeley National Laboratory, and is the Program Manager for the West Coast Regional Carbon Sequestration Partnership (WESTCARB) projects in California and Arizona. Dr. Beyer earned a Ph.D. in Engineering Geoscience from the University of California at Berkeley in 1977, an M.A. in Geophysics from Washington University in St. Louis, and a B.S. in Physics from Lafayette College in Pennsylvania. Before returning to Berkeley Lab in 2007, he spent seven years at the California Energy Commission managing energy-related research projects funded by the Public Interest Energy Research (PIER) Program. As an independent consultant he managed geophysical exploration surveys of geothermal areas in Indonesia, the Azores, and Japan. He was the General Manager of a 50-employee company that developed innovative geophysical capabilities and performed magnetotelluric surveys to explore for geothermal and oil resources. This company was a spin-off from Woodward-Clyde Consultants in San Francisco, where he worked as a Senior Project Scientist developing geophysical data analysis techniques and managing geothermal resource exploration.

Appendix 2

Seismic Monitoring Stations

This map shows the proposed injection well location (near MH1); locations of two temporary seismic monitoring stations, MH1 and MH2 (yellow pins); and very tentative locations for four permanent seismic monitoring stations (green and red pins).

The two temporary stations were installed by LBNL on May 18, 2010, for the purpose of measuring seismic noise (vibrations) from the windmills and other local sources, and to see if any microearthquake events are recorded at the gain settings used. The intent is to leave the instruments in the field for about two months to acquire data that will help to determine specifications for a permanent microseismic monitoring array.

The final locations for permanent seismic monitoring stations will depend on several factors, including an appropriate distribution around the well site, low vibration noise from cultural sources, line-of-sight radio telemetry for data transmission, land owner agreements, ease of access, security, and avoidance of interference with farmers, ranchers, and wind turbine operators.

Acknowledgment/Auspices

This work was partially supported by the U.S. Department of Energy and LBNL under Contract No. DE-AC02-05CH11231

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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West Coast Regional Carbon Sequestration Partnership (WESTCARB)

Down-Select Report for Task 7: The King Island Characterization Well at King Island, San Joaquin County, California

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DOE Contract No.: DE-FC26-05NT42593

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Executive Summary

As outlined in WESTCARB's SOPO, WESTCARB will use preliminary collection of available geologic and nontechnical data to select two top-ranked candidate sites for its Phase III field characterization projects: a preferred site and a backup location. WESTCARB has reached Decision Points 1 & 2 for these tasks for the California project (Task 7). This report provides a summary of the data and criteria that were used to support down-selection to the King Island site, with the Kimberlina site as a back-up. This report fulfills the deliverable to DOE as the go/no-go decision report for Task 7 to enable the DOE to determine if there is sufficient evidence including favorable geology to support a decision to proceed with the installation of the test borings. Additional information on access and permitting is also provided.

Under its new Phase III directive, WESTCARB will not be performing an injection at any scale; thus, the major technical objective of its site selection process is to find a site which would allow sample and data collection from as many of the key storage and sealing formations of the Sacramento-San Joaquin Basin as possible, the same formations which were targets for injection at the Phase II and Phase III candidate sites.

WESTCARB developed a set of geologic and geographic criteria and nontechnical/logistical criteria to rank potential characterization well sites. In addition, the site was evaluated to assure that the well plan would be able to meet the scientific objectives of the characterization well project.

WESTCARB has been performing site characterization work in California in collaboration with the California State Geologic Survey, with various industry partners with interest in CCS development, and in preparing for its Phase II pilot injection and Phase III large volume storage test phases. The knowledge gained in these endeavors was reviewed and used as a starting point for the characterization well down-selection.

Four sites were considered: King Island, Thornton, Kimberlina and Montezuma Hills. As is explained below, all sites met the geologic/geographic criteria, however the geology at King Island and available data offer some advantages over the other sites. King Island site meets the scientific objectives better than the other three sites considered. Furthermore, King Island is the only site that completely fulfills the nontechnical/ logistical criteria. Kimberlina is a close second based on these criteria and was chosen as a back-up on that basis. King Island meets the criteria, related to liability, permitting, site access and other non-technical factors necessary to assure successful completion of the project. In the case of the other sites selected, as is described in more detail below, these non-technical factors were the criteria eliminated the sites from further consideration.

1.0 Definition and Objectives of the Characterization Study

The overall goal of the California Characterization Well project is to gain practical experience with subsurface characterization, and demonstrate the potential for safe CO_2 storage in deep underground geologic formations in a location near large CO_2 sources and with large CO_2 storage resource potential. In addition, the project should define characterization approaches and provide technology and knowledge transfer to governmental agencies and the public. The project has three defining themes:

1) Demonstrate and test methods for acquiring high-quality data and samples for characterizing potential CO_2 storage sites in geologic formations;
2) Evaluate laboratory testing techniques and numerical modeling codes capabilities to predict the location, movement, and fate of CO_2 in storage reservoirs; and
3) Provide knowledge sharing to the public, policymakers, and permitting agencies through project-related outreach.

The primary scientific objectives of the project, and the activities planned to address these objectives, are summarized in Table 1.

Table 1. Summary of the scientific objectives and proposed test plan elements

Scientific Objective	**Measurement Approach**
Demonstrate site characterization techniques	• Geologic analysis of existing well data • Baseline characterization data from new well • Numerical simulation modeling of CO_2 plume using existing data
Assess the storage formation	• Collection and testing of whole and rotary core from the reservoir formation • Collection of geophysical log and wireline formation(s) testing data from the reservoir formation(s)
Assess the spatial extent and behavior of injected CO_2 scenarios	• Numerical modeling of hypothetical CO_2 injection scenarios to mimic small pilot or large-scale injections
Assess seal integrity	• Collection and testing of whole and rotary core from the seal formation • Collection of geophysical log and wireline formation test data from sealing formations
Assess formation fluids	• Collection of formation fluid samples • Geochemical testing and modeling

2.0 Methodology

The methods for site down-selection for a characterization well include developing criteria for site selection and collecting relevant available data that address those criteria. Based on these data, a ranking of sites can be made. Criteria include elements of the geology and geography that define the suitability of the site for geologic storage including location relative to sources and presence of storage and sealing formations, how representative the formations at the site are of the major geologic storage targets in the region, as well as non-geologic criteria that must be met to assure a successful project. Such criteria include site access, liability assumption, and permitting constraints. Table 2 lists these criteria by category.

Table 2. Characterization well site selection criteria

Category	Criteria Description
Geologic and Geographic Criteria	Well-defined stratigraphy or structure that should minimize CO_2 leakage
	No impact on low-salinity (<10,000 mg/L TDS) aquifers; minor impact on a deep, high-salinity aquifer beneath a confining seal formations
	Location is unlikely to cause public nuisance (noise, traffic, dust, night work, etc.) and does not disturb environmentally protected or other sensitive areas
	Well will intersect formations identified as potential major storage resources for the region
	Area is in sufficiently close proximity to large volume CO_2 sources
	Sufficient preliminary geologic data (hydrogeologic data, well logs, seismic surveys, rock and fluid properties) available to inform site down-select process yet not so much as to make characterization well unnecessary to fill knowledge gaps
	Major faults in area are known and can be assessed for their potential as leakage pathways
	Depth of storage formations are greater than 800 m (~2,600 feet) to keep CO_2 in dense supercritical state
	Potential for CO_2 utilization at site improve likelihood of early CCS development opportunities
Non-technical/ Logistical	Surface owner grants project access
	Subsurface (mineral rights or well) owner grants project access and accepts well liability
	Pre-existing roads and easy access for heavy equipment
	Pre-existing well pad or well to eliminate or minimize surface disturbance and easy access for heavy equipment
	Ease of permitting process

The criteria that sites be within reasonable proximity to large volume CO_2 sources was addressed through use of the GIS NATCARB databases, which WESTCARB has assembled. Urbanization is concentrated on the coasts, predominantly in the San Francisco Bay Area and Los Angeles Basin and many large CO_2 sources are also within these regions. The Central Valley of California, composed of the Sacramento basin in the north and San Joaquin basin in the south, contains numerous saline formations and oil and gas reservoirs that are the state's major geologic storage resources. The saline formations alone are estimated to have a storage capacity of 100 to 500 Gt CO_2, representing a potential CO_2 sink equivalent to greater than 500 years of California's current large-point source CO_2 emissions.

The formations of interest in California for geologic storage have been the subject of many previous investigations by WESTCARB and its partners. These formations include the Mokelumne, Starkey, Winters, Domengine, and Vedder sandstones. The methodologies used to assess these units as potential storage resource are exemplified by a WESTCARB study done by the California Department of Conservation, California Geological Survey (CGS), which conducted a preliminary regional geologic assessment of the carbon sequestration potential of the Upper Cretaceous Mokelumne River, Starkey, and Winters formations in the southern Sacramento Basin (Downey & Clinkenbeard, 2010). Approximately 6,200 gas well logs were used to prepare a series of three maps for each formation. Gross sandstone isopach (thickness) maps were prepared to define the regional extent and thickness of porous and permeable sandstone available within each formation. Depth-to-sandstone maps were then generated and used to identify areas of shallow sandstone that might not be suitable for supercritical-state CO_2 injection. Finally, isopach maps of overlying shale units were prepared for each formation to identify areas of thin seals. The maps were digitized and GIS overlays were used to eliminate areas where sandstone has been eroded by younger Paleocene submarine canyons, areas of shallow sandstone, and areas exhibiting a thin overlying seal, to arrive at an estimate for each formation meeting minimum depth and seal parameters. The maps reveal that approximately 1,045 square miles are underlain by Mokelumne River sandstones, 920 square miles by Starkey Formation sandstones, and 1,454 square miles by Winters sandstones, which meet minimum depth requirements of 1,000 meters (3,280 feet) and seal thickness of over 100 feet and may be suitable for carbon sequestration. Since the formations are vertically stacked, only 2,019 net surface square miles meet depth and seal criteria. However, stacking provides the potential for much thicker total sandstone sequences than individual formations. The estimated storage resource for the portions of the three formations meeting depth and seal criteria is 3.5 to 14.1 Gigatons of CO_2.

Given that early opportunities for commercial-scale CCS are likely to be linked to opportunities for CO_2-EOR or other CO_2 utilization, such as enhanced gas recovery, cushion gas for natural gas storage or as compression gas for energy storage, another criteria used for site screening was to look for sites where such opportunities were available. Depleted petroleum reservoirs are especially promising targets for CO_2 storage because of the potential to use CO_2 to extract additional oil or natural gas. The benefit of EOR using injected CO_2 to swell and mobilize oil from the reservoir toward a production well is well known. Enhanced gas recovery (EGR) involves a similar CO_2 injection process, but relies on sweep and methane displacement. CO_2 injection may enhance methane production by reservoir re-pressurization or pressure maintenance of pressure-depleted natural gas reservoirs or by preferential desorbing more methane in any gas-bearing formation. Thus, potential sites that are near oil fields, gas fields, natural gas storage sites, or areas being studied for compressed gas energy storage were given preference in the ranking process.

Another criterion was to locate an area where the data gathered by a characterization well would have high value through filling knowledge gaps balanced against the need to have sufficient data available for selected sites for informed decision-making. In other words, areas that were already rich in subsurface data would rank lower than areas where a characterization well would significantly improve knowledge of the character of storage formations and sealing units. However, this automatically did not preclude selecting sites in the oil and gas-bearing regions of the state. Although the oil and gas regions in California have been extensively drilled and studied, the focus of data gathering has been on the hydrocarbon-bearing formations that typically overlie the deep saline formations of interest for CO_2 storage. Of the gas exploration wells drilled to the depths needed for CCS site characterization, few have collected sampling and logging data for these deep formations. In addition, the characteristics of the sealing units are typically neglected in traditional oil and gas exploration. Because CO_2 for enhanced natural gas recovery remains experimental, the types of data needed for dynamic modeling of CO_2 behavior are not typically collected in the gas-bearing formations.

At the field level, criteria include establishing that storage and sealing formations meet general thickness requirements, incorporating any data on geohydrologic properties, including permeability and formation water salinities, and examination of the properties of any faults in the area. Methods include reviewing existing well or seismic data to create a preliminary geologic model. However, at this level, other criteria related to site access, permitting, liability, and minimizing new construction activities also are part of the ranking. For example, being able to use existing well pads and roads may favor one site for well drilling within a field over another site where formations are predicted to be of greater thickness. Side-tracking the well might be used to plan a project to balance these competing objectives. Similarly, a field where the owner may be willing to take liability and obtain permits would rank more highly than one where WESTCARB would have to purchase an insurance bond or take permitting responsibility.

Final ranking criteria used include reviewing well plan scenarios of the potential sites for compatibility with the scientific objectives of the project given logistical and budgetary limitations. For example, a site where formations of interest were shallower might be preferred over one where they were deeper because the savings in drilling costs could be used to acquire more logging data or a greater number of core or fluid samples.

3.0 Down-Select Results

WESTCARB has been in the process of identifying sites in California for pilot tests under Phase II since 2005 and Phase III since 2008. The down-select process which resulted in selection of the King Island site for a characterization well study built on the extensive work WESTCARB did in Phase II to select a site for a small-scale CO_2 injection and in Phase III to select a site for a large-volume storage test. It is important to note that prior to the selection of each of the Phase II or III sites, independent down-selection processes were undertaken by and with the industry partners to establish a preferred site.

The sites that were short-listed in the down-select process were the King Island Gas Field, the Thornton Gas Field and the Montezuma Hills sites in the southern Sacramento Basin and the Kimberlina site in the southern San Joaquin Basin. The selection details and history of site down-selection for Thornton are reported in the WESTCARB Phase II Final Report (pp. 45-53). C6 Resources, LLC performed its own proprietary evaluation of over 100 potential sites before selecting the Montezuma Hills site. WESTCARB geologists concurred with the

C6 Resources conclusions regarding the suitability of the site for a small-scale pilot and potentially for a large-scale Phase III WESTCARB project.

For a characterization well, the King Island site meets the geologic criteria and provides equivalent or better scientific opportunities compared to the Thornton and Montezuma Hills sites. Much of the geologic data acquired for the Thornton sites, and to some extent at the Montezuma Hills site, are applicable to the King Island site, which is 12 miles to the south of Thornton and about 15 miles to the east of Montezuma Hills. King Island also meets the nontechnical/logistical criteria whereas the Thornton and Montezuma Hills sites do not. Kimberlina was selected as a back-up site, meeting geologic and non-technical/logistical criteria but was judged to provide less knowledge gain and fewer scientific opportunities than King Island.

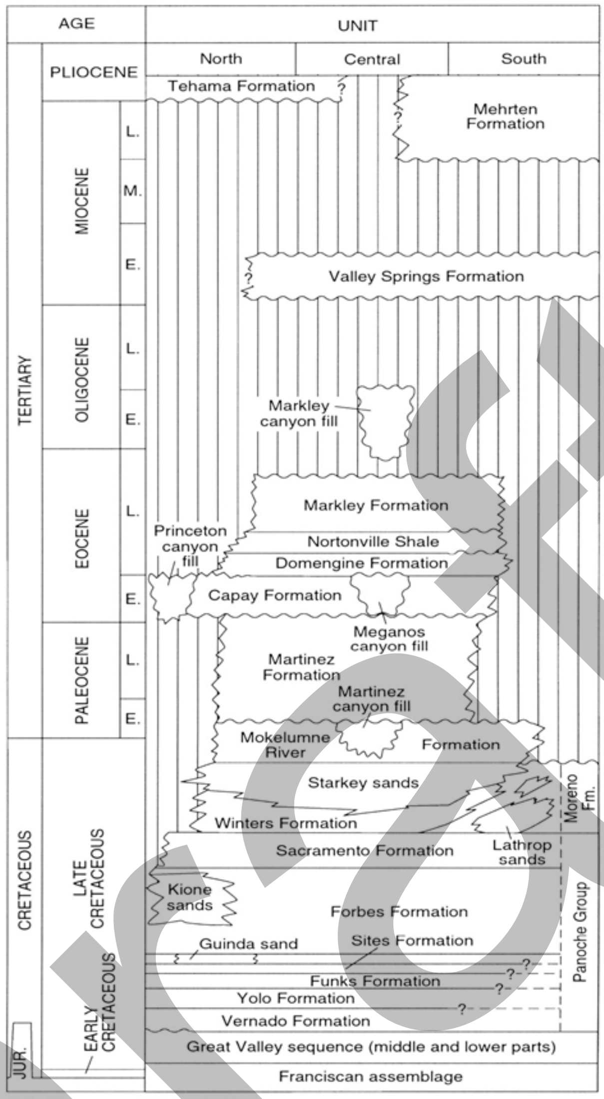
3.1 Geologic and Geographic Criteria

Based on the methods described above, WESTCARB has identified the characterization site area with the highest potential in California as the Sacramento-San Joaquin Basin. The target storage formations are the extensive sedimentary deposits in the Sacramento-San Joaquin Basin, associated with gas-bearing and oil-bearing formations and the underlying saline units.

There are over 11 megatonnes per year of CO_2 emissions from sources within the southern Sacramento Basin alone, and the area lies in close proximity to numerous power plants and large industrial sources in the San Francisco Bay Area, the California Delta, Stockton, and Sacramento areas. In addition to saline formation storage opportunities, there is the possibility for enhanced hydrocarbon recovery or CO_2 utilization in gas storage or energy storage. The southern Sacramento-northern San Joaquin basin contains producing gas fields and gas storage reservoirs. Thornton, King Island, and Montezuma Hills are within this gas-bearing region. The oil fields in the southern San Joaquin Basin (as well as the nearby Ventura oilfields) are close to large sources, and some are suitable for CO_2-enhanced oil recovery. The Kimberlina site, which is near Bakersfield, is in the oil region.

The California Geological Survey divides California into 11 Geomorphic Provinces based on a common geologic record, landscape, or landform. Each province represents a unique area of the state with distinct geology, structure (i.e., faulting), topographic relief and climate. The candidate sites are located in the Great Valley Geomorphic Province, a structural trough or basin filled with up to 40,000 ft (12.2 km) of Jurassic to Holocene marine and nonmarine clastic sediments. Marine and deltaic sediments were deposited along the western convergent margin of the Cordilleran Mountains, which underwent rapid uplift and erosion during the Late Jurassic to Late Cretaceous Cordilleran Orogeny.

Thick marine sediments continued to accumulate along the Farallon-North American Plate boundary during the early Cenozoic era before the California Coastal Range began its rapid uplift during the middle Cenozoic. Cenozoic evolution of the Coastal Range, characterized by intense faulting and alternating periods of uplift and subsidence, created the western boundary of the structural trough. Corresponding uplift and subsidence of the Central Valley resulted in deposition of alternating layers of undifferentiated nonmarine and marine sediments, respectively, across the Sacramento-San Joaquin Basin (Figures 1 and 2).



After Magoon and Valin, 1995

Figure 1. General stratigraphic section for the Sacramento Basin, California.

The Kimberlina site lies within the southern part of the San Joaquin Basin. The southern part of the San Joaquin basin is filled by more than 7000 m of Tertiary marine and nonmarine sediments that bury the downwarped western margin of the Sierra Nevada metamorphic-plutonic terrane. The stratigraphic section is generally thin and predominately continental on the east side of the basin, but it thickens into largely deepwater marine facies to the west. The structure is basically a monocline dipping toward the west, characterized by block faulting and broad, open folds. A major feature of the basin is the Bakersfield Arch, a westward-plunging structural bowing on the east side of the basin. This structure plunges south-southwest into the basin for approximately 25 km, separating the basin into 2 sub-basins. The structural feature is the site of several major oil fields.

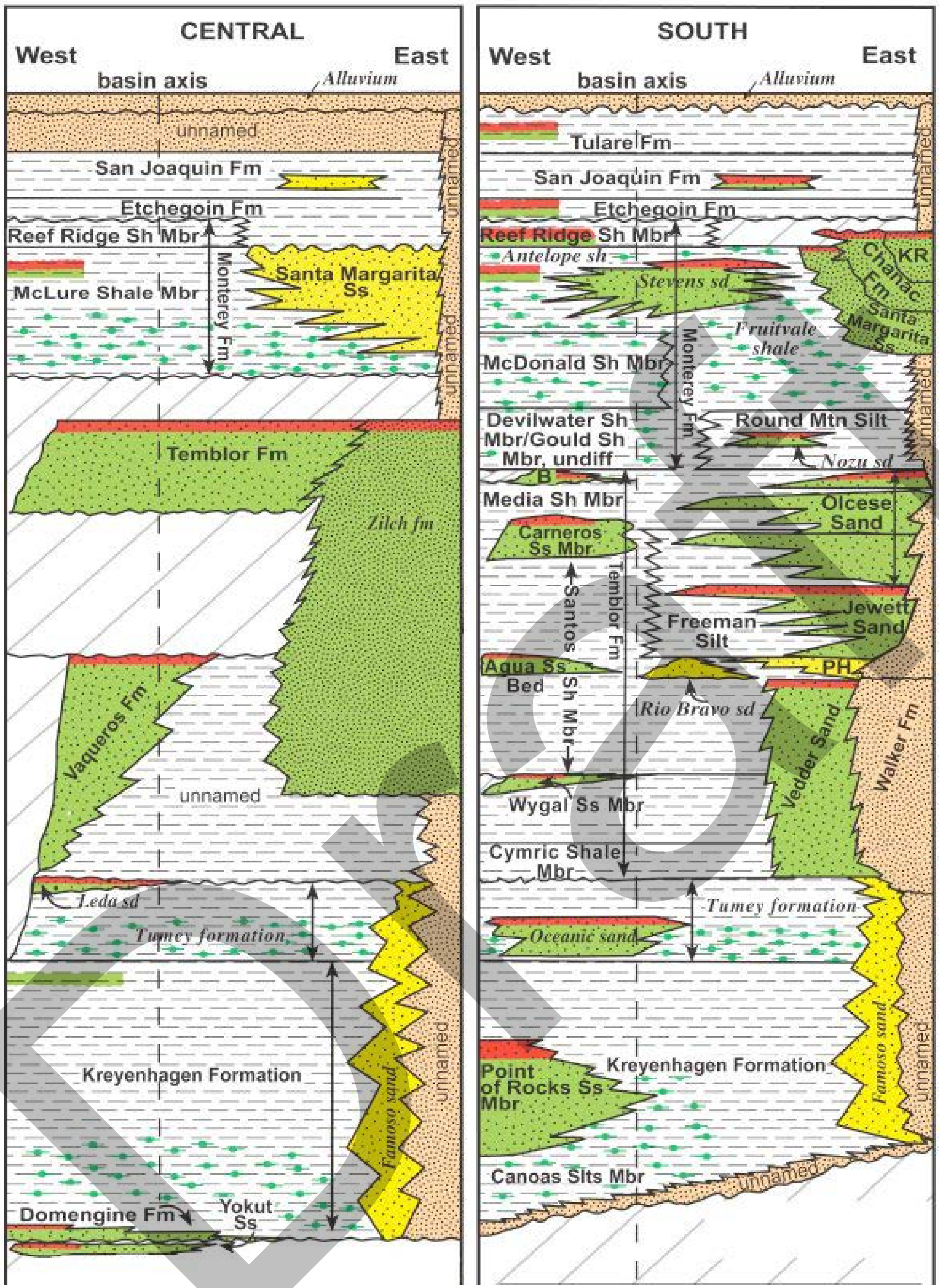


Figure 2. Generalized stratigraphic section for the southern San Joaquin basin (Scheirer and Magoon, 2007).

Because Kimberlina was a candidate site for a Phase III large volume storage test, WESTCARB constructed a regional 3D geologic model of the southern San Joaquin basin encompassing an area within a 50 km radius of the Kimberlina site (Figure 3). This regional model was developed to improve our understanding of the location and character of potential sequestration targets in this part of the basin. This model provides a framework for constructing smaller, more detailed models of potential injection sites. The regional framework model is approximately 84 km x 112 km in size. Mapped geologic units included Quaternary basin fill, Tertiary marine and continental deposits, and pre-Tertiary basement rocks. Detailed geologic data, including surface geologic maps, borehole data, and geophysical surveys, were used to define the geologic framework. Fifteen time-stratigraphic formations were mapped, as well as >140 faults. The free surface is based on a 10 m lateral resolution DEM. Most of the geologic information integrated into this model originated from the oil and gas industry and is now available from the California Division of Oil, Gas and Geothermal Resources (DOGGR). Individual fault data are taken from DOGGR documents on specific oil and gas fields in the basin. Our current understanding of the faulting between the oil and gas fields is poor, and this is an area in which more work is required.

Definition of the lithology and lithologic properties was provided by well logs from a reference well, Kimberlina 1-25 ls. Based on this well, target sequestration formations were identified and capacity estimates were made (Table 3). The Phase III plan was to inject 250,000 tons of CO_2 per year for four years into the saline formations fluids beneath the Kimberlina site. Storage formations identified were the Stevens, Olcese, and Vedder formations at 7,000 ft, 8000 ft, and 9000 ft, respectively. The geology, structure, tectonics, and reservoir properties of this subsurface area are broadly recognized from drilling and production data from nearby oilfields. This geology makes prediction of injectivity, injection-induced pressure increases, brine flow pathways, CO_2 migration, and trapping behavior relatively straightforward, and general effects and potential impacts of the injection of CO_2 can be anticipated. However, the acquisition of seismic survey data will greatly improve subsurface understanding.

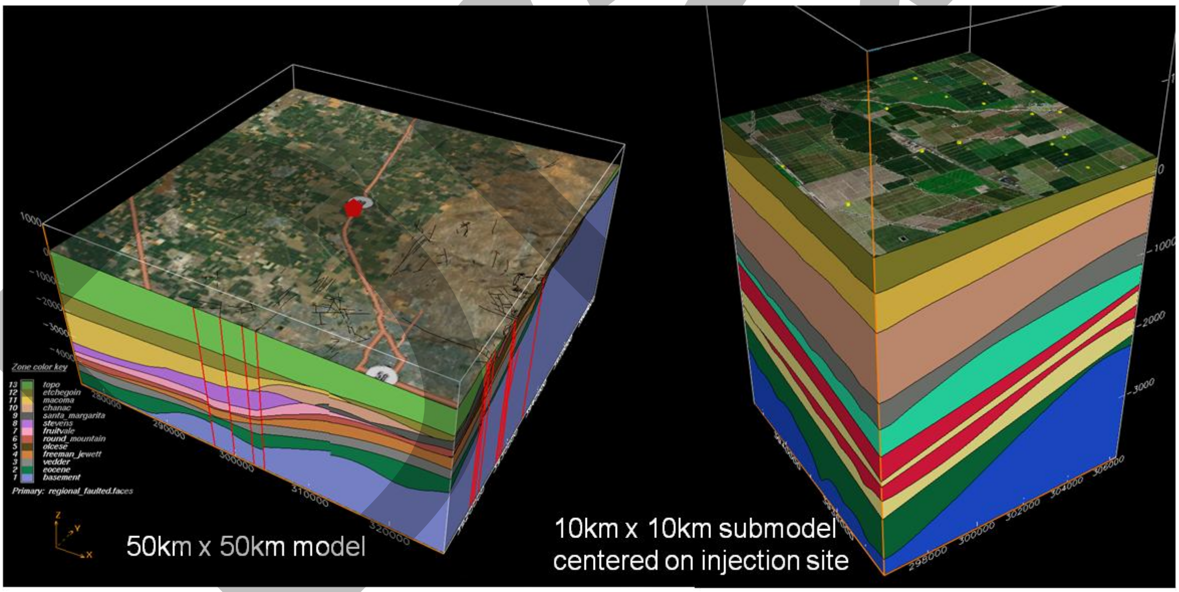


Figure 3. Kimberlina geologic framework model at 50 km scale and 10 km scale showing stratigraphy of southern San Joaquin basin. Well locations used to inform the model are shown as red vertical lines in the lefthand model.

The shallowest injection target is the 400-foot thick Stevens Sandstone located at about 7000 ft depth. The depositional environment for the Stevens is a deep-water fan. Below the Stevens is the Olcese, at a depth of about 8000 ft. The Olcese is a regionally continuous, fluvial-estuarine unit of moderate injectivity. Its thickness at the site is on the order of 800 ft. The lowest unit at a depth of about 9000 ft, is the Vedder, which is also regionally continuous. At the site, the Vedder is a braided stream unit with a thickness of about 500 ft. Thick shale units provide good overlying seals at the site and surrounding areas.

Storage capacity of the target formations were made assuming that 5% of the pore volume contained dissolved fraction CO_2, 8% contained residual phase-trapped CO_2, and 65% was available for free phase trapped by physical processes (seals). Injectivity measures are high (20-300 mD). These initial estimates show a very significant and effective (due to stratal continuity and functional seals) potential in the Kimberlina region of up to 800M tons of CO_2. While the data obtained during Phase II activities and prior data from the literature and from the USGS are sufficient to proceed with confidence, the geological characterization must be considerably refined and risk reduced through the acquisition of seismic surveys.

Table 3. Capacity estimates for Kimberlina formations

Formation	Capacity Type	Capacity (M tonnes CO2)
Vedder	Dissolved & Residual	207
	Physical	715
Olcese	Dissolved & Residual	214
	Physical	739
Stevens	Dissolved & Residual	382
	Physical	1,320
Total	Dissolved & Residual	c. 800
	Physical	c. 2,800

The Sacramento Basin Province is a gas-producing province with 73 gas fields throughout the province and two small oil fields in the southern part of the basin. The Domengine Formation, a late Eocene sandstone, provides most of the gas production in the southern Sacramento Basin; however, other reservoir rocks include sandstones in the Winters Formation, Starkey sands, Mokelumne River Formation, Martinez Formation, Capay Formation, Nortonville Shale, Markley Formation, Lathrop sands, Tracy sands, Blewett sands, Azevedo sands and Garzas sand. Most of these sandstones are of marine origin, ranging in thickness from 4 to 550 ft (1.2–168 m) and having porosities and permeabilities ranging from 10 to 34% and 5 to 2406 milliDarcy (mD; 4.9E-15–2.37E-12 m^2). The DOGGR reports pool data for the Mokelumne River Formation ranging from 31-35% for porosity, 40-45% for water saturation, 55-60% for gas saturations, and water salinity (NaCl) of 14,379 parts per million. Organics in the Winters Shale or Sacramento Shale are suspected of being the source of hydrocarbons for the gas pools within the Winters through the Domengine formations.

These formations are the producing zones for dozens of gas-producing fields in California, including King Island (Figure 4). The cumulative storage capacity of these fields is estimated at 1.7 gigatonnes CO_2. Storage capacity of the largest, the Rio Vista field, is estimated to be over 300 megatonnes CO_2, sufficient to accommodate CO_2 emissions for over 80 years from the nearest large (650 MW) gas-fired power plant. Depleted natural gas reservoirs are attractive targets for sequestration of CO_2 because of their demonstrated ability to trap gas, proven record of gas recovery (i.e., sufficient permeability), existing infrastructure of wells and pipelines, and land use history of gas production and transportation.

The Mokelumne River Formation consists of a series of interbedded sands and shales deposited in a deltaic system. The Molelumne is the producing formation at King Island. The lower Capay Shale was deposited in an outer neritic environment and the upper Capay was deposited in an inner-neritic to brackish water environment, implying a partial shoaling of the basin during the Eocene. The Domengine Sand consists of alternating layers of marine sand and shale with sand being the dominant lithology. The Markley sand is a poorly consolidated deltaic deposit containing interbedded sand and shale (Johnson, 1990). The Eocene sediments are unconformably overlain by approximately 2,000 to 2,300 ft (610–701 m) of Miocene and Pliocene undifferentiated nonmarine strata.

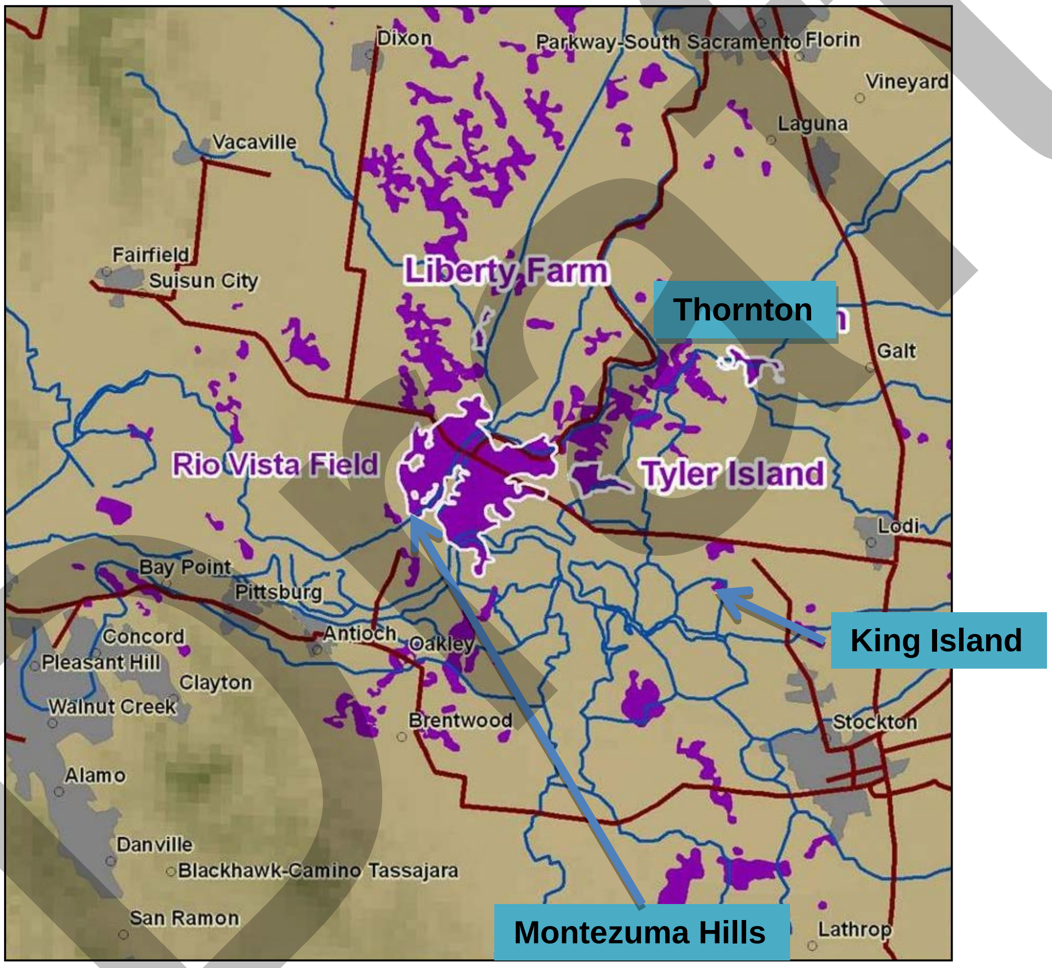


Figure 4. Gas fields of the southern Sacramento-northern San Joaquin Basins and locations of the WESTCARB candidate sites: Thornton Gas Field, King Island Gas Field, and Montezuma Hills area.

Structural and stratigraphic information for King Island is provided by two wells in the King Island gas field and two in the nearby East Island gas field, which provide logging data (Figure 5), and a 3D seismic survey of the King Island field. The King Island field is in a northeast-southwest trending structure with a seal provided by a mudstone-filled gorge cut. King Island Field has produced 10.3 bcf of gas, with an EUR of about 11 bcf (California Department of Conservation—Division of Oil and Gas). Natural gas was produced primarily from the top of the Mokelumne

River Formation. Additional sequestration potential may be present in the overlying Domengine sandstone and the underlying Starkey sandstones.

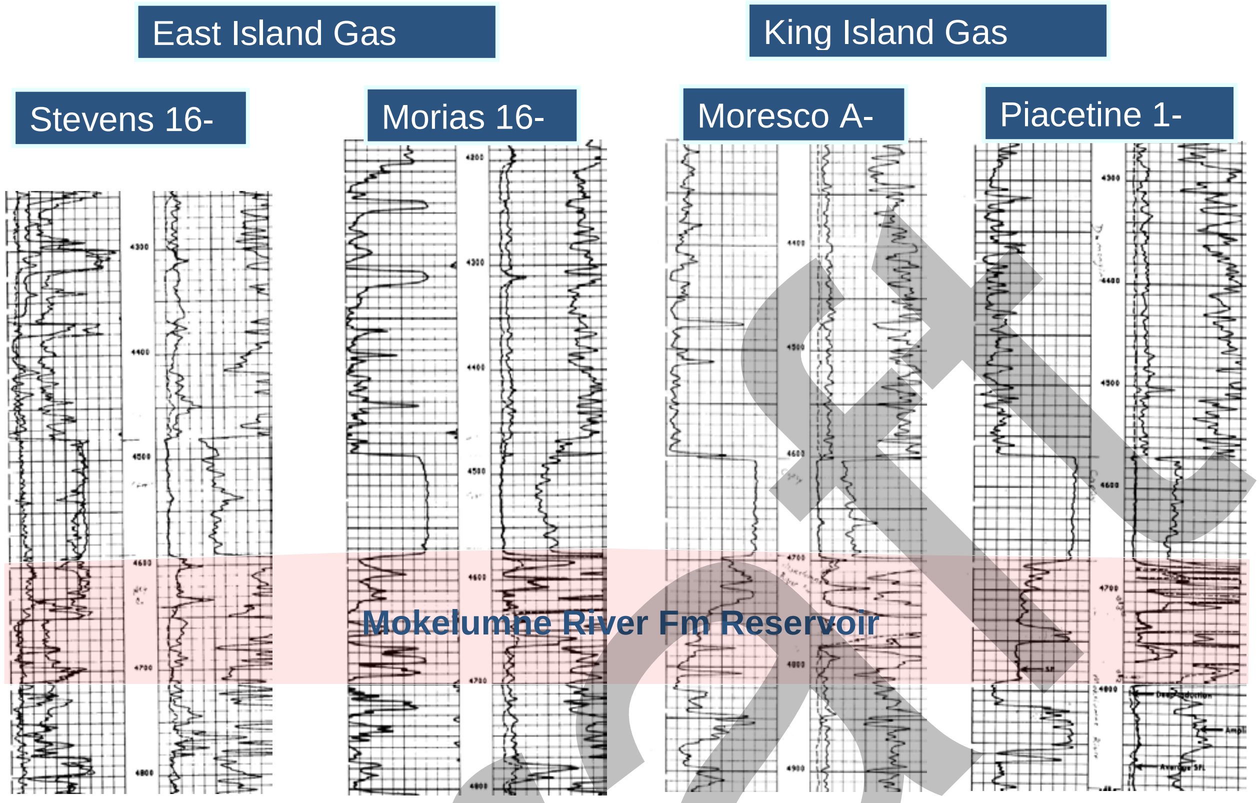


Figure 5. Stratigraphic cross section through East Island and King Island Gas Fields.

The Thornton Gas Field consists of an east-west trending anticline structure with an estimated maximum productive area of approximately five square miles. The original gas-water contact was reportedly at a depth of 3,360 ft (1,024 m). Natural gas was produced primarily from the top of the Mokelumne River Formation (known locally as the Capital Sand) with smaller localized plays found in the overlying Domengine sandstone (known locally as the Emigh) and sand stringers in the Capay Shale and Nortonville Shale. Production began in the mid-1940s, producing nearly 53.6 billion cubic feet (bcf; 1.52 x 109 m3) of natural gas through the 1980s from approximately 15 now abandoned wells. In Phase II, geologic logs and electrical logs were reviewed by WESTCARB from these wells to look for CO_2 injection intervals within a gas-bearing zone and a saline zone beneath a competent shale layer located below the original gas-water contact (-3,360 ft; -1,024 m) (Figure 6). Estimated depth to the bottom of the shale unit is 3410 ft (1039 m). Core samples collected from deviated well Bender #1 at a true vertical depth of approximately 3,330-3,400 ft (1,015–1,036 m) have permeabilities ranging from 46 to 1,670 mD (4.5E-14–1.65E-12 m2) and porosities ranging from 26.5 to 28.8% for the sands in the upper Mokelumne River Formation. Geologic logs and electrical logs were also consulted to look for a thin sand stringer or layer in the middle Capay Shale where gas was produced from abandoned production well Capital Co. 2. This thin sandy unit is continuous across the section, expressing itself in several well logs throughout the area.

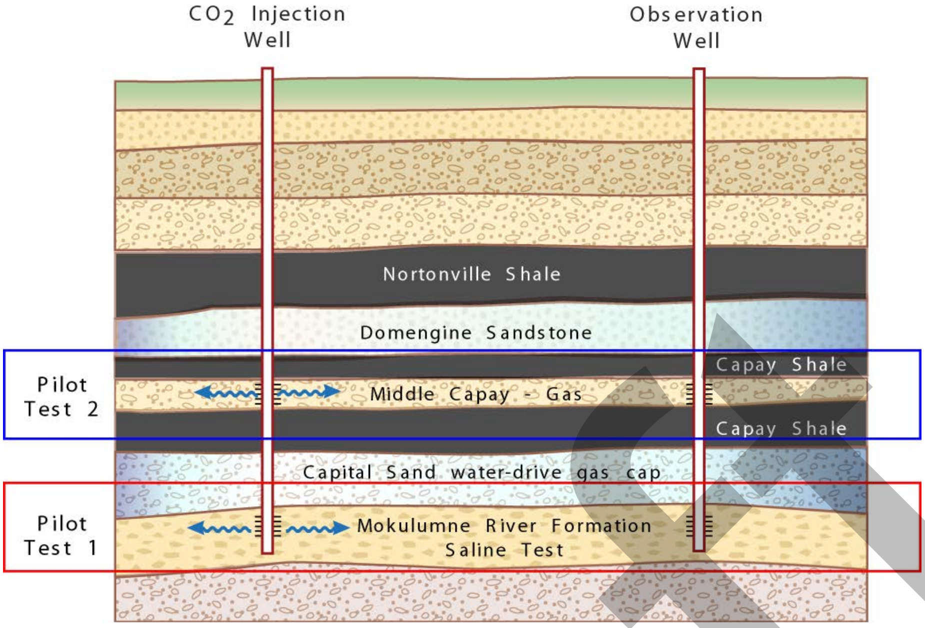


Figure 6. Proposed pilot test configuration for Thornton when it was a potential Phase II injection pilot site, with injection planned in the gas-bearing and saline units. The stratigraphy shown is equivalent to the upper section that will be drilled and sampled at King Island.

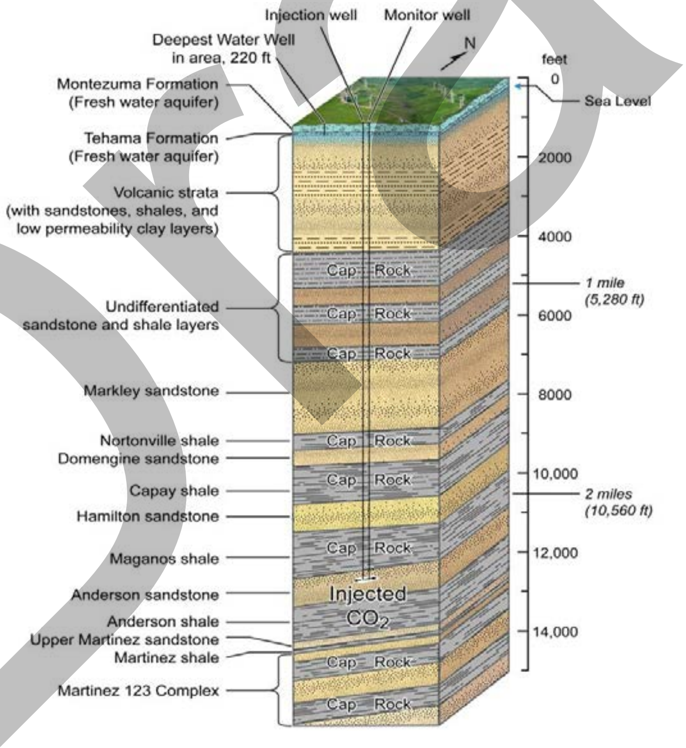


Figure 7. General Stratigraphy at the Montezuma Hills site. The Domengine, Capay and Maganos are present, but are significantly deeper than to the east at the King Island and Thornton sites.

Data on reservoir properties could not be found for the Capay Shale, so production data were analyzed using the transient wellhead pressure response matched to the Theis (1935) type curve (i.e., exponential integral solution). The wellhead pressures were not converted to equivalent bottom hole pressures, and the natural gas was assumed to be ideal and flowing under isothermal conditions. Therefore, the permeability value of 4 mD (4E-15 m2) determined using this approach should be considered a rough estimate of the Capay's true permeability.

A regional unconformity separates the Mokelumne River Formation from the younger Eocene Capay Shale. The intervening Paleocene sediments including the McCormick Sand, Anderson and Hamilton sands and Martinez and Meganos Shales are missing from the stratigraphic column and were either removed by erosion or not deposited when the Midland fault was active up through the early Eocene.

The stratigraphy at the Montezuma Hills site has similarities with that further eastward at King Island and Thornton. Some of the same sandstone and shale formations occur, but here they are significantly deeper (Figure 7). A characterization well at Montezuma Hills would have required drilling to about 11,000 ft (3 km) in order to obtain information on the formations of interest.

The Midland fault is the closest major fault zone to the gas fields of the southern San Joaquin Basin. It is located approximately 10 to 15 mi (16–24 km) west of Thornton and King Island and east of Montezuma Hills. The Midland fault does not exhibit a surface trace; rather it is thought to be a blind, high-angle west-dipping normal fault with a north-northwest trend or strike. The Midland fault trace was identified and mapped using subsurface correlation between stratigraphic units and seismic reflection data derived from wells and geophysical surveys collected during gas exploration. The Midland fault accommodated extension and subsidence that occurred in the late Cretaceous to early Tertiary Sacramento Valley forearc basin. Normal displacement along the fault ended by the Eocene epoch; however, minor normal displacement may have occurred in late Miocene time. Seismic reflection data indicates that post-Miocene reactivation of the Midland fault occurred to accommodate reverse slip caused by horizontal shortening of the crust. Estimates for the long-term average slip rate for the Midland fault range between 0.004–0.02 in/year (0.1-0.5 mm/yr).

It is important to note that the gas zones in much of the Sacramento Basin are structural traps against sealing faults; however at King Island, the trap is stratigraphic, Thornton is at the top of an anticline, and Montezuma Hills is synclinal. There are very few faults identified in the immediate vicinity of the candidate sites, but some specific issues arose during activities associated with WESTCARB's Phase II and Phase III site planning.

Two minor faults are identified on the DOGGR structural contour map of the top of the Capital Sand in the Thornton field and these faults are located outside the productive area. The faults have normal displacement and strike north-south. These faults were not considered to be an issue for the planned CO_2 injection at that site.

Faulting became a permitting issue, however, for a pilot-scale Phase II CO_2 injection proposed for the Montezuma Hills site. Researchers at the Lawrence Berkeley National Laboratory (LBNL) and the Lawrence Livermore National Laboratory (LLNL) prepared a seismic hazard reports for Solano County to address concerns (Daley et al., 2010; Myer et al., 2010; Oldenburg et al., 2010). The closest known fault to the proposed injection site is the Kirby Hills Fault. Shell's proprietary seismic survey data also indicated two unnamed faults more than 3 miles east of the project site. These faults do not reach the surface as they are truncated by an unconformity at a depth of about 2,000 ft (610 m). The unconformity is identified as occurring during the Oligocene Epoch, 33.9–23.03 million years ago, which indicates that these faults are not currently active. Farther east are the Rio Vista Fault and Midland Fault at distances of about 6 miles (10 km) and 10 miles (16 km), respectively. These faults have been identified as active during the Quaternary (last 1.6 million years), but without evidence of displacement during the Holocene (the last 11,700 years).

The Kirby Hills Fault is probably the site of microearthquakes as large as magnitude 3.7 over the past 32 years. Most of these small events occurred 9-17 miles (15-28 km) below the surface, which is deep for this part of California. However, attributing recorded earthquakes to specific faults using data from events in the standard seismicity catalog for the area is subject to considerable uncertainty because of the lack of nearby seismic stations. Installation of local seismic monitoring stations near the site would greatly improve earthquake location accuracy.

The stress state (both magnitude and direction) in the region is an important parameter in assessing earthquake potential from injection activities. Although the available information regarding the stress state is limited in the area surrounding the injection well, the azimuth of the mean maximum horizontal stress is estimated at 41° and it is consistent with strike-slip faulting on the Kirby Hills Fault, unnamed fault segments to the south, and the Rio Vista Fault. However, there are large variations (uncertainty) in stress estimates, leading to low confidence in these conclusions regarding which fault segments are optimally oriented for potential slip induced by pressure changes. Uncertainty in the stress state could be substantially reduced by measurements planned when wells are drilled at the site.

The Phase II pilot would have injected about 6000 metric tons of CO_2 at about two miles depth. This injection would result in a reservoir fluid pressure increase greatest at the well and decreasing with distance from the well. After the injection stops, reservoir fluid pressures would decrease rapidly. Pressure changes have been predicted quantitatively by numerical simulation models of the injection. Based on these models, the pressure increase on the Kirby Hills Fault at its closest approach to the well due to the injection of 6,000 metric tons of CO_2 would be a few pounds per square inch (psi), which is a tiny fraction of the natural pressure of approximately 5,000 psi at that depth. The likelihood of such a small pressure increase triggering a slip event is very small. It is even more unlikely that events would be induced at the significantly greater depths where most of the recorded earthquakes are concentrated, because it is unlikely that such a small pressure pulse would propagate downwards any appreciable distance.

Therefore, in response to the regulatory agency's specific question of the likelihood of the CO_2 injection causing a magnitude 3.0 (or larger) event, the preliminary analysis suggested that no such induced or triggered events would be expected. However, it is possible that a fault, too small to be detected by the existing seismic data, yet sufficiently large to cause a magnitude 3.0 event, could exist in close proximity to the injection point where the pressure increase could cause slippage. However, the existence of any such faults would be detectable by data collection from the well prior to injection. It should be noted that natural earthquake events of up to 3.7 in magnitude have occurred in this area and would be expected to occur again regardless of the proposed CO_2 injection.

There appear to be no major faults and no minor ones in the King Island field at the resolution of a recent seismic survey of the area. During early 1999, Eagle Geophysical acquired a 250 mi 3D seismic survey in western San Joaquin County, including King Island. DDD Energy and Enron Oil and Gas formed an area of mutual interest (AMI) and underwrote the proprietary shoot. OXY USA later acquired Enron's position as part of a larger trade of property and data. The seismic survey targeted multiple stratigraphic and structural objectives that extend from Cretaceous submarine fans and channels deep in the basin up through fluvial-deltaic reservoirs in the shallow Cenozoic section. Three pound dynamite charges, inserted at depths of 20 ft, provided the acoustic source. The source spacing and group interval were both 220 ft. The spread was eight lines with 120 channels each, for a total of 960 channels. The sample rate was two ms down to eight s. Two companies processed the data, producing numerous versions of the volume. Processing parameters include DMO gathers, DMO, migration, spectral whitening, TVF, FXY, and trace equalization by Matrix Geophysical; and prestack migrated gathers and an enhanced migration (DMO prestack) by Vector Geophysical. These data are the basis for a research publication providing a structural-stratigraphic interpretation of King Island and surrounding potential gas plays (Figure 8) (May et al., 2007).

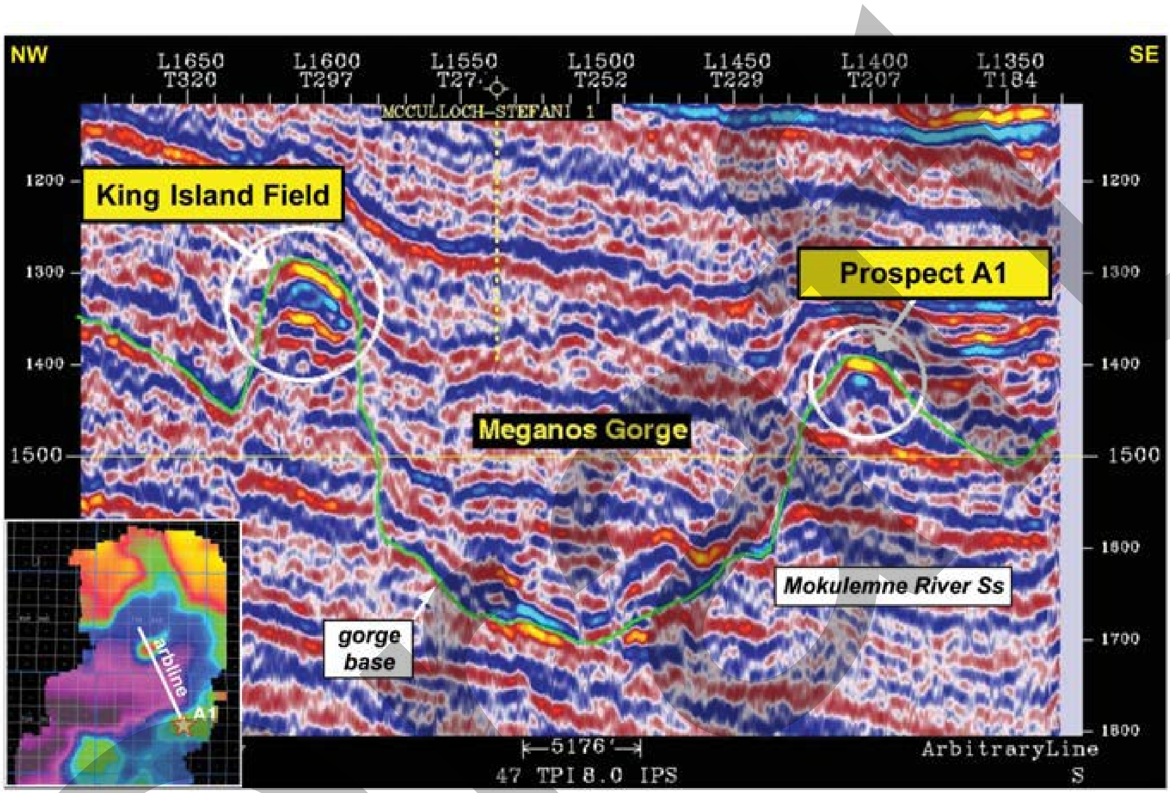


Figure 8. Seismic line extending from King Island gas field across the Meganos stratigraphic gorge to another potential gas play in the region (also shown on the inset map). In this variable-density display, the seismic troughs are presented in red, grading though white at the zero crossing, with the peaks in blue. The strongest trough amplitudes are highlighted in yellow and the strongest peak amplitudes are in cyan. From May et al, 2007.

Because of the availability of the three-dimensional seismic survey data, WESTCARB decided that pursuing the subtasks to obtain additional seismic data through purchase or new shoots was unnecessary as part of the down-selection process to determine a well location or deviation at the King Island site. In this respect, King Island outranks the Kimberlina site where three dimensional seismic data are lacking. The specific site for the King Island well location is constrained by surface issues rather than subsurface, and the seismic data were included in the data used in well planning to determine the optimum drilling angle to intersect the formations of interest. An assessment of the need to purchase additional seismic data that may be available in adjacent areas to assist in developing commercial-scale CO_2 injection simulations will be addressed after the data from the well have been analyzed and during construction of the simulation models.

Regional groundwater elevations in the adjacent Sacramento Valley Groundwater Basin indicate that a steep hydraulic gradient exists at the margins of the Central Valley and Sierra Nevada mountains, where valley recharge takes place. Groundwater discharges near the axis of the Central Valley as base flow, adding to the overland component of the surface water runoff derived from snow pack and precipitation originating in the adjacent Sierra Nevada Mountains. The Thornton and King Island field sites are located in a low-lying swampy area with groundwater elevations near land surface, characteristic of a regional groundwater discharge location. The Montezuma Hills site is slightly higher, in the foothills of the Coast Range to the west.

The Thornton and King Island sites lie within the Central Valley Hydrogeologic Province in the Cosumnes Subbasin (groundwater basin 5-22.16, DWR, 2003). The Cosumnes Subbasin is defined by the aerial extent of unconsolidated to semi-consolidated sedimentary deposits that are bounded on the north and west by the Cosumnes River, on the south by the Mokelumne River, and on the east by consolidated bedrock of the Sierra Nevada Mountains. Annual precipitation ranges from approximately 15 in (0.38 m) on the west side of the sub-basin to 22 in (0.56 m) to the east. The Cosumnes Subbasin aquifer system is made up of three types of deposits including younger alluvium, older Pliocene/Pleistocene alluvium and Miocene/Pliocene volcanics of the Mehrten Formation (DWR, 2003). The cumulative thickness of these deposits ranges from a few hundred feet near the Sierra foothills to nearly 2,500 ft (762 m) at the western boundary of the subbasin. The Mehrten consists of alternating layers of “black” sand, stream gravels, silt and clay, with interbedded layers of tuff breccia. The gravel aquifers are highly permeable and the interbedded tuffs serve as confining layers. Wells completed in this unit typically have high yield. The deposit ranges in thickness from 200 to 1,200 ft (61–366 m) and forms a discontinuous band of outcrops along the eastern margin of the basin. Specific yields range from 6 to 12%. The older Pliocene/Pleistocene sediments were deposited as alluvial fans along the eastern margin of the Central Valley. These sediments consist of loosely to moderately consolidated silt, sand and gravel deposits ranging from 100 to 650 ft (30.5–198 m) thick. The older alluvial sediments are exposed between the foothills of the Sierra Nevada and the overlying younger alluvium near the western margin of the sub-basin and valley center. Calculated specific yields are about 6 to 7% and the aquifers in this unit exhibit moderate permeability. The younger alluvial deposits include recent sediments deposited in active stream channels, overbank deposits and terraces along the Cosumnes, Dry Creek, and Mokelumne Rivers. These unconsolidated sediments primarily consist of silt, fine to medium sand, and gravel with maximum thickness approaching 100 ft (30.5 m). The courser sand and gravel are highly permeable and produce significant quantities of water. Calculated specific yields for the younger alluvial deposits range from 6% for the alluvium to 12% for the channel deposits.

Data for groundwater wells near King Island and Thornton (e.g., State Well Number 05N05E28L003M (California Department Water Resources monitoring network) indicate that depth to groundwater ranges from 1.5 to 12 ft (0.46–3.6 m) below ground level, depending upon the time of year. Shallow groundwater at the King Island site is also expected to be within a few feet of land surface and expected to respond to seasonal changes in surface water levels in the adjacent rivers and sloughs.

3.2 Nontechnical/Logistical Criteria

Nontechnical and logistical issues proved to be the critical risk elements in WESTCARB’s Phase II and Phase III pilot test projects. WESTCARB attempts to site a northern California

Phase II pilot injection test with Rosetta Resources, Inc., at Thornton were aborted by internal decisions at Rosetta that resulted in the company being unable to continue as WESTCARB's industry partner. Subsequently, C6 Resources, LLC, a Shell Oil Company subsidiary, approached WESTCARB about the possibility of performing a pilot test at another site in the Montezuma Hills, but also subsequently withdrew from the project for business reasons. For Phase III, WESTCARB collaborated with Clean Energy Systems (CES) in preliminary characterization of the Kimberlina site, but business reasons also precluded CES from continuing as a WESTCARB partner.

Following the withdrawal of Rosetta Resources from the Northern California CO_2 Storage Project, a partnership with C6 Resources, LLC, an affiliate of Shell Oil Company, was discussed and WESTCARB's intended pilot test site was shifted to the Montezuma Hills of Solano County, California. C6 Resources was interested in evaluating the site's potential for a commercial-scale CCS project to sequester captured CO_2 from Shell's Martinez refinery. WESTCARB and C6 planned to jointly (1) undertake a pilot injection test and supporting outreach and permitting activities, (2) coordinate geophysical, hydrological, geochemical, and geomechanical characterization work, and (3) explore options and perform background work to support a possible scale-up from a small-volume (6000 metric tons) CO_2 injection pilot to a Phase III large volume (several 100,000 metric tons) injection project to a commercial-scale (1 million tons per year). Outreach activities and permitting applications were pursued successfully for the 6000 metric ton test. However, in mid-August 2010, C6 informed WESTCARB that a corporate decision had been made not to pursue CCS activities further at the Montezuma site, citing reasons such as a continued lack of clarity in California regarding the status of CCS in the GHG regulatory framework and the outcome of corporate strategic business decisions.

Due to such nontechnical factors, WESTCARB does not have site access to Thornton or Montezuma Hills, so neither of these sites currently pass the criteria for a characterization well project in Phase III. CES has agreed verbally to provide site access to Kimberlina for WESTCARB to drill a characterization well. This site was determined to be suitable as an alternate site for a characterization well project.

At King Island, WESTCARB has site access permission from both the well and mineral rights owner and, through that company, the land owner. The mineral rights beneath the King Island site and the well are owned by WESTCARB's key collaborator (Princeton Natural Gas), who is providing free access to the well and the rights. The landowner has given permission to access the extant well pad, which is on un-improved, private roads.

King Island is "drill-ready" in that it has existing gas wells, well pads and access roads, and is in a rural agricultural area. The Kimberlina site is located at the CES power plant facility, in a rural agricultural area, but is not "drill-ready."

The mineral rights and well owner has procured the drilling permit at his own expense and has taken the legal liability for the well. The owner will also assume ownership and responsibility for the well after completion of the WESTCARB project.

In the area near King Island, demographic highlights from the 2000 U.S. Census indicate that the population is about 50% Hispanic or Latino, 45 % White, 3% Asian, 2% Black or African American, and <1% American Indian and Alaska Native. The King Island site is located west of the Interstate 5 and south of Kettleman Lane (State Highway 12). The nearest communities are Stockton (290,000), about 8 miles away, and Lodi (63,000), about 5 miles away (Figure 9). The immediate vicinity is a rural area. The Thornton site is approximately

23 miles north of Stockton, but only two miles north of the unincorporated town of Thornton California, (population 1467). It is about 12 miles north of the King Island site.

Figure 9. Map and aerial photograph of King Island area showing Stockton and Lodi, Interstate 5, and surrounding agricultural areas. The location of King Island (marked at blue balloon on the map) is northwest of the city of Stockton and southwest of Lodi, close to the Interstate 5. King Island is an island which was formed during the dredging and channeling of the Sacramento-San Joaquin Delta into a system of sloughs for agriculture and flood control over the last 150 years.

The King Island site is at an elevation of minus 6 ft below mean sea level. The site is located within the Sacramento River drainage basin, which joins the San Joaquin River (which drains the southern part of the Central Valley) to form the Sacramento-San Joaquin River Delta system. The project site is located in a low-lying area protected by levees that have been installed along the rivers to prevent the property from flooding during winter and spring, when peak precipitation and surface runoff occur.

The King Island well will be drilled as a deviation in order to take advantage of an existing well pad from an operational but no longer productive well, the Source Energy Corporation's "King Island" 1-28 well (Figure 10 and lower left of aerial photo in Figure 9). There are no residences anywhere near the well pad and the surrounding fields are planted in bell peppers, corn or fruit trees. The existing well pad is 240 ft by 120 ft. This is more than sufficient space to accommodate well operations without any need for new surface construction. All facilities for fueling, waste storage tanks, power generators, and so on, will be brought by trailer to the site for temporary use during the project and will fit within the footprint of the existing well pad. The well pad is accessible by all equipment by existing private and levee roads.

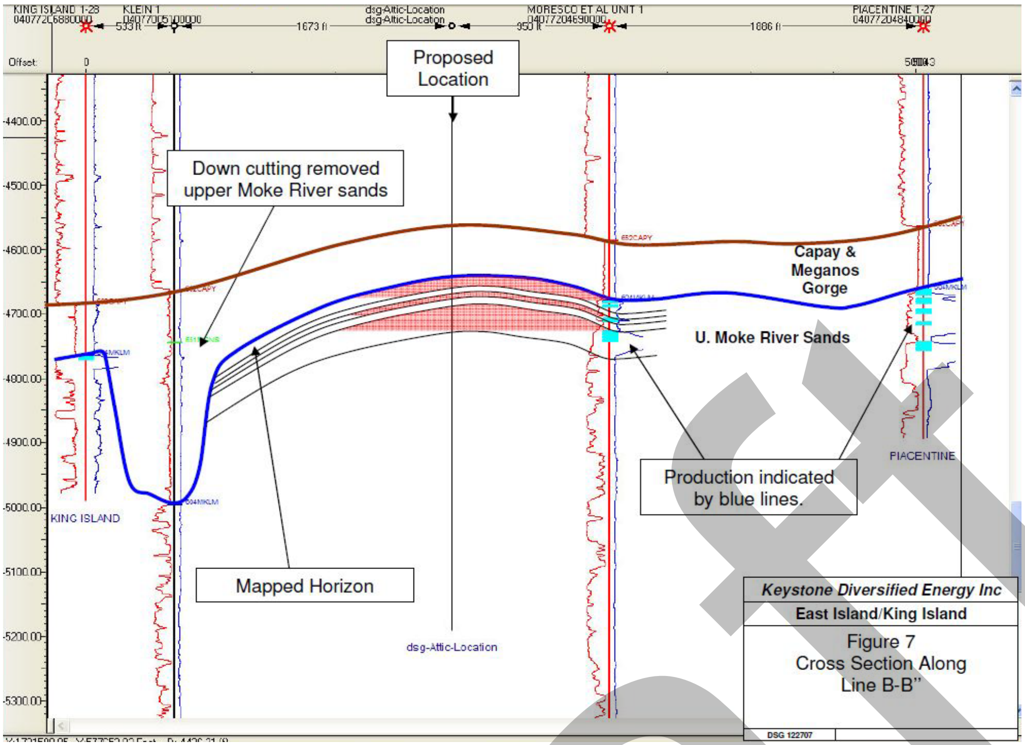


Figure 10: Cross-section of the East Island-King Island gas fields showing inferred formation tops from resistivity logs of several gas wells within these fields. The proposed characterization well site is shown as a vertical well, however, to avoid surface disturbance, the project team decided to drill a deviated well to utilize and existing well pad and well head.

Permitting has been facilitated at the King Island site by the well owner. A California DOGGR permit for drilling the characterization well was obtained. DOGGR has developed regulations governing the drilling, disposition or abandonment of oil, gas, geothermal, and injection wells in compliance with CEQA, NEPA and EPA UIC regulations as applicable. The California Code of Regulations specifies the requirements.

The well is permitted to a target depth of 8,500 ft (2,500 m). A service rig will be deployed to pull old casing over the interval necessary for subsequent deviated drilling (approximately 500-700 ft) and to plug back the existing well. The integrity of the cement plug and the surface casing (0 to 500 ft) will be tested in compliance with DOGGR permitting requirements.

WESTCARB was unable to pursue a large volume test at the Kimberlina site because CES could not complete construction of the power plant that would have provided the CO_2 for the large-volume test planned in time. However, the site passes the geologic and geographic criteria and non-technical/logistical criteria to be a characterization site. Seismic data would likely be required to better establish any faulting in the area, as noted above.

4.0 Scientific Objectives

WESTCARB technical staff and scientists at LBNL worked to assure that the down-selection process resulted in a well site and test plan that would be able to meet the scientific objectives for the Phase III characterization well projects. Even though CO_2 injection in the field is not part of the Phase III project, a test plan was developed to include field measurements, sample collection, laboratory measurements and testing, and development of simulations that could be used to provide information about the formations' suitability for a large volume CO_2 storage project.

Both core samples from gas-bearing and saline units will be collected at King Island. These samples will undergo laboratory testing at LBNL to obtain some of the information about CO_2-rock interactions that would have been gathered through field tests. While field tests are arguably the only method for testing and verifying monitoring techniques, LBNL will be able to perform some laboratory tests on the King Island samples to test petrophysical responses to injected CO_2 which will contribute critical information to developing some new monitoring tools.

The scientific test plan developed for Thornton included CO_2 injection under Phase II. The plan for the Thornton site called for two wells to be installed, perforated, and utilized for both pilot tests. One of the wells was to be used as a CO_2 injection well and the second as an observation well. Both wells were to be drilled from a single drill pad at land surface to a maximum depth of 4,000 ft (1,220 m). Drill core was to be collected during drilling for subsequent off-site testing and mud logging was to be conducted on-site for each hole to provide input to a site geologic conceptual model. Open and cased well logs were to be run to further characterize site geology and to determine reservoir conditions and parameters. Baseline site characterization activities were to consist of geophysical measurements, pressure-transient testing, and baseline monitoring of reservoir fluid composition, reservoir static pressure and temperature, shallow groundwater quality and water level, and leak detection around a now-abandoned nearby gas production well. Upon completing the baseline activities, up to 2,000 tonnes of CO_2 were to have been injected into the saline formation at an anticipated depth of 3,400-3,500 ft (1,035-1,065 m) (Pilot Test 1). The injection period would be approximately 10-14 days in duration with a series of measurements performed to track the spread of CO_2 as it moves through the formation. Post-injection monitoring of the horizontal CO_2 plume would be conducted for a three-six month period following injection to look for CO_2 leakage from the saline formation into overlying formations and to track the movement of the buoyant CO_2 after injection ends. The well perforations were to be cemented shut after the saline formation pilot test was completed and new perforations shot through the well casing across the targeted gas reservoir in preparation for the gas reservoir pilot test (Pilot Test 2). Up to 2,000 tonnes of CO_2 were to be injected into the gas reservoir at an anticipated depth of 3,045-3,050 ft (~930 m). Again, the injection period would be approximately 10-14 days in duration. Monitoring of CO_2 was to be repeated for the gas reservoir to characterize and track CO_2 movement over a second three-six month period. Commercial grade, manufactured CO_2 was to be trucked in and used for both pilots. Upon completion of the project, the wells were to be abandoned in accordance with California State law and the site restored.

The King Island characterization well will provide core and fluid samples from the same zones that were identified for the Phase II pilot injections at the Thornton site as well as additional zones at greater depths. Fluid sampling and analysis of deep and shallow hydrocarbon and aqueous gas and liquid phases will be useful to establish whether flow paths exist from the deep subsurface to shallower formations. Fluid analyses may include bulk composition, trace gases, and isotopic composition to establish relationships between the fluids, their origins, and their ages. Shale cap rock and storage sandstones will be included in the coring program. The samples will be transported to laboratory test facilities at LBNL where CO_2 injection tests will be done to provide data on CO_2-rock-fluid interactions at the core scale, to provide data for geohydrologic simulations of CO_2 fate and transport, and to inform development of new monitoring techniques. At Sandia National

Laboratory, shale samples will be tested to improve understanding of the geomechanical behavior of cap rocks. Other samples will be analyzed at commercial laboratories to acquire specific data to inform simulation activities. Part of the research outcome of the King Island studies will be to improve understanding of the scalability of laboratory and field logging data.

In addition, earth science researchers at LBNL will use sophisticated numerical codes, TOUGH2 and TOUGHREACT, for modeling the movement of fluids in geologic formations (Pruess, 2004; Xu et al. 2006). Simulation of the CO_2 injection and storage based on detailed site-specific hydrogeological models will be performed. The well constrained stratigraphy and structure from nearby wells and seismic surveys, multiple stacked sands, including gas-bearing and saline zones, and the acquisition of a robust set of petrophysical and geochemical data from the characterization well logs and samples will allow for a significant simulation effort. A geologically realistic mathematical model of the multiphase, multi-component fluid flow produced by CO_2 injection is indispensable for determining the viability of a potential storage site, because capacity and trapping ability are both strongly impacted by the coupling between buoyancy flow, geologic heterogeneity, and history-dependent multi-phase flow effects, which is impossible to calculate by simpler means. Modeling may also be used to: 1) optimize CO_2 injection by assessing the impact of various rates, volumes, and depths; 2) choose monitoring sensitivity and range by providing the expected formation response to CO_2 injection; and 3) assess the state of understanding by comparing model predictions to field observations.

LBNL also will undertake a preliminary leakage risk assessment for King Island. Such an assessment was performed for the Montezuma Hills and Kimberlina sites using the Certification Framework methodology. In the absence of a long track record, leakage risk assessment methods are needed to address concerns by the various stakeholders about the effectiveness of CO_2 trapping and the environmental impacts resulting from CO_2 injection. For the last two years, investigators at the LBNL, the University of Texas at Austin (UT), and the Texas Bureau of Economic Geology (TBEG) have been developing a framework called the Certification Framework (CF) for estimating CO_2-leakage risk for GCS sites. Risk assessment methods such as the CF rely on site characterization, predictive models, and various methods of addressing the uncertainty inherent in subsurface systems. The King Island dataset can be used to perform sensitivity analyses of the CF.

5.0 Conclusions

The down select history for the California characterization well (Task 7) incorporates new information as well as substantial site information WESTCARB compiled during its attempts to find locations for its Phase II pilot injection well and Phase III large volume storage tests. Locations generally passed geologic and geographic criteria, but failed to meet nontechnical/logistical criteria.

King Island was selected as the best site to meet site down-select criteria and the scientific objectives of the project. Kimberlina was selected as a back-up.

King Island.

WESTCARB has been in discussions with a gas operator in the southern Sacramento Basin since about 2006. The King Island Gas Field, near the Thornton site, would permit characterization of both the gas-bearing and saline formations of importance in the southern Sacramento-northern San Joaquin Basin. The general geology of the site is very similar to the original Thornton site, which lies 12 miles to the north, but includes the ability to access deeper sand units and shales. It also includes some of the formations of interest at the Montezuma Hills site, but which occur at shallower depths at King Island. Thus, King Island is the best site at meeting the geologic and geographic criteria outlined by the down-select process.

The site is located within a couple of miles of U.S. Interstate 5, providing ready access to California's major ground transportation corridors, serving the San Francisco Bay, Sacramento, and Stockton metropolitan areas and is close to significant CO_2 sources serving power to these areas and to industrial sources such as Bay area refineries. The site presents no problems with regard to site access. WESTCARB will be able to use an existing as well as a re-entry point to drill a deeper well so that WESTCARB activities can be performed without new surface construction or disturbance, saving budget for the scientific program and streamlining permitting with the California DOGGR , CEQA, and NEPA.

Kimberlina

An alternate site was identified in the southern part of the San Joaquin Valley, near Bakersfield, in the oil-bearing part of the state. A geological assessment, construction of a static geomodel, dynamic simulations, and a thorough risk assessment were undertaken for this site because it was a strong candidate for a Phase III LVST. Given the lack of seismic data specific to the Kimberlina area to constrain structure and the greater general availability of data surrounding Kimberlina in the oil-producing areas because of extensive oil exploration and production nearby, it was felt that at this time, Kimberlina would not be our top choice for a characterization well.

Because of a lack of industry matching funds to provide a CO_2 source, however, this site could not be implemented as a primary candidate for a small-scale CO_2 injection test or LVST. The industry partner also is reconsidering its interest in CCS development at the Kimberlina site since it has acquired another site for some of its CCS-relevant operations recently so it does not rank as highly as a potential early commercial CCS opportunity.

Thornton

The original site selected for the Northern California Pilot Storage Test Phase II project, for which a test scale CO_2 injection was planned, was near Thornton, California. The Thornton site contains saline formations and gas reservoirs that could be used for geologic storage of CO_2. Depleted gas reservoirs are especially promising targets for CO_2 storage because of the potential to use CO_2 to extract additional natural gas through EGR. Based on favorable results of numerous EGR modeling studies, Thornton Gas Field (abandoned) was selected for the purpose of studying EGR processes. Depleted natural gas reservoirs are attractive targets for sequestration of CO_2 because of their demonstrated ability to trap gas, proven record of gas recovery (i.e., sufficient permeability), existing infrastructure of wells and pipelines, and land use history of gas production and transportation. The formations at the Thornton Gas Field are representative of dozens of gas-producing fields in California, the cumulative storage capacity of which is estimated at 1.7 gigatonnes CO_2.

The proposed site was about two miles north of the unincorporated town of Thornton California, (population 1467), so it is less isolated from residences than the King Island site. However, the industry partner for this project was unable to proceed with the Phase II project, and WESTCARB did not re-establish access to the site for a characterization well.

Montezuma Hills

A second industry partner offered to partner with WESTCARB on the Northern California Pilot Storage Test Phase II project, but in this case C6 Resources determined the precise location based mostly upon their extensive proprietary subsurface geological analysis. This site was in the Montezuma Hills, approximately 20 miles northwest of the Thornton site and 15 miles west of the King Island site. This site lay on the west side of the Central Valley and was structurally somewhat different than the Thornton site. However, this site would have suited WESTCARB's scientific objectives, although target formations are considerably deeper and therefore more expensive to drill.

C6 was responsible for procuring access rights and all state and county permits, which were submitted. Unfortunately, C6 made a decision to withdraw from pursuing CCS projects in California in 2010 in this area. The easement on the site remains with C6, and cannot be used by WESTCARB to drill a characterization well.

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CENTRALIA (WASHINGTON STATE) GEOLOGIC FORMATION CO_2 STORAGE ASSESSMENT

Scott Stevens
Advanced Resources International, Inc.

DOE Contract No.: DE-FC26-05NT42593
Contract Period: October 1, 2005 - May 11, 2011

Abstract

As part of the West Coast Regional Carbon Sequestration Partnership (WESTCARB), Advanced Resources International, Inc. evaluated the CO_2 storage potential of deep coal seams and interbedded sandstone saline aquifers in the Centralia-Chehalis basin of west-central Washington State. These reservoirs could be used for long-term geologic storage of CO_2 captured from TransAlta's 1,404-MW coal-fired steam power plant near Centralia, Washington.

Identified coal seam targets at Centralia could store an estimated 13 years of CO_2 emissions (50% capture). Saline aquifers interbedded with the coals may provide an additional 9 to 73 years of storage capacity. However, reservoir storage capacity and quality is highly uncertain. A corehole testing program would be needed to refine these estimates as well as the feasibility of a commercial-scale CO_2 injection and storage project.

Corehole data from the Centralia coal mine provided by study partner TransAlta, as well as coalbed methane pilot production testing in the region, allow detailed evaluation of the coal seam storage potential. Lithologic and petrographic data and a limited number of wells logs permit a more generalized view of the saline-aquifer sandstone storage potential. A combined coal seam and saline aquifer test program, involving 3-5 coreholes, would be needed to measure reservoir properties at Centralia and better define their CO_2 storage characteristics and capacities.

CO_2 storage may be feasible in deep coals and sandstone saline aquifers near TransAlta's 1,404-MW coal-fired power station at Centralia. Eocene Skookumchuck Formation coal seams of sub-bituminous rank total approximately 18 m thick and buried at depths of 150-500 m could store an estimated 22 m^3/t of CO_2. Geologic mapping and analysis indicates that about 52 million t of CO_2 could be stored in coal seams, equivalent to about 13 years of current emissions (50% capture). While not large, this capacity could be augmented by deep coals elsewhere in the Centralia-Chehalis or greater Puget Sound region.

In addition, thick sandstone saline aquifers occur in the Eocene Cowlitz, Northcraft, and Skookumchuck Formations. Most are of poor reservoir quality, comprising hydrothermally altered and poorly sorted volcanic-derived sediments. However, some sandstones have good reservoir quality, with porosity as high as 30% and permeability of up to 3 darcys. Anticlines near Centralia could provide structural traps. Comparable reservoirs and traps occur at the Jackson Prairie storage field near Centralia. The lateral and vertical distribution of saline aquifer sandstones at Centralia is uncertain given sparse available well log control.

Centralia's interbedded coals and sandstones with limited individual capacity make the site a candidate for the "Stacked Storage" strategy, being pursued by SECARB in the Appalachian region for example, where multiple lower-quality zones are targeted for enhanced storage with reduced risk of leakage. Low land costs ($1/acre) typical in the Northwest would benefit a storage project. On the other hand, a major risk at Centralia appears to be significant structural

deformation, ubiquitous folding and faulting -- some potentially active. In addition, the individual coal deposits are of relatively small size and partly mined out, while the coals and sandstones have been intruded by igneous dikes and sills. A low-cost reservoir testing program could mitigate these risks and help define the commercial viability for CO_2 capture and geologic storage at Centralia, which currently appears to be one of the best such opportunities in the Pacific Northwest region.

Executive Summary

This report serves as a preliminary evaluation of the CO_2 storage potential of deep coal seams and saline aquifers in the Centralia-Chehalis basin of west-central Washington State, performed by Advanced Resources International, Inc. as part of the West Coast Regional Carbon Sequestration Partnership (WESTCARB). It was written to assess the feasibility of a potential CO_2 injection and storage test near TransAlta's 1,404-MW coal-fired steam power plant near Centralia, Washington. Our preliminary estimate is that deep coals and interbedded saline aquifer sandstones within an identified target area may have 90 to 345 million tonnes of storage capacity, sufficient for 22 to 86 years of Centralia emissions (assuming 50% capture rate).

Corehole data from the Centralia coal mine provided by study partner TransAlta, as well as coalbed methane pilot production testing in the region, allow detailed evaluation of the coal seam storage potential. Storage data for sandstone saline aquifers at Centralia is more limited -- mainly lithologic and petrographic data as well as analog data on underground gas storage and natural gas production fields in the region -- permitting only a more generalized view of their storage potential.

Carbon dioxide captured at the 1,404-MW coal-fired Centralia power station could be injected into nearby deeply buried coal seams, the mining of which ceased in 2006. Thick, well-developed, sub-bituminous rank coal seams in the Eocene Skookumchuck Formation are capable of storing about 20 m^3/t of CO_2 at typical depths of 150-500 m. Coalbed methane testing in the region, though not commercially successful to date, has recorded encouraging levels of permeability (1-7 mD) and methane content (5-15 m^3/t). CBM testing experience indicates that land costs are low ($1/acre) and drilling services can be available with good planning.

Geologic mapping indicates that approximately 52 million t of CO_2 could be stored in coal seams adjacent to the power station, equivalent to about 13 years of current emissions (50% capture). Scoping reservoir simulation indicates that 0.16-km^2 (40-acre) injector spacing using vertical frac wells would be the most efficient and cost-effective design for CO_2 storage, minimizing breakthrough, swelling, and fracture gradient risks. This capacity could be augmented by saline aquifers or deep coals elsewhere in the Centralia-Chehalis or greater Puget Sound region.

Thick sandstone saline aquifers also occur in the Eocene Cowlitz, Northcraft, and Skookumchuck Formations. The vast majority of these are of poor reservoir quality, comprising poorly sorted volcanic-derived sediments that have been hydrothermally altered with secondary chlorite, zeolite, and quartz mineralization. However, certain Skookumchuck sandstones interbedded with the coals have good reservoir quality, with porosity as high as 30% and permeability of up to 3 darcys. Anticlines near Centralia could provide structural traps. Comparable reservoirs and traps occur at the Jackson Prairie storage field 20 km south of Centralia, which holds 650 million m^3 (23 Bcf) of natural gas. However, the lateral and vertical

distribution of saline aquifer sandstones at Centralia is uncertain given sparse available well log control and additional testing is required to gather key data. Our initial estimate is that sandstone aquifers interbedded with the coal seams could store roughly 38 to 292 million t, adding 9 to 73 years of storage capacity (@50% capture).

Certain geologic characteristics at Centralia appear to be unfavorable for a CO_2 injection project. The Centralia region is strongly folded and faulted, including some potentially active faults. Fault compartmentalization may hinder effective CO_2 injection and storage and increase the number of injection wells required. The individual coal deposits are of relatively small size and partly mined out. The coals and sandstones are intruded by igneous dikes and sills. These challenges have hindered the commercial production of coalbed methane throughout the Pacific Northwest.

Centralia's interbedded coals and sandstones with limited individual capacity make the site a candidate for the "Stacked Storage" strategy, being pursued by SECARB in the Appalachian region for example, where multiple lower-quality zones are targeted for enhanced storage with reduced risk of leakage. Given the routine permitting experience of CBM and gas storage operations in Washington to date, a CO_2 injection test at Centralia should be low cost and straightforward to permit and implement. Success would provide a rare opportunity to advance CO_2 capture and geologic storage in the challenging Pacific Northwest region. A joint coal seam and saline aquifer test program, involving 3-5 coreholes, would be the next step to measure coal seam and saline aquifer reservoir properties at Centralia and better define their CO_2 storage characteristics and capacities.

1.0 Introduction

Options for sub-surface CO_2 storage in geologic strata are relatively less abundant in Washington and Oregon than in many other regions of the US, such as the Gulf Coast or Midcontinent, where large structurally simple sedimentary basins along with oil and gas production provide huge capacity and commercial storage opportunities. However, one of the best candidates for large-scale CO_2 capture with geologic storage in the Pacific Northwest is near Centralia in west-central Washington State, where TransAlta operates a major 1,404-MW coal-fired power plant. Although data control is incomplete, it appears that the deep coal and saline aquifer sandstone deposits that occur near this plant could provide long-term CO_2 storage.

This study, by Advanced Resources International, Inc. as part of the West Coast Regional Carbon Sequestration Partnership (WESTCARB), provides a preliminary assessment of the storage capacity of the sub-surface targets near Centralia, as well as recommendations for future testing that could provide the basis for an industrial-scale storage project. The report is organized into the following sections :

- **1.0 Introduction.** An overview of the WESTCARB project, geologic storage targets in the Northwest; TransAlta's power plant and coal mine operation at Centralia; and the research approach employed for the current CO_2 storage study.

- **2.0 CBM, UGS, UCG Near Centralia.** This section discusses energy industry activities in the Pacific Northwest that provide general data and insights for CO_2 storage at Centralia. It includes an introduction to coalbed methane production technology; CBM exploration drilling results in Washington and Oregon; the Jackson Prairie underground natural gas storage field; and an underground coal gasification test program that USDOE conducted at Centralia during 1979-82.

- **3.0 Coal and Sedimentary Deposits in the Centralia-Chehalis Region.** This section discusses coal deposits in Washington and Oregon; the geologic history of the Centralia-Chehalis region; Cenozoic sedimentary rocks in the region, with emphasis on the stratigraphy and lithology of saline aquifer formations; structural geology and tectonics; as well as coal seam thickness, distribution, and physical properties. Because well log data on saline aquifers at Centralia is limited, the descriptive data on sandstone texture, mineralogy, and geochemistry discussed here are of particular importance.

- **4.0 CO_2 Storage Capacity and Pilot Design.** This section covers estimation of CO_2 storage capacity in deep coals and saline aquifers near Centralia. Scoping reservoir simulation, comprising six sensitivities, provides insights for CO_2 storage dynamics. Finally, the design of delineation drilling and a recommended CO_2 injection pilot is discussed.

WESTCARB Project

The West Coast Regional Carbon Sequestration Partnership is one of seven research partnerships established in 2003 and co-funded by the U.S. Department of Energy (DOE) to characterize regional carbon sequestration opportunities and to develop action plans for pilot-scale validation tests. WESTCARB is evaluating opportunities in a six-state region (California, Oregon, Washington, Nevada, Arizona, and Alaska) for removing carbon dioxide (CO_2) from the atmosphere by enhancing natural processes and by capturing it at industrial facilities before it is emitted; both will help slow the atmospheric buildup of this greenhouse gas and its associated climatic effects.

A key part of the project is identifying subsurface locations to store the captured CO_2. These geologic sinks are expected to include deep formations (such as oil and gas reservoirs as well as saline aquifers) that are essentially leak-proof. These potential sinks will then be matched with major anthropogenic CO_2 sources, such as large utilities and industrial emitters.

DOE's intention is to combine WESTCARB's findings with those of the other six partnerships to create a national "carbon atlas" to better understand how sequestration technology can help the United States reduce the carbon intensity of its economy and mitigate climate changes. On the basis of the source and geologic characterization, WESTCARB will prioritize geologic sequestration opportunities within the region and will propose pilot-scale projects that combine industrial CO_2 capture, CO_2 transport via pipeline, and injection into geologic formations for storage or enhanced oil and gas recovery. ***(Larry: I based the 3 preceding paragraphs on language in the Golder final report. Please advise/update as needed).***

Geologic CO_2 Storage in the Northwest

Due to the extensive distribution of igneous and metamorphic rocks, as well as active tectonics in the Pacific Northwest, opportunities for geologic CO_2 storage in sedimentary strata in this region perhaps are less abundant compared with other U.S. regions with thicker sedimentary sequences with proven reservoir quality, such as the Gulf Coast or Midcontinent.

However, the deep coal seams and associated sandstone saline aquifers in Washington State appear to offer significant locally attractive storage potential for anthropogenic CO_2 sources. The main coal deposits are of Eocene age and occur in several correlative formations, including the Skookumchuck Formation at Centralia as well as the Carbonado Formation in the Puget Sound region (**Figure 1**).

In addition, sandstone saline aquifers occur in the Skookumchuck and overlying Oligocene Lincoln Formation. Although these sandstones are volcanic-sourced, poorly sorted, and generally have limited porosity and permeability, they can be of good reservoir quality locally, such as at the Mist gas field and Jackson Prairie gas storage field.

One recently developed concept that may have application at Centralia is the "Stacked Storage" model. The Southeast Regional Carbon Sequestration Partnership (SECARB) is employing this strategy in the Central Appalachian region.[1] Coal seams here are relatively thin while the adjacent sandstones are low in permeability. However, defining a stack of multiple injection targets makes CO_2 storage more feasible. It also helps to increase the surface area available for chemical reactions and permanent storage of CO_2 through mineralization within the thin intervals. This approach seems very relevant to Centralia.

Phase 1 of this study examined deep coals in three regions of Washington State (**Figure 2**).[2] The Bellingham Basin in northwestern Washington holds some potential, but there has been almost no coalbed methane testing here. Few data exist to characterize coal reservoir quality. Also, the Bellingham basin is located far from anthropogenic CO_2 sources. The Coos Bay basin in southwestern Oregon has small deep coal deposits that have undergone much more CBM testing, but reservoir quality is uncertain and it is even more remote from CO_2 sources.

By far the greatest potential for carbon sequestration in coal seams is in the coals of central Washington State, in the Puget Sound region south and east of the Tacoma-Seattle metropolitan area and the Centralia-Chehalis region. These coals have been more extensively tested by coal mining and coalbed methane exploration companies, thus their CO_2 sequestration potential can be more readily characterized.

The other type of target for geologic CO_2 storage in the Pacific Northwest are the saline aquifers, mainly sandstones, in the Cenozoic sedimentary basins which extend throughout western Washington into Oregon. These saline aquifers were discussed regionally by Golder Associates Inc. as part of a parallel WESTCARB project.[3] Although data at Centralia are limited, the potential of these saline aquifers near the power plant is examined in more detail in Sections 3 and 4 of this report.

TransAlta Centralia Power Station and Coal Mine

The focus of this report is a detailed evaluation of the CO_2 storage potential of deep coal seam and saline aquifers near the 1,404-MW Centralia power plant. TransAlta, which operates the Centralia power station and its related coal mine, participated in the WESTCARB study as an active partner, providing essential data, site access, and local geologic and mining expertise. TransAlta also leads Project Pioneer, Canada's first fully-integrated carbon capture and storage (CCS) plant. Planned for operation in 2012, the project aims to capture 1 Mt of CO_2 from an existing coal-fired power plant near Edmonton and utilize it for enhanced oil recovery or inject it into a geological storage site.[4]

TransAlta operates coal-fired, gas-fired, and hydroelectric power plants at Centralia. The coal-fired plant produces 1,404 megawatts, enough electricity to supply a city the size of Seattle

(**Figure 3**). TransAlta also operates a 58-km^2 (14,450-acre) coal mine at Centralia, which until recently had supplied about 70% of the coal used by the adjacent power plant. The open-pit Centralia mine started up in 1971 and had typically recovered about 4 million tons annually. TransAlta also operated drilling rigs which were used for corehole drilling to define coal resources and plan mine operations (**Figure 4**).

Early in 2006 TransAlta had considered expanding the Centralia mine and filed permits to open "Pit Seven" later in the year. They also considered leasing an additional 7-8,000 acres of prospective land adjacent to the current mines, suggesting that coal resources in the area remain abundant. However, in November 2006 TransAlta finally decided to close the Centralia coal mine and switch the plant's supply entirely to Powder River basin coal delivered from Wyoming and Montana. A number of factors influenced this decision, including depletion of coal reserves in the currently held acreage and the relatively high cost of operations. Lewis County officials also cited conditions sought by the state Department of Ecology, the USEPA, and the U.S. Army Corps of Engineers as influencing factors.[5]

The closure of the Centralia coal mine actually improves the outlook for CO_2 storage in deep coals at this location. More of the identified coal resource is likely to remain undisturbed and available for future CO_2 storage. It also potentially opens up access to the deeper coal seams remaining at the mine, underneath the shallow mining targets, which previously were off limits due to active mining operations near the surface (**Figure 5**). And while reclamation work continues as the mined-out pits are restored and replanted (**Figure 6**), these activities are less likely to conflict with CO_2 storage operations. Refilling the mined-out pits will restore reservoir pressure to the remaining underlying coal seams and increase their CO_2 storage capacity. Meanwhile, the detailed geologic database developed by the mine over several decades is available to guide CO_2 storage planning.

Site Location and Description

The Centralia-Chehalis coal field is located in west-central Washington State, about midway between the major cities of Seattle and Portland in the Pacific Northwest region of the US (**Figure 7**). The nearest cities are Centralia and Chehalis, 3 km apart, with populations of 15,000 and 7,000, respectively. Local industry includes timber, farming, distribution, and tourism. Interstate 5, the major north-south highway along the West Coast, runs near the cities, as do major passenger and freight rail lines. Numerous smaller paved and unpaved mining and timber roads provide access essentially to the entire mining area.

Surface topography in the mining area is defined mainly by low rounded hills which range in elevation from 130 to 300 m (**Figure 8**). The Chehalis River drains the area in a generally northwest direction, discharging ultimately into the Puget Sound. The main tributaries of the Chehalis are the Skookumchuck and Newaukum Rivers, draining the western Cascade Foothills.

With a moist temperate climate, local river flows vary widely by season, being heaviest in the winter months.

Flooding of low areas is not infrequent. For example, heavy rains in December 2007 closed a 30-km stretch of Interstate-5 for several days. However, the coal mining areas are 100 m or so above the flood plains and, apart from deep active pits which eventually will be backfilled and restored, generally less prone to flooding. Second-growth coniferous forests dominate the hills, while the lower valley terraces generally are farmed or ranched.

Research Approach

For this study, Advanced Resources International, Inc. (ARI) worked with Centralia power plant and coal mine operator TransAlta, as well as with other WESTCARB participants. ARI gathered and integrated geologic, geochemical, and geophysical data from a variety of sources. The most useful data and insights came from working with TransAlta's coal mining professional staff and data files during several site visits.

We also gathered supplementary data from conventional oil and gas exploration and production wells, coalbed methane pilot testing programs, underground coal gasification coreholes, underground gas storage operations, and water production and quality monitoring wells at Centralia and nearby locations. We reviewed published information on the lithology, coal geology, surface geologic mapping, tectonics, and seismic hazards of the Centralia region. We integrated this information using GIS mapping and compared Centralia with other sites where CO_2 injection has taken place. Finally, we modeled the CO_2 injection potential and dynamics at Centralia using reservoir simulation based on measured and inferred data.

This report is intended to be a preliminary evaluation and pre-feasibility study of the CO_2 storage potential at Centralia. Should an actual storage project be initiated, the first step would be to select and characterize specific locations for 3-5 test coreholes which would gather, for the first time at Centralia, measurements of the actual reservoir quality and injectivity of sandstone saline aquifers and deep coal seams. Next, a small-scale CO_2 injection test should be site-selected and implemented. Only then -- using the full set of information gathered from the CO_2 injection test, the coreholes, and this study – could a full-scale commercial injection program be properly designed and implemented at Centralia.

2.0 CBM, Underground Gas Storage, & Underground Coal Gasification Near Centralia

No field tests of geologic CO_2 storage in coal seams or saline aquifers have occurred to date in Washington or Oregon. The region is not considered to be particularly well endowed with subsurface storage resources, although opportunities do exist locally as documented in this study. And while not major energy production centers, these two states have experienced certain energy-related activities that are potentially relevant to geologic CO_2 storage at Centralia. This section examines industry's experience in Washington and Oregon with coalbed methane exploration, underground natural gas storage, underground coal gasification, as well as conventional petroleum exploration and production activities.

CBM Production Technology

Production of natural gas from deep coal seams -- coalbed methane (CBM) -- is commercially mature technology widely applied today in the US, Canada, and Australia. Fostered by initial R&D funded by USDOE and GRI in the 1970's and 80's, industry has invested a cumulative total of over $20 billion since 1988 to drill over 50,000 CBM wells in the United States alone.

By 2007, CBM production had reached 50 billion m^3 (1.75 Tcf; 4.8 Bcfd) from 620 billion m^3 (21.9 Tcf) of proved reserves.[6] In relative terms, CBM accounted for 10% of total natural gas production and 9% of natural gas reserves in the US. During the past decade, CBM development also has gone commercial on a large scale in Canada (1 Bcfd), Australia (0.5 Bcfd), and China (0.1 Bcfd).[7] CBM testing is underway in a dozen other countries.

The design of CBM production wells varies depending on local geologic and reservoir conditions.[8] The simplest configuration is the vertical, open-hole, unstimulated completion of a single coal seam, common in the Powder River basin in Wyoming. More typical are vertical, cased, hydraulically fractured CBM wells that complete multiple coal seams (Uinta, Raton and many other basins). The most complex and costly design is the horizontal, multi-branched well that may complete as much as 10 km of total coal length in-seam (Central Appalachian and other basins). Each of these designs could be tested and adapted to Centralia. However, the vertical frac well seems best suited for Centralia's multi-seam, low-permeability coal setting.

Unlike conventional natural gas reservoirs, coal seams store natural gas mainly by adsorption under the pressure of overburden, which is transmitted by formation water.[9] Gas production typically starts out low, as this formation water must be pumped off first to reduce reservoir pressure and induce the methane to desorb from the coal. Gas production usually increases gradually for several years as the well dewaters, then plateaus for several more years, followed by gradual decline over the well's 10-50 year productive lifespan. Commercial success depends on favorable geologic conditions, principally thick coal, high initial adsorbed gas content and saturation, and adequate permeability. Low capital and operating costs along with high gas sales price also are key success factors.

Coalbed methane (CBM) production and CO_2 storage in deep coal seams are separate but related activities that follow similar reservoir principles and operational methods. Basins with a track record of established commercial CBM production offer real advantages for subsequent CO_2 storage projects. The reservoir data collected during years of production history from thousands of CBM wells provides an invaluable foundation for the selection, evaluation, design and operation of a CO_2 storage project.

In addition, having access to CBM drilling rigs, completion units, and existing production infrastructure at the surface can lower the costs of CO_2 storage. So too can the economic benefit of improving methane recovery, a process called enhanced CBM recovery (ECBM). Environmental and regulatory permitting procedures generally are more established in mature CBM production areas. This is why the San Juan basin, long the leading CBM production region, also is the most advanced site for CO_2 storage demonstrations.[10]

To date, neither the Centralia-Chehalis region nor the other coal basins in Oregon/ Washington have experienced successful commercial CBM production. There is no established CBM reservoir description or surface infrastructure for a CO_2 injection project to build on. However, there have been a handful of CBM pilot tests in the region, discussed in detail below, which provide limited but still useful data on coal reservoir properties, operational costs, and permitting procedures essential for planning a CO_2 storage operation at Centralia.

CBM Exploration Activity in Washington/Oregon

Successful commercial development of coalbed methane resources is probably the best single indicator that an enhanced coalbed methane or deep coal CO_2 storage project can succeed, because these two different types of projects share many similar reservoir and surface requirements. Despite test programs by roughly a dozen companies over the past two decades, commercial CBM production has not yet been achieved in Washington and Oregon. However, the data collected by these commercial projects are invaluable for evaluating the CO_2 storage potential at Centralia.

The initial phase of CBM exploration activity took place during 1982-93, when the CBM industry was just beginning and the wells qualified for temporary Section 29 non-conventional gas tax credits, which expired at the end of 1992. These projects were unsuccessful due to structural complexity, faulting, steep dips, and poor well completion practices, as well as relatively low prevailing wellhead gas prices in the \$2/Mcf range.[11]

A second CBM testing phase started about 2000 and continues today, stimulated by higher gas prices (>\$5/Mcf), new exploration concepts, and improved well completion technology. These more recent projects, though still not economically successful, have tested encouraging levels of coal seam gas content and permeability in the region. This tends to support the concept of CO_2 storage in deep coal seams at Centralia.

Early CBM Exploration Testing

The very earliest CBM project in the Pacific Northwest occurred during the early 1980's, when Amoco drilled several test wells in the Carbonado and Black Diamond regions south of Seattle (**Figure 9**). Although these wells penetrated over 30 m of coal, production results were disappointing. In 1987, Carbon River Energy completed a five-well pilot in the Carbonado field. Gas content and production results were promising but the venture was ultimately shut-in and abandoned.

Palo Petroleum, Texaco, and Boeing teamed up in 1992 to drill three wells near Black Diamond. One of the wells was hydraulically fractured with nitrogen foam and sand. The other two wells were completed with open-hole cavitation. One of the cavitated wells tested 1,000 to 6,000 m^3/day of methane with no water from Eocene coal seams at depths of 800 to 1000 m, probably reflecting free gas in the coal and adjacent sandstones rather than desorbed CBM. Steep dips in this area led to severe borehole deviation during drilling and caused hole collapse during the cavitation operations.

After a period of no or little CBM drilling during 1993-2000, several companies have recently conducted CBM leasing and/or exploration drilling in the Centralia area. These include Duncan Oil, El Paso Corporation, Torrent Energy, and Comet Ridge Ltd. Considerably more information is available on these more recent CBM projects.

El Paso Corp. and Duncan Oil (Black Diamond, Carbonado, Storm King)

El Paso Corp. and Duncan Oil tested the largest CBM pilot attempted to date in the Northwest. Starting in 2000 Duncan leased a large position and tested CBM in the Black Diamond field (west of Seattle), the Carbonado field (southwest of Tacoma), and the Storm King prospect (southwest of Mt. Rainier). In 2001 El Paso Corp. purchased a half interest in the Duncan project and become operator. El Paso expanded the pilots but eventually abandoned the project due to high water and low gas production.

El Paso's Carbonado CBM project covered 1,070 km^2 (264,014 acres) in King and Pearce Counties, located 45 km SE of Tacoma.[12] A total of 14 CBM production wells and 4 coreholes were drilled, targeting more than two dozen coal seams in the Puget Group totaling nearly 25 m thick at depths of approximately 900 m. **Figure 10** shows a typical lithologic log for a well in the Carbonado field, which is worth examining as there are no comparable complete well logs for deep coals at Centralia. The individual coalbeds are often thin (1 m) with high ash content (avg. 60%) and are separated by 50 m or so of sandstone and shale. Intrusive dikes and sills occur sporadically. Coal rank was high-medium volatile bituminous. Gas content varied with depth and location, with highest values in the southern part of the prospect. Using a minimum 600-m depth cutoff, the average in-situ gas content was reported to be 15 m^3/t (d.a.f.).

All 14 production wells were hydraulically stimulated, using a variety of fluids (**Figure 11**). Eight of the wells were frac'd using nitrogen foam with sand proppant, pumped at a rate of 4-5 m^3/minute (25-30 bbl/min) and injecting 90 t of sand in each zone. Four wells were frac'd using slickwater KCl fluid, pumped at 1.3 to 2 m^3/minute (8-12 bbl/min) with 23 t of sand per zone. Two of the wells utilized polymer fluid, pumped at 1.3 to 2 m^3/minute with 42 t of sand injected per zone. Fracture gradients ranged from 0.7 to 1.5 psi/foot.

El Paso did not release detailed production data. Their later wells reportedly produced at high water rates, sometimes exceeding the 170-m^3/day (1000-Bwpd) installed pump capacity (**Figure 12**). Based on injection/falloff testing and production analysis, the company estimated coal seam permeability to range from 1 to 300 mD, with a regional average 1 to 7 mD. This is lower permeability than found in the San Juan and Powder River basins, but similar to the levels encountered in the Warrior basin of Alabama.

Produced water was quite fresh and discharged into surface streams under permit from the State of Washington. Discharge capacity constraints required some of the water to be trucked to a local water utility. El Paso estimated drilling, completion, and stimulation costs to be $640,000 per well (a useful benchmark for costing out a potential CO_2 storage project at Centralia). Despite operating in what many consider to be an environmentally restrictive part of the country, El Paso had no issues obtaining drilling permits because the locations were situated on private timberlands that were scheduled for clear cutting anyway. Had the project proceeded, access to Northwest Pipeline's 76-cm diameter trunk line would have required construction of a 16-km connecting pipeline.

Torrent Energy, Duncan Oil, Inc., Comet Ridge Ltd. (Chehalis Basin, Washington).

Torrent Energy Corporation recently conducted two CBM exploration projects in the Pacific Northwest region, one in the Chehalis basin of Washington about 20 km southwest of the Centralia coal mine, and the second in the Coos Bay basin of southwestern Oregon. At the Chehalis project, Torrent targeted CBM in the Cowlitz Formation, along with natural gas trapped in conventional sandstone reservoirs. The company had planned to introduce horizontal drilling, improve hydraulic stimulation and well completion, and reduce costs.

During the 1980's Kerr-McGee had drilled shallow coal exploration coreholes along the southwest flank of the Chehalis basin (**Figure 7**). These coreholes remain confidential but reportedly encountered gas shows in both coals and sandstones. One of the coreholes was offset by Duncan Oil, Inc. in 2001, flow testing 714 Mcfd from a shallow (750') sandstone zone. Duncan reportedly was able to map a sizeable prospect area using seismic data.

Duncan farmed out its project to Torrent Energy in 2004. During 2004-2008, Torrent Energy conducted CBM leasing and exploration programs in Washington and Oregon. Some of Torrent's Washington leases were adjacent to the Centralia CO_2-ECBM project area, in the Centralia-Chehalis coal district of the Morton and Toledo coal fields. Unfortunately, Torrent's funding ran out before it could establish commerciality and the company filed for bankruptcy protection in June 2008.

At its peak holding in June 2007, Portland-based Torrent Energy held 176,000 acres of mineral leases in the Chehalis basin and an additional 107,000 acres in the Coos Bay basin. Torrent had executed a 1-year lease option agreement with Weyerhauser Company on August 9, 2005 to lease 100,000 acres selected from an overall 365,000-acre block in the Chehalis Basin. Given the high risk and lack of commercial CBM development in the Pacific Northwest, Torrent paid a relatively low signing bonus of $100,000 or $1/acre (by comparison signing bonuses in proven commercial CBM basins such as the Powder River basin typically are $500/acre or more.) Torrent later acquired additional acreage in the Cowlitz and Lewis County portions of the Chehalis basin at similar terms. (Again, these land costs are quite relevant to a potential CO_2 storage project at Centralia.)

The Torrent projects represent the most recent CBM activity in the region of the Centralia project and thus provide useful technical, economic, and regulatory insight. Torrent considered the access to its Chehalis acreage to be excellent year-round via logging and fire control roads maintained by the forest service or the timber industry. Timber recovery staging areas provided potential drill sites and the company (through subsidiary Cascadia Energy Corp.) drilled three stratigraphic data holes in 2007 (data remains confidential).

Comet Ridge Limited, based in Sydney, Australia, invested in Torrent's Chehalis project and remains a partial owner. Its subsidiary St. Helens Energy LLC is conducting a CBM and conventional gas exploration project in the Grays Harbor area southwest of Seattle, where they hold mineral rights to 202 km^2 (50,000 acres) and a $1 million lease option for another 1,700 km^2 (420,000 acres). Note that the land bonus costs here are very low (<$0.50/acre). The company has completed a 3D seismic survey in the block and is nearing completion of a 2D seismic shoot. After processing and interpreting the seismic data, Comet Ridge plans its first test well during 2009.[13]

Torrent Energy (Coos Bay Basin, Oregon)

Although Torrent did not production test its acreage in the Chehalis basin, it conducted extensive CBM testing at its Coos Bay block further south in southwestern Oregon. The project was located along the Pacific coast, about 300 km south of the Columbia River and 120 km north of the California border (**Figure 13**). The Coos Bay basin is the southernmost of a series of coal-bearing Tertiary sedimentary basins (the Puget-Willamette Trough) that stretch from southern Oregon to northern Washington.

Coos Bay basin contains a thick section of nonmarine Eocene coal-bearing sediments forming the Coos Bay coal field (**Figure 14**).[14] Coal seams are contained in the Lower and Upper Members of the Middle Eocene Coaledo Formation, which correlates approximately with the Eocene Skookumchuck Formation at Centralia. Net coal thickness totals up to 20 m and 10 m, respectively, in the Lower and Upper Coaledo units. Coal mining began in 1854 and continued through the mid-1950's. The coal rank ranges from sub-bituminous to high-volatile bituminous, with heating value of 8,300 to 14,000 Btu/lb. Approximately 20 conventional oil and gas exploration wells were drilled in the Coos Bay basin between 1914 and 1993, many of which encountered gas kicks in the coal seams penetrated during drilling.

Torrent's Oregon acreage typically comprised 5-year leases with options for an additional 5-year renewal.[15] Annual payments were a relatively low \$1/acre, comparable to the company's Washington state leases. Royalty was 12.5% on gross sales. There was an additional 4% overriding royalty to be paid to the project originators. An independent volumetric estimate placed total gas in place on Torrent's acreage at approximately 34 billion m^3 (1.2 Tcf).

Torrent commenced an initial multi-hole CBM coring program at Coos Bay in October 2004. The company drilled and tested a total of 12 exploration wells in three pilot areas : Beaver Hill (5 wells), Radio Hill (2), and Westport (5). In May 2008 Torrent completed initial fracture stimulation of 5 CBM wells at Beaver Hill and started production testing. Torrent claims the coal seams were saturated with pipeline-quality natural gas, but the project did not book proved reserves and placed on hold due to the company's financial difficulties.

Core samples from 11 coal seams at the three test sites were desorbed at the well site. Data analysis was completed by mid-2005. Based on initial results, the Beaver Hill corehole site was selected for a 5-well production pilot.[16] Its original corehole was cased and converted to a production well. Four new wells were directionally drilled around it in a pattern from the same drilling location. All five wells penetrated multiple Lower Coaledo coal seams at depths of 1280 to 1340 m. The 5-m thick "D" seam in each well was stimulated with a nitrogen frac. Short-term rates of 5700-14,000 m^3/day (200-500 Mcfd) were reported.

Torrent tested one well at its Radio Hill site, completing 10 Lower Coaledo coal seams at depths of 830-1200 m and with a cumulative net coal thickness of 10 m. The coals were stimulated with nitrogen fracs. Reported gas rate was much lower than at the Beaver Hill pilot, about 1,000 m^3/day (30 Mcfd) with about 1 m^3/day of water. The low water rates at both pilots suggests that produced gas may be free rather than desorbed, and could be coming from sandstones as well as coal seams.

Produced water chemistry was not reported but appears too saline for surface discharge. The produced water from the Torrent pilots was trucked to a dilution facility adjacent to the municipal water-treatment plant at Coos Bay. Torrent had planned to evaluate fractured basalts beneath the Coaledo Formation at its Westport project site as a possible injection zone for produced water. The Oregon Department of Environmental Quality would require an approved water disposal/containment plan for any commercial-scale CBM production and has ruled out surface discharge.[17]

Even though it was did not progress to the commercial phase, the Coos Bay CBM pilots at least showed that fairly high short-term flow rates were possible from Eocene coals in the Pacific Northwest region.

Duncan Oil, Inc. (King County)

The company drilled 4 test wells in King County and desorbed gas contents of up to 86 scf/ton in the 40' thick Blue Seam in Duncan's NWCH 42-9A test well.[18]

Jordan Exploration Company (Bellingham Basin)

Jordan Exploration Company, LLC (Traverse City, MI) acquired 61,000 acres of mainly fee lands in the Bellingham basin of northwestern Washington State. Coal targets are in the 4-km thick mid-late Eocene Huntington Formation and the underlying Cretaceous-Early Eocene Chuckanut Formation. Coal rank ranges from sub-bituminous C to anthracite, with most of the coal in the high-volatile C to B bituminous range. Individual coal seams are 0.3 to 5 m thick, with the 7 best developed seams 2 to 5 m thick. The Sumas gas trading hub is located at the eastern edge of the lease block. Two 36" diameter gas lines cross Jordan's leases.

Insights from CBM Testing

Reservoir Quality. Although none of the CBM projects conducted to date in Washington and Oregon achieved commerciality, nearly all tested thick coal seams with decent permeability (>1 mD) and initial methane saturation (close to 100%). The main challenge seems to have been structural complexity (faulting and folding) which hindered beneficial communication between the production wells. Another challenge was poor well completion, notably ineffective hydraulic stimulation and cavitation. These issues are likely to reoccur in a CO_2 storage project and require additional efforts to position wells between structures as well as to improve the effectiveness of well completions.

Land Costs. Lease bonus and royalty terms for CBM projects to date in Washington and Oregon have been economical, typically $1/acre or less with a 12.5% royalty. Landowners in other parts of the US with more intense oil and gas activity often demand much more onerous terms, with bonuses in the range of $100 to $10,000/acre and 25-30% royalties. Low land costs would greatly benefit a CO_2 storage project in the Northwest, given the large area and long time scale required.

Permitting. The CBM test projects to date demonstrate that drilling activities are not unreasonably difficult to permit in many portions of Washington and Oregon, particularly where forestry and mining has already been occurring. For example, Duncan Oil obtained its drilling permit from the Washington State Department of Natural Resources under routine oil and gas permitting procedures. The company also obtained a Conditional Use Permit from King County to drill and test four CBM wells on private timberland owned by Weyerhauser and Plum Creek – Burlington. These agencies likely would be involved in the permitting of a CO_2 injection test at Centralia, although large-scale storage will probably require new specific regulations.

Operations. Again, the experience of CBM operations in the Northwest indicates that suitable rigs, completion, and production equipment can be available for CO_2 injection projects, albeit at higher cost than for areas such as the Rockies, which have a much larger level of activity and more competition among service company. In addition, access is generally good in the Northwest, including Centralia, thanks to the numerous timber and mining roads supplementing the paved road system.

For example, Duncan utilized a truck-mounted drill rig slightly larger than a standard water well rig to drill four wells to total depth of 1050 m. Each drill site occupied 0.5 to 1.0 acres during drilling and testing. The sites were near existing private access roads on the timberland company's property. Roads and drill pads were surfaced with crushed gravel. Drill sites were kept a minimum of 60 m from any surface water body or wetland area and 90 m from any structure. During testing, produced gas was collected from the wells to a central flare via buried PVC lines.

Duncan's drilling and testing operations were conducted 24-7 with an on-site supervisor present during all operations. Surface casing was set at least 30 m into the bedrock and then cemented back to the ground surface to isolate and protect overburden soils and groundwater from potential contamination with drilling fluids and/or saline produced water. After completion, the well was plugged with cement per state regulations and abandoned.

Petroleum Exploration in the Centralia-Chehalis Region

Despite sporadic exploration wells since 1900, there has been little commercial production of oil and gas in Washington State.[19] Due to the low geothermal gradient the shallow wells drilled to date have not penetrated deeply into the gas-generative window.

The only significant commercial field in the Pacific Northwest region is the Mist gas field. Located in the Astoria-Nehalem basin of northwestern Oregon (**Figure 7**), Mist field produces from sandstone reservoirs in the Eocene Cowlitz Formation, which are overlain by sealing mudstones in the Cowlitz (**Figure 15**). (Note that that the Skookumchuck Formation coals in the Chehalis basin are of similar age and lithology.) Gas composition at the Mist field is high in nitrogen which, along with isotopic data, suggests the gas was of biogenic rather than thermogenic origin.

One of the better studied recent gas wells at Mist field, OM-41A-10, penetrated 191 m of Clark and Wilson reservoir sandstone in the Cowlitz Formation.[20] It recovered a coarsening upward sequence of moderately to well-sorted, fine-grained, micaceous sandstone with minor laminated dark gray siltstone. The top contact of the Clark and Wilson member with the overlying upper mudstone member of the Cowlitz Formation is identified by a sharp positive deflection of spontaneous potential log response, while the base is more gradational. The better-quality reservoir portions of the core had porosity ranging from 30-36% (average 33%) and horizontal permeability from 331-1104 mD (average 721 mD).

The Clark and Wilson sandstones are overlain by the upper mudstone member of the Cowlitz Formation, which comprises coaly siltstone and mudstone facies. At a depth of 700 m the calcareous concretions within this mudstone had 2.1% porosity and 0 mD measured permeability. This is probably the sealing unit at the Mist gas field.

As the individual gas pools became depleted at Mist field, a few were converted to underground gas storage fields. Gas is injected and stored in the Clark and Wilson sandstone units of the Upper Eocene Cowlitz Formation at depths of 370 to 820 m.[21] These are marine deltaic sandstones with good porosity and permeability. The field is structurally complex and recent wells are horizontal for better access to the various structural blocks (**Figure 16**).

Several petroleum wells dating to the 1920’s have been drilled in the Centralia-Chehalis basin close to the mining area (**Figure 19)**. Unfortunately, none of these old wildcat wells have detailed well logs or lithologic descriptions available. In 1962 Shell drilled the Thompson No. 1 well to total depth of 3,300 m about 15 km south of the Centralia mine at the southern edge of the Centralia-Chehalis basin (**Figure 7).** The well penetrated 2,220 m of coal-bearing, marginal marine clastic rocks in the Eocene Skookumchuck Formation and 1,070 m of volcanic rocks in the Eocene Northcraft Formation. The well bottomed near the gas generation window, which is fairly deep in this basin due to the low geothermal gradient. The Chehalis block was one of five areas nominated by the state of Washington for its 2005 lease auction.[22]

Recently, a promising new sub-basalt tight gas play is undergoing testing by EnCana, Shell, and other companies in the Columbia basin about 100 km east of Centralia. This play targets low-permeability Tertiary lacustrine sandstones at depths of 4,400 m, which are buried beneath about 1 km of flood basalt. However, the Columbia basin is an entirely separate province different geologic characteristics than those at Centralia.[23]

Jackson Prairie Underground Gas Storage Field

Puget Sound Energy (PSE), a privately owned utility, operates the Jackson Prairie underground natural gas storage facility located about 15 km south of the city of Chehalis in Lewis County (**Figure 7**).[24] Although the facility is used for short-term storage of natural gas, it also demonstrates that geologic traps and reservoirs suitable for CO_2 storage may be present near Centralia. Note that carbon dioxide, as a much larger molecule than methane, is less buoyant and should be less prone to leakage. Thus seals capable of storing natural gas should also contain CO_2.[25] The positive experience at Jackson Prairie also suggests that an industrial facility comparable to a CO_2 injection and storage project can be permitted, safely operated, and achieve broad public support in the region.

The Jackson Prairie site was discovered by a petroleum exploration well drilled in 1958. Although this well failed to locate commercial quantities of hydrocarbons, it penetrated thick wet sandstone saline aquifers with good porosity and permeability **(Figure 17a).** An anticlinal structure provides closure to trap the buoyant natural gas within the sandstones at depths of 300 to 900 m. Comparable sandstones and structural closures occur in the vicinity of the Centralia power plant and could be used for long-term CO_2 storage.

In 1963 Washington State passed a law authorizing underground gas storage. The Jackson Prairie storage facility was developed in the late 1960's, the first such facility in the state but today one of some 400 similar UGS facilities in North America. The field covers an area of 13 km^2 (3,200 acres; **Figure 17b**). PSE leased the land from approximately 60 individual landowners, who maintain control of nearly all of the surface and typically use it for farming, forestry, housing or other uses.[26] The field has been in operation continuously since 1970 with no significant safety or leakage incidents.

Jackson Prairie field consists of 45 injection/withdrawal wells and surface pipeline, dehydration, and compression facilities to handle gas off take and re-injection into the main pipeline. The surface facilities and footprint are not dissimilar to those anticipated for a CO_2 injection and storage project at Centralia (**Figure 17c**). This provides an indication that industrial facilities of this type can be permitted and constructed in Washington State, particularly in areas of low population density such as the Centralia-Chehalis coal region (at least outside of the cities proper).

Natural gas at Jackson Prairie field is injected during low-demand summer months and then withdrawn in winter months when seasonal and daily demand is higher. Working capacity of the field currently is 650 million m^3 (23 Bcf). PSE expanded the field during 2007-8, drilling 10 wells and installing new pipe and compressors to boost withdrawal capacity to 32.6 million m^3/day (1.15 Bcfd), ranking it in the upper 5% of U.S. storage fields on deliverability.

With further expansion underway, working storage capacity is scheduled to reach 708 million m^3 (25 Bcf) by 2012. Including the "cushion gas" volume, which remains in the reservoir throughout the year and provides pressure for the working gas, the total gas volume injected and stored underground will be 1.4 billion m^3 (48 Bcf). PSE owns the 3,200-acre reservoir jointly with Avista and Williams, holding leases for subsurface natural gas storage. Most of the surface acreage is privately owned and used for timber production or livestock grazing.

The storage reservoirs at Jackson Prairie field are good quality sandstones in the Eocene Skookumchuck and Oligocene Lincoln Creek Formations at a depth of about 600 m. (Note that these are the same geologic formations, lithologies, structures, and depths as occur at Centralia 20 km to the north.) One of the Lincoln Creek sands tested 25% porosity with 1800 mD of permeability, [27] while other sands at the field tested up to 36% porosity and average 1500 mD.[28] Reservoirs with such high porosity and permeability are fairly unusual in the Pacific Northwest region, where poorly sorted and clay-rich sandstones predominate. Native gases in the sandstones tested at 12 of the field wells were primarily methane (60-74%) and nitrogen (26-30%).

One interpretation of the trapping mechanism at the Jackson Prairie field, based on 3D seismic and repeated sections seen in several well logs, attributes the field to gouge along a high-angle reverse fault.[29] Smectite clays within the fault gouge are thought to form an impermeable seal to gas within the reservoir, including across sand-on-sand fault contacts. Fault motion is dated to middle Oligocene to Miocene (36 to 24 Ma), becoming inactive prior to Columbia River Basalt time (Grande Rhone, Miocene), as it does not offset these flows. The fault has throw of up to 150 m and juxtaposed Eocene Skookumchuck sandtone over Oligocene Lincoln Creek mudstone. Smaller faults also occur in the field but apparently do not hinder gas communication across the reservoir.

Underground Coal Gasification Field Test at Centralia

During 1978-82, the U.S. Department of Energy conducted a site characterization and field test of underground coal gasification (UCG) technology at Centralia. This process involves introducing oxygen to combust deep coal seam in situ and then producing the gasified coal to the surface for utilization. Due to technical and economic challenges, UCG technology has not yet achieved commercial operation. However, higher energy prices and new drilling technologies have reignited interest in the UCG process in recent years.[30]

USDOE’s Sandia and Lawrence Livermore National Laboratories conducted most of the work on the Centralia project.[31] One conclusion reached by the project was that a UCG demonstration test at Centralia, targeting the 14.5–m thick Big Dirty coal seam at a depth of 180 m, could be feasible. Although the demonstration did not progress to the commercial stage, the activities conducted by this project – which included surface seismic and logging of several coreholes, and the collection of detailed data on the Tono syncline portion of the Centralia Mine -- are useful for the current deep coal seam CO_2 sequestration evaluation.

In selecting Centralia for the UCG test, the USDOE evaluated coal deposits throughout Washington State using these basic geologic screening criteria:

- Coal thickness of at least 1.8 m.
- Burial depth in the range of 90 to 300 m.
- At least 50 million t of coal in situ.
- Overlying and underlying strata are relatively competent, impermeable, and free of aquifers.
- Simple geologic structure, preferably free of faulting and folding.
- Close to an existing power station and easy to access.

Based on these screening criteria, USDOE concluded that none of the coal basins in Washington State was a perfect fit. The search was narrowed to three areas with adequate coal reserves: the Bellingham coal field in Whatcom County, the Roslyn coal field in Kittitas County, and the Centralia-Chehalis coal field in Lewis and Thurston Counties. As a result of the screening, the Centralia-Chehalis basin was selected, being the largest coal field in Washington as well as close to the Centralia steam electric power plant.

USDOE further evaluated three possible sites at Centralia for the UCG test. These included the Thompson and Snyder Creek synclines, the Mendota syncline, and the Tono basin. The Tono basin was selected because the Big Dirty seam is up to 15 m thick, up to 300 m deep, and relatively less mined out at the time.

USDOE selected a drilling site in the northwest edge of the Tono basin (**Figure 18**), a small coal deposit within the Centralia mine. Low-resolution (by today's standards) 2D seismic reflection, seismic refraction, and electromagnetic surveys were shot to define the local structure prior to drilling. Although the geologic structure in this area was known to be fairly complex, many of the coreholes that USDOE drilled encountered additional faults not detected by seismic, demonstrating that the structure was even more complex than initially believed.

In all, USDOE drilled and tested eight coal exploration coreholes and two hydrology wells in a small area of the Tono coalfield in 1979. Cores retrieved were described and tested for coal proximate, ultimate, free swelling, and equilibrium moisture content. Physical and chemical properties of some sandstones also were measured, showing that siltstones above the coals would act as effective gas seals. The coreholes also were logged using fairly conventional gamma ray, density, sonic, and resistivity logs. The two hydrology wells demonstrated that groundwater intrusion into the coal zone was minimal.

Following the corehole tests, several experimental burns of increasing scale were performed at the surface to try to simulate UCG processes. Short-term (3-day) experimental burns were conducted within cavities excavated approximately 15 m behind the mining face of the Big Dirty seam, providing indications of anisotropic permeability.[32] A longer-term (30-day) experimental burn in a 274-m long borehole drilled along the 14° structural dip angle of the Big Dirty seam demonstrated that this coal seam is stable enough to support horizontal drilling.[33] While these tests represented useful steps for demonstrating UCG technology, their principal contribution to the current CO_2 storage project is the data collected by the coreholes. These are discussed in further detail in Section 3.

3.0 Coal and Sedimentary Deposits in the Centralia-Chehalis Region

Coal Deposits of Washington and Oregon

During late Eocene time, clastic sediments including significant coal deposits formed within a north-south striking depositional system that extended from the Seattle area south into northwestern Oregon.[34] These coal-bearing units have been given a variety of names, reflecting local terminology and the intertonguing nature of the coal deposits (**Figure 1**), but they are genetically related. Coal-bearing formations include the Cowlitz, Skookumchuck, Carbonado, Spiketon, Tiger Mountain, and Renton Formations, as well as the undivided Puget Group. Coals in the Centralia-Chehalis basin are mainly within the Skookumchuck Formation.

The Oregon-Washington Eocene depositional system was segmented by faults and influenced by the intrabasinal Tukwila and Northcraft volcanic centers. Paleobotanic studies indicate that the climate was coastal, warm, and humid with moderate rainfall, while paleocurrent data indicate that sediment transport was from east to west across the basin. Sandstone composition within the basin is arkosic (clay-rich) and was mainly derived from crystalline rocks in the east. The proportion of volcanic detritus generally increases upward in the section, but also varies locally as a function of proximity to volcanic centers.

Coal-bearing formations in the Oregon-Washington trough were deposited in a variety of deltaic, fluvial, brackish, and shallow-marine environments.[35] Fluvial and distributary channel deposits typically form thick cross-bedded sandstone bodies. Inter-channel deposits formed within a variety of sandstone, mudstone, and coaly facies deposited in crevasse channels and splays, floodbasins, shallow lakes, and mires. Shallow-marine and brackish water deposits consist mainly of stratified to massive sandstone and mudstone deposited in tide- and wave-influenced shoreface, mouthbar, and shallow shelf environments. Coals are bracketed by both nonmarine and brackish or shallow marine facies and developed in both upper and lower delta and coastal plain settings.

Previous work by Golder Associates Inc. as part of the WESTCARB project evaluated the regional CO_2 storage characteristics of non-coal strata in the sedimentary basins of Washington and Oregon.[36] The coalbed methane potential of the region has been investigated sporatically,[37] but there has been no rigorous resource assessment based on detailed mapping of the relatively complex coal basins in the Pacific Northwest region.

Centralia-Chehalis Coal Basin

Initially described by various researchers in the early 1900's, the Centralia-Chehalis coal region was mapped, cored at a reconnaissance level, and interpreted more extensively by the U.S. Geological Survey in the 1950's.[38] Coal mining companies later drilled thousands of proprietary coreholes which helped to further define the geology of the coal deposits, although none of this information has been published. During the late 1970's and early 1980's the USDOE conducted coring and geophysical measurements as part of a small-scale field test of underground coal gasification technology in one of the Centralia-Chehalis coal fields.[39] In addition, there have been several deep petroleum exploration test wells drilled in the basin. This information was compiled and synthesized in the current study, resulting in hopefully a more complete geologic interpretation of the Centralia-Chehalis basin.

Eocene to Quaternary rocks are exposed in the Centralia-Chehalis region, comprising a total sedimentary sequence about 4 km thick. The deepest petroleum exploration well in the basin was the Shell Thompson 1 State was drilled in 1962 to a total depth of 3,300 m at the southern edge of the Centralia-Chehalis basin (**Figure 19).** The well penetrated 2,220 m of coal-bearing, marginal marine clastic rocks in the Eocene Skookumchuck Formation and 1,070 m of volcanic rocks in the Eocene Northcraft Formation. A regional seismic and magnetotelluric geophysical study identified 3 to 5 km of sedimentary rock in this southern portion of the Centralia-Chehalis basin (**Figure 20**).[40]

Potential saline aquifers in these formations would appear to be deep enough to store CO_2 in the supercritical phase (about 800 m), although current data does not allow detailed depth mapping on a regional scale. For deep coal storage, the storage mechanism is by adsorption on the coal. Thus, significant volumes of CO_2 can be stored even at shallow depths, depending on the shape of the sorption isotherm curve, and the 800-m depth threshold is not significant.

Sedimentary rocks in the Centralia-Chehalis basin typically include marine, brackish-water, and non-marine sedimentary rocks with interbedded volcanics. The rocks have been folded and faulted along a NW-SE trend, reflecting NE-SW compression. Basalt dikes and gabbro sills have intruded the Eocene and Oligocene rocks. At the surface they are extensively overlain by unconsolidated glacial till and outwash dating from Quaternary to Recent.

The Centralia-Chehalis region has a number of sub-bituminous and lignite coal fields, lying in a trough between the eastern margin of the Coastal Ranges and the western margin of the Cascades (**Figure 7**). Coal-bearing regions include the Centralia-Chehalis coal district in the north -- the largest mining area -- as well as the Morton coal field in the east and the Toledo coal field in the south. These relatively small individual coal basins are separated by faults and erosional highs.

Compared with commercially developed coalbed methane basins elsewhere in the US, Canada, and Australia, the Centralia-Chehalis coal deposits are much less continuous and structurally more disrupted. **Figure 21** shows the relative size and structural complexity of the Centralia-Chehalis coal fields compared with the Powder River basin CBM basin, shown at identical scale. By comparison, the Centralia-Chehalis coal fields are much smaller and have more rapidly changing reservoir parameters such as depth, strike direction, and dip angle.

Stratigraphy (Eocene-Recent)

Eocene to Quaternary rocks are exposed in the Centralia-Chehalis district, comprising a sedimentary sequence totaling about 4 km thick. These rocks include marine, brackish-water, and non-marine sedimentary rocks with interbedded volcanics. The rocks have been folded and faulted. Basalt dikes and gabbro sills have intruded the Eocene and Oligocene rocks. At the surface they are extensively overlain by unconsolidated glacial till and outwash dating from Quaternary to Recent. **Figure 19** shows the surface geology of the Centralia-Chehalis district.

The Cenozoic sedimentary and igneous intrusive formations at Centralia-Chehalis are discussed in order from oldest to youngest, as follows:

Eocene Cowlitz (or McIntosh) Formation. The Cowlitz Formation (or McIntosh as referred to by the early USGS reports) is the basal sedimentary unit in the Centralia-Chehalis basin. Although a few sporadic and poorly developed coals occur in the Cowlitz, most of the organic material occurs in high-ash carbonaceous shales. Not considered a mining target, neither do the Cowlitz coals appear to be attractive targets for CO_2 storage. And while sandstones in this formation are common, they are poorly sorted, hydrothermally altered, and appear to have very low porosity and permeability in this region. Overall, the Cowlitz coal seams and sandstones are not considered attractive targets for CO_2 storage.

The Cowlitz crops out east of the mining area, where it consists of mainly siltstone with massive arkosic sandstone and coal beds. Further west where the formation is structurally deeper, the Mottman #1 well (Section 12-T16N-R2W) penetrated more than 1 km of siltstone, sandstone, and interbedded volcanic pyroclastic rock, while the Chehalis #1 well (Section 17-T14W-R3W) logged nearly 500 m of siltstone and sandstone. These deposits are interpreted as deepwater marine siltstone with near-shore arkosic and basaltic sandstone in the lower and upper parts. In the deep test wells, porphyritic basaltic flows and pyroclastic rocks are interbedded with siltstone and sandstone.

Rocks in the Cowlitz Formation mainly consist of dark-grey, well-indurated tuffaceous siltstone and claystone with thin interbeds of tuff. Carbonaceous material (coal) and pyrite are common. Although some beds are massive, most are laminated. The lower portion is dark-grey basaltic sandstone interbedded with light-grey arkosic sandstone. The upper 75 m of the Cowlitz is a massive arkosic sandstone, which has been quarried for building stone near the city of Tenino. Sandy strata with interbedded carbonaceous layers east of the mining area defines the paleo shoreline during deposition.

Petrographic analysis of the arkosic sandstone within the Cowlitz Formation shows it to consist of 75-90% clastic grains, with matrix accounting for the remaining 10-25%. Plagioclase, mainly andesine as expected by the andesitic volcanoes of this region, accounts for 25-40% of the clastic grains. Quartz, commonly sub-rounded and strained, accounts for 15-30% of the rock. Biotite and muscovite micas form 10-15%, while basalt fragments are generally <10%. The matrix consists of calcite, clay minerals, chlorite, and altered volcanic glass components.

Interbedded volcanic rocks within the Cowlitz are massive porphyritic and vesicular basalt flows, dominated by plagioclase feldspar and pyroxene phenocrysts. Pyroclastic material in the rock is mainly tuff, consisting of basalt fragments and crystals of plagioclase, augite, and magnetite. Tuffs in outcrop appear so highly welded that they resemble basalt flows. Hydrothermal alteration formed chlorite, biotite, kaolinite, magnetite, and zeolites.

Eocene Northcraft Formation. The Northcraft Formation is a sequence of volcanic and sedimentary rocks conformably overlying the Cowlitz Formation.[41] The Northcraft crops out in the north and east of the coal mining area and was penetrated at depth in several wells further west. It ranges in thickness from 220 to 300 m.

The lower portion consists mainly of coarse basaltic conglomerate, sandstone derived from basalt, and pyroclastics. Voids are filled with secondary zeolites, chalcedony, or chlorite. The upper unit consists of ferromagnesian basaltic lavas, breccia, and pyroclastic rocks. The lava flows are largely andesite, with some basalt. Textures range from vesicular, trachytic, porphyritic, to aphanitic. Some flows contain breccia with andesite or basalt blocks 2 m in diameter. Secondary quartz, calcite, and zeolite minerals fill irregular joints and voids.

Even more so that the Cowlitz, the Northcraft Formation does not appear to be a suitable reservoir for CO_2 storage. There are no coal seams. The clastic rocks are primarily volcanic-derived. Though porous at one time, they have experienced extensive secondary mineralization. They are unlikely to have significant porosity and permeability.

Eocene Skookumchuck Formation. The Skookumchuck Formation contains most of the coal deposits in the Centralia-Chehalis region and also contains sandstone with promising reservoir characteristics. Thus, it is the focus for this evaluation and should be considered the primary target for a possible CO_2 storage pilot at Centralia.

The Skookumchuck Formation is present throughout the Centralia-Chehalis basin and consists of marine, non-marine, and brackish sedimentary rock, with occasional thick and economically mineable coal seams. It mostly conformably overlies the Northcraft Formation, apart from a local angular unconformity in the mining area near the outcrop. Up to 1 km thick, the Skookumchuck generally includes a lower and upper sandstone units separated by a westward-thickening siltstone unit in between. Lithologies change rapidly vertically and laterally, reflecting the alteration of marine and non-marine deposition near the littoral zone. Massive cross-bedded and thinly laminated sandstones and siltstones reflect shallow-water deposition. This is inter-tongued with marine, fine-grained sandstones and siltstones.

Sandstone in the Skookumchuck is blue-grey, fine- to medium-grained, micaceous and carbonaceous (coaly), basaltic and andesitic, and locally contains fine tuff. Poorly sorted generally, some of the more massive beds exhibit better sorting. Mostly friable, in places it may be cemented with calcite, iron oxide, and silica derived from volcanic glass. Some of the sandstones contain as much as 40% calcite. Sandstone beds are lenticular but some may be traced out for several kilometers.

Petrographic analysis of Skookumchuck sandstones shows they consist mainly of angular feldspar (andesine; 10-40%), sub-rounded quartz (10-40%), muscovite and biotite (up to 10%), and sub-rounded lithic fragments of tuff, basalt, and andesite (5-80%). In total, clastic grains account for 50-80% of the rock. Matrix and cement comprise the remaining 20-50%, consisting of calcite, clay minerals, chlorite, and altered volcanic glass.

Siltstone in the Skookumchuck ranges from dark brown to greenish grey and is finely micaceous, carbonaceous, tuffaceous, and often fissile. Conglomerate, uncommon in the Skookumchuck, does occur at the base of the formation near the eastern outcrop. Derived from the underlying Northcraft Formation, the conglomerate comprises 6-60 m of poorly sorted basaltic and andesitic sandstone and conglomerate.

Laboratory analysis of shallow cores from the Skookumchuck sandstones showed porosity ranged from 5.3 to 35.2% and permeability from 1.42 to 3,506 mD. The thicker, more massive beds generally have better reservoir characteristics.

Economically important coal and related carbonaceous shales are interbedded with the clastic sedimentary rocks in the Skookumchuck Formation. Individual coal seams range from several centimeters to 5 m in thickness. Coal seams grade laterally and vertically to carbonaceous shales. The coal beds usually have sharp contacts with the overlying and underlying sedimentary rocks. In place, the upper parts of some coal seams are cut by erosional channels filled with sandstone.

Oligocene Lincoln Formation. Comformably overlying the Eocene Skookumchuck Formation, the Lincoln Formation in the Centralia-Chehalis region is a 600-m thick sequence of tuffaceous and basaltic marine sandstone and siltstone. Continental deposits derived from volcanic and pyroclastic sources also occur. The basaltic sandstone member of the Lincoln, best developed east of the Chehalis River at 500 m thick, consists of massive, well-indurated, fine-grained tuffaceous sandstone and siltstone. At its base, pebble conglomerates of basalt and andesite occur. In contrast to the Skookumchuck sandstones, the Lincoln Formation sandstones consist primarily of volcanic material with only minor feldspar, quartz, and mica. The volcanic material includes rounded basalt and andesite fragments, probably derived from the Northcraft Formation. Pyroclastic pumice and glass shards also occur. The basaltic sandstone is more resistant than the underlying Skookumchuck and erodes to form rugged topography.

Petrographic analysis of the Lincoln basaltic sandstone shows that clastic grains are 40-60% rounded basalt or andesite, 5-25% angular plagioclase (andesine or labradorite), and up to 10% magnetite. The matrix consists of altered volcanic glass, chlorite, zeolites, and clay. Thin (< 1 m) pyroclastic tuff beds, consisting largely of volcanic glass and pumice, also occur sporadically.

The Lincoln tuffaceous sandstone member consists mainly of fine-grained to very fine-grained tuffaceous sandstone and siltstone. It is massive apart from occasional thin inter-beds of basaltic sandstone. Petrographically, the tuffaceous sandstone consists of volcanic glass (34%), basalt and andesite fragments (26%), plagioclase (oligoclase; 25%), chlorite (6%), hornblende (5%), and magnetite (4%). Though it appears impermeable, calcite is often leached out of the siltstone to a depth of 8 m in outcrop.

Miocene Astoria Formation. Uncomformably overlying the Oligocene Lincoln Formation is a sequence of continental and marine conglomerate, sandstone, and siltstone up to 150 m thick of the Miocene Astoria Formation. An episode of folding and faulting in the region had preceded deposition of the Astoria. Completely eroded in the coal mining area today, the Astoria occurs only in three widely separated areas in the Centralia-Chehalis district. The largest preserved Astoria deposits are found in the Centralia and Chehalis Synclines southwest of the coal mine. The lower portion of the Astoria Formation consists of a friable, medium-grained, tuffaceous sandstone. The upper portion is fine-grained arkosic sandstone with abundant siltstone fragments and quartzite pebbles. Petrographic analysis of the Astoria sandstones shows they consist mainly of volcanic lithic fragments derived from the underlying Lincoln Formation, plagioclase, and quartz. Fossil wood, including tree stumps, is common in this continental deposit.

Miocene Columbia River Basalt. Flood basalt occurred widely in Washington State during Miocene and later times. However, this Columbia River Basalt is not present in the mining area, where it was never deposited or has been eroded. It currently is found only in the southwestern portion of the Centralia-Chehalis area, within the Centralia and Chehalis Synclines, which were paleo lows. There it is 20-30 m thick and consists of dark grey, aphanitic, basalt that rests unconformably on sedimentary rocks of the Lincoln and Astoria Formations. It is jointed in prismatic, columnar, or rosette styles 3 to 5 m in length.

Pleistocene Logan Hill Formation. This unit comprises glacial till, outwash, and glaciofluvial deposits formed by Pleistocene glaciation of the western Cascade Mountains rests on the Columbia River Basalt. The Logan Hill Formation consists of partly consolidated gravel and sand which form flat-topped eroded partly plateaus throughout the Centralia-Chehalis region. 20-60 m thick, its tilted surface demonstrates that sourcing came from the east. It is weathered and frequently forms landslides along stream cuts.

Intrusive Rocks. Identified igneous intrusions are not common in the Centralia-Chehalis region but are difficult to detect and may well be more prevalent than current mapping indicates.

Intrusions have been identified when they are exposed by stream cuts or rock quarries or when penetrated by exploration wells. The intrusions appear to become more numerous towards the coal mining area in the eastern side of the region.

Igneous dikes and sills which have been identified are mainly gabbro porphyry and porphyritic basalt which intrude the Eocene to Oligocene sedimentary section. The intrusions do not affect Miocene or later strata, thus are dated late Oligocene. These two rock types are probably of similar age. Similar-aged intrusions occur in the Coastal Ranges of Oregon.[42]

Two petroleum exploration wells encountered intrusions in the vicinity of the mining area. The Bannse #1 (22-T15N-R2W), located about 5 km northwest of the mining area, encountered an igneous intrusion and was abandoned at a total depth of 1280 m. It consisted of gabbro porphyry, similar to that better exposed at the Columbia rock quarry (11-T15N-R1E), where it is massively jointed, medium grained, and has granular and porphyritic texture. Plagioclase (labradorite) phenocrysts form about 60% of the rock. Augite in the groundmass, about 10-25% of the rock, has been altered to chlorite and biotite. Hydrothermal alteration has added biotite, chlorite, zeolites, calcite, and hematite.

The Wulz #1 exploration well (29-T13N-R1W), located about 5 km south of the mining area, encountered a porphyritic basaltic intrusion between depths of 692 m and 875 m in the upper part of the Skookumchuck Formation. Its total thickness of about 180 m makes this the thickest sill recorded in the region. The basaltic intrusions in the Centralia-Chehalis region typically are dark greenish grey with porphyritic and vesicular texture and contain significant volcanic glass. Zeolites and chlorites fill most of the vesicles. Plagioclase phenocrysts ranging from andesine to labradorite form about two-thirds of the rock, with altered augite the remainder. Hydrothermal alteration, similar to that affecting the gabbro porphyry, also has added biotite, chlorite, zeolites, calcite, and hematite.

Structural Geology

Surface mapping augmented with detailed coal coreholes and oil and gas exploration wells helps define the structural geology of the Centralia-Chehalis region (**Figure 22**). Eocene and Oligocene coal-and sandstone-bearing strata have been deformed into a series of NW-SE trending faults and folds. Dip angles generally are moderate (0-30º) but can reach vertical close to faults.

Faults are mainly high-angle reverse or normal faults; there are no apparent low-angle thrust. The main faults generally trend NW-SE and are downthrown on the southwest side. Fault geometry suggests that they could have a right lateral strike-slip component given the generally east-west compression stress orientation, but this has not been demonstrated. The faults usually transect the larger folds in the region.

There are four main reverse faults in the Centralia-Chehalis region. These include the west-trending Doty Fault, and the NW-trending Kopiah, Newaukum, and Coal Creek Faults. Sedimentary strata adjacent to these faults exhibit fault drag, dipping at high angles or overturned in places to the southwest. Coal beds affected by faults often exhibit bedding plane slip as well as a crush zone 30 cm wide.

The four main reverse faults are, in order from the mining area in the northeast toward the southwest:

- ***Coal Creek Fault.*** A high-angle reverse fault, the Coal Creek fault parallels the southwest side of the Coal Creek anticline. Displacement is approximately 120 m. It becomes difficult to map south of Hanaford Creek, where it disappears in the volcanic rocks of the Northcraft Formation. The Coal Creek fault defines the northeastern limit of the TranAlta mining lease, although coal deposits continue northeast of the fault within the Snyder Creek and Thompson Creek synclines.
- ***Newaukum Fault.*** This reverse fault, also down on the south, generally parallels the Coal Creek and Kopiah faults. Displacement is uncertain. Towards the north close to the mining area the Newaukum fault disappears beneath the Meridian Hill Anticline.
- ***Kopiah Fault.*** Extending a distance of some 30 km, the Kopiah fault west of the mining area is the principal reverse fault in the Centralia-Chehalis region. It generally trends northwest, apart from an abrupt deviation to EW trend for a distance of 5 km south of Centralia. Displacement is about 150 m, down on the southwest side as demonstrated by the overturned sedimentary strata. The Kopiah fault splits and displacement decreases to about 70 m.
- ***Doty Fault.*** This EW-trending, high-angle reverse fault extends from the western edge of the basin to the Chehalis River valley, southwest of the mining area, where it apparently terminates against the Salzer Creek fault. Displacement increases to the west, ranging from 60 to 120 m of throw. Downthrown on the south, this fault caused drag folding of sedimentary strata adjacent to it. The Doty fault is inferred to be an active transform fault related to subduction.[43]

In addition to the major reverse faults, smaller normal faults also occur in the Centralia-Cehalis region. Normal faults are typically oriented west to northwest and can have up to 450 m of throw, but generally much less. These include the Salzer Creek, Scammon Creek, and Chehalis faults. Smaller normal faults, with throws typically 3 m or less, are commonly observed in the coal mines. Nearly all of the USDOE underground coal gasification coreholes penetrated faults which had not been previously mapped or identified by seismic and geophysical surveys which had been run specifically to find them (**Figures 23** and **24**).

The main normal faults are, in order from the mining area in the northeast toward the southwest:

- ***Salzer Creek Fault.*** The largest normal fault in the region, it extends westward about 20 km from Deep Creek almost to South Hanaford Creek. Displacement (high-angle and down to the north) reaches maximum 450 m west of the Chehalis River, decreasing to the east as it cuts the north part of the Chehalis anticline.
- ***Scammon Creek Fault.*** This NW-trending normal fault (also down to the north) extends just south of the town of Independence southeastward about 15 km, disappearing under Chehalis River alluvium. Maximum displacement is about 300 m north of Lincoln Creek.
- ***Chehalis Fault.*** West-trending from near the head of Coal Creek, where throw reaches 250 m, and disappearing beneath alluvium of the Chehalis River valley. It cuts the south-plunging Chehalis anticline. Motion along the Chehalis fault pre-dated Miocene strata, which are uncut.

Folds. A number of anticlinal and synclinal folds parallel the major NW-SE trending faults in the Centralia-Chehalis region. Sedimentary strata in the region range from flat-lying to near vertical, generally dipping at moderate angles towards the fold axes. Folds are relatively open in in the western region and become tighter towards the mining area in the east. Major folds are likely related to basement faults, while some smaller folds resulted from fault drag.

The main synclines are, in order from the mining area in the northeast toward the southwest:

- ***Snyder Creek and Thompson Creek Synclines.*** These two adjacent and closely related synclines, each about 8 km in length, are tight, narrow folds within the Skookumchuck Formation. Trending NW-SE in the northeastern part of the mining area, they are separated by an equally tight, unnamed anticline. Dips are moderate, apart from the east limb of the Thompson Creek syncline, which terminates against a high-angle reverse fault and dips quite steeply (30-60º). These synclines have not been extensively mined and contain significant undisturbed coal resources that could be used for CO_2 storage.
- ***Hanaford Creek Syncline.*** Another NW-trending fold, about 7 km in length, is divided into two elliptical basins by a cross-folded arch. The arch portion of the syncline, its structurally highest point, has been extensively mined and little usable coal resource remains. However, some undisturbed coal resources probably remain in the southeast and northwest portions of the syncline.
- ***Mendota Syncline.*** The largest syncline in the mining area, the Mendota extends a length of about 20 km in a NW-SE direction southeast of the Centralia power station. The central portion of this syncline has been extensively mined and contains little usable coal resource, apart from its unmined far southeastern and northwestern extents.
- ***Tono Basin.*** Unique in this area in being more circular than elongate, the Tono basin is a broad, shallow downwarp with gentle 10º dipping flanks. The Tono No. 1 seam has been

extensively mined but deeper coals are still extant and could be used for CO_2 storage. The Tono basin was the site of the USDOE underground coal gasification test conducted in the early 1980's (discussed separately).

- ***Centralia Syncline.*** A broad, shallow, NW-SE trending downwarp about 25 km in length located west of the mining area and passing directly through the city of Centralia. The Centralia syncline has not been mined and it is possible that significant coal resources are present, although if present they are probably quite shallow. The population center of Centralia may inhibit CO_2 injection along this portion of the syncline, but much of its length passes through lightly populated areas.

The main anticlines are, in order from the mining area in the northeast toward the southwest:

- ***Coal Creek Anticline.*** Plunging to the northwest, the Coal Creek anticline is asymmetric, with a high-angle reverse fault along its steeply dipping southwestern limb. Coal Creek anticline merges into the Coal Creek fault.
- ***Meridian Hill Anticline.*** Paralleling the Coal Creek anticline and with a similar high-angle reverse fault on its southwest limb, the Meridian Hill anticline separates the important coal mining basins defined by the Hanaford Creek and Mendota synclines.
- ***Tenino Anticline.*** The sole major NE-SW trending fold of note in the region, the Tenino anticline partly defines the northwesternmost extent of coal in the mining area. Coal outcrops to the southeast generally parallel its trend.
- ***Lincoln Creek Uplift.*** This is the main structural fold in the region, a broad NW-SE trending, SE-plunging anticline that has been cut by faulting. Structural relief is about 1 km and the limbs dip at 20º to 70º angles. The eroded core of this flexure exposes the Skookumchuck Formation.
- ***Chehalis Anticline.*** West of the mining area, this narrow, SE-plunging fold extends from the Salzer Creek fault across the city of Chehalis. The Chehalis anticline is the southeastern extension of the Lincoln Creek uplift but is more tightly folded.

Structural History. The Cenozoic structural history of the Centralia-Chehalis region began with downwarping along a north-south trend during Eocene time, probably associated with oblique subduction of the Kula plate with North America during the Late Cretaceous to Early Eocene,[44] resulting in deposition of the Cowlitz (McIntosh) Formation. Right-lateral strike-slip faulting and associated pull-apart rifting probably accompanied the oblique subduction.

This was followed by upwarping and volcanic activity along the margins of the region in mid to late Eocene that formed the pyroclastic flows of the Northcraft Formation, dividing the basin into a number of smaller sub-basins. Deposition continued in the troughs as the Skookumchuck and Lincoln Formations formed during late Eocene to early Oligocene time. Significant deformation and erosion then occurred in Miocene time, forming the structural elements recognized today. Slight downwarping during the middle Miocene led to deposition of the Astoria Formation. Local extensional tectonics led to small-scale igneous and volcanic activity including the Columbia River Basalts.

Faulting continues today with active seismicity in the Pacific Northwest region related to subduction of the Juan de Fuca plate,[45] although the Centralia area appears to be a fairly inactive area. **Figure 25** shows the distribution of historical earthquakes in Washington State. There is a gap in recent seismicity near Centralia. **Figure 26** shows a more detailed distribution of historical earthquakes by magnitude and decade of occurrence. There have been several small seismic events near the mining area but these have generally magnitude 3.0 or smaller. Much more intense seismic activity has occurred in the foothills of the Cascades about 30 km southeast of Centralia.

Coal Geology

Extensive coal deposits occur within the Eocene Skookumchuck Formation in the Centralia-Chehalis area. The coal seams are affected by local structure and dip at varying angles up to vertical. They are also affected by faulting and, as planes of weakness, can be sheared by bedding-plane slip and become brecciated.

A total of nine laterally persistent, mineable coal seams occur in the upper coal group of the Skookumchuck Formation (**Figure 27).** The coal seams are named after the geographic localities where they occur. The clastic rocks interbedded with the coal seams are generally arkosic and tuffaceous sandstones and siltstones (**Figure 28**). The coals generally have low ash content, high moisture content, and increase in rank from top to bottom (**Table 1**), as follows:

Table 1 : Typical Coal Properties at Centralia[46]

Seam	Thickness (m)[1]			Proximate Coal Analysis				
	Min	Max	Avg	Moisture	Ash	Volatile Matter	Fixed Carbon	BTU /lb
Tono 1	3.05	6.10	4.57	29.1	8.0	32.0	30.9	7940
Tono 2	1.22	1.83	1.52	24.4	9.3	32.4	33.9	8270
Upper Thompson	1.22	1.83	1.52	25.5	11.6	32.1	30.8	7824
Lower Thompson	2.44	3.66	3.05	26.1	12.0	31.0	30.9	7810
Big Dirty	7.62	15.24	11.43	21.6	12.2	32.7	33.5	8622
Little Dirty	0.61	1.52	1.07	28.7	11.1	33.8	33.0	8615
Smith	2.44	4.57	3.51	21.3	10.9	33.2	34.7	8800
Penitentiary	2.13	2.74	2.44	19.5	13.8	33.1	33.6	8657
Mendota	2.74	3.35	3.05	20.4	13.2	32.8	33.6	8626
Total			32.16					
Big Dirty + Smith + Mendota			**17.99**					

- ***Tono No. 1.*** Laterally the most continuous coal seam in the Centralia-Chehalis district, the Tono No. 1 averages about 4.57 m thick, with low 8% ash content. The underlying **Tono No. 2** seam also has low ash content (9.3%) but is less well developed at only 1.52 m thick. Moisture for the two Tono seams is fairly high, 29.1% and 24.4%, respectively, reflecting their low thermal maturity (approximately 8,000 Btu/lb heat content). The Tono seams are considered to have lower potential for CO_2 injection because they are stratigraphically and structurally shallow, have high moisture, low rank and probably low CO_2 storage capacity.
- ***Upper Thompson.*** Persistent throughout the Centralia-Chehalis district, this coal seam averages 1.52 m thick (**Figure 30**). Moisture content is fairly high at 25.5% but ash is moderately low at 11.6%. Several tuffaceous siltstone partings about 30 cm thick commonly occur near the middle of the seam. The **Lower Thompson** seam is thicker (3.05 m) and has similar ash and moisture (12.0% and 26.1%, respectively) but is more lenticular and thus laterally quite variable. Locally it is an important mining target.
- ***Big Dirty.*** The thickest coal seam, most prominent stratigraphic marker in the Centralia-Chehalis district, and probably the main target for CO_2 storage, the Big Dirty averages 11.43 m thick and can exceed 15 m in places. However, it thins markedly in the Thompson Creek and Snyder Creek synclines, where it is less than 2 m thick. The Big Dirty is slightly higher in rank than the overlying coal seams, with 8622 Btu/lb heat content, 33.5% fixed carbon, and reduced 21.6% moisture. Ash is moderately low (12.2%), though partings totaling several meters in thickness can occur (**Figure 31**). Overall, the Big Dirty probably represents the best individual coal seam target for CO_2 storage in the Centralia region. The ***Little Dirty*** seam is much thinner than the Big Dirty seam at only 1 m thick.
- ***Smith.*** A substantial coal seam averaging 3.51 m thick, the Smith frequently is scoured by sandstone channels. Silicified tree logs and stumps are fairly common, inhibiting mining operations. The Smith seam has moderate moisture (21.3%), low ash (10.9%), and relatively high heat content (8800 Btu/lb). It probably is the next most prospective seam for CO_2 storage after the Big Dirty.
- ***Penitentiary.*** Locally developed, notably along the western Tono basin and NE flank of the Kopiah fault, the Penitentiary seam is not a laterally widespread target. It averages 2.44 m thick, with slightly reduced 19.5% moisture, slightly higher 13.8% ash content. It is high in sulfur (1.6-4.4%), which makes it less attractive for mining but is not a significant factor for CO_2 storage.
- ***Mendota.*** Best developed around Kopiah and Mendota, it averages 3.05 m thick with moderate 13.2% ash content and 8626 Btu/lb heat content. It often contains "cannel" coal, a type of tectonically sheared coal high in wax content. The cannel coal is easily ignited with a match and has anomalously high heat content of 12,380 Btu.

Coal Rank. Most of the coal suitable for mining at Centralia is sub-bituminous C in rank, contains 14-35% moisture, 5-25% ash, and has a heating value of 8,300-9,500 Btu/lb. As discussed in Section 4, coal rank directly affects sorption behavior, with higher rank permitting more adsorption of methane and CO_2.

Coal Permeability. The most valid test for coal seam permeability is to conduct single-phase injection/falloff testing in a CBM test well under in-situ conditions of reservoir pressure, stress, and equilibrium moisture. This type of well test has not yet been performed at Centralia at depth. As part of the USDOE underground coal gasification program, the permeability of the Big Dirty seam was tested in a hydrologic corehole at very shallow depths (about 20 m).[47] Permeability tends to decrease sharply with depth and so it is not surprising that the Big Dirty seam tested fairly high permeability (3.2 to 38 mD).

To the north of Centralia, El Paso tested at coal seam permeability at more typical CBM reservoir depths of about 600 m in four CBM test wells.[48] Coal here is higher rank (high-volatile bituminous) than at Centralia and probably better cleated with higher permeability. Injection/falloff permeability ranged from 1 to 13 mD near the wellbore, while the production information suggested 1 to 7 mD.

Permeability at the target CO_2 storage depth of about 500 m at Centralia likely would be an order of magnitude lower than that measured by USDOE at very shallow depths. For simulation purposes, we estimated permeability to range from 0.1 to 10 mD, with a most likely value of 1.0 mD.

Coal Mining

Coal mining began in the Centralia-Chehalis area as early as the 1870’s. With mostly steep dips, mining progressed quickly to underground operations. However, coal conditions are not favorable for underground mining, as the roof of most seams is friable, unstable sandstone. Ground water seeped into the mines and required continuous pumping. Numerous faults also caused delays and added costs in repositioning the mining face.

Coal production reached about 300,000 t/year in the 1920’s but then declined to low levels. During this earlier period more than 50 coal mines were active, mostly quite small. Mining increased dramatically around 1970, when the Centralia power plant was constructed and open-pit mining was established on a large scale in the relatively flat-lying portions of several synclines. However, today all of the mines have been closed due to depletion of coal reserves and the relatively high cost of production.

The largest and most recently active mine in the state was TransAlta’s 57-km^2 (14,000-acre) Centralia mine, which recently produced about 4.3 million t per year.[49] Coal mined at Centralia was used locally to power TransAlta’s 1,404-MW Centralia Steam power station, which was built in 1971 (TransAlta also operates a smaller 248-MW gas-fired plant built in 2002 and a 1-MW hydroelectric plant built in 1970).

The Centralia mine comprises four separate open pits targeting coal seams in the Skookumchuck Formation. These pits are easily visible on an aerial photograph of the mining area (**Figure 32**). Coal seams mined were the Upper and Lower Thompson, the Big Dirty and Little Dirty seams, and the Smith seam.

TransAlta closed down its 35-year-old Centralia coal mine in December 2006, citing high production costs and stricter safety regulations.[50] The Centralia power station has switched to utilizing coal shipped from the Powder River basin. Surface reclamation work continues at the Centralia mine to backfill and replant the abandoned pits. As recently as early 2006 TransAlta had applied for permits to increase mining to about 5 million t/year, lease additional acreage outside the current holdings, and extend the life of Centralia mine for another 25 years. Clearly, a significant coal resource remains which, though not economic to mine, could be targeted for CO_2 injection and storage.

4.0 CO_2 Storage Capacity and Testing

CO_2-ECBM/Storage Project Screening Criteria

Geologic and surface conditions need to be reasonably favorable for a CO_2-ECBM/Storage project to succeed. At this early stage of technology development, with only a handful of small-scale CO_2-ECBM/Storage pilots having been tested, a preliminary but probably accurate understanding of screening pre-conditions has emerged. These reservoir screening criteria may be summarized as follows: [51]

- **Homogeneous Reservoir:** The coal seam reservoir(s) should be laterally continuous and vertically isolated from surrounding strata. This ensures containment of injectant within the reservoir as well as efficient lateral sweep through the reservoir.

Note that Centralia coal seams are reasonably laterally continuous, on a scale of several kilometers. They are vertically isolated from surrounding strata by impermeable shales, which should ensure containment of CO_2 within the coal seams. And the UCG coreholes found permeability to be fairly isotropic, at least in laboratory samples.

- **Simple Structure:** The reservoir should be minimally faulted and folded. Closely spaced faults can compartmentalize the reservoir into isolated blocks, inhibiting effective sweep. The faults themselves may divert injectant away from the reservoir, reducing the efficiency of enhanced recovery and sequestration. In addition, structurally complex areas frequently have damaged coal cleat systems and low permeability.

Centralia fares poorly on this criterion. The geologic structure is relatively complex, with considerable folding and faulting on close spacing. Structure is much more complex than at any successful commercial CBM development. Complex structure has been a principle cause for commercial failure for CBM exploration pilots in China, Poland, and other countries.[52]

- ***Adequate Permeability:*** Although no minimum permeability criterion can be specified, preliminary simulation indicates that at least moderate permeability is necessary for effective ECBM (1 to 5 mD).

Coal seam permeability has not yet been measured in-situ in the Centralia area at target depth (500 m). The USDOE coreholes tested 3.2-38 mD but at very shallow depth (20 m). Other CBM projects in similar Eocene coal seams located in other parts of Washington and Oregon have tested low-moderate levels of permeability (1-10 mD). This suggests that permeability may be adequate at Centralia, although that would need to be confirmed by in-situ testing.

- ***Optimal Depth Window:*** Just as for conventional CBM projects, CO_2 storage projects have an optimal depth window that will vary by basin. Minimum depth depends on the shape of the sorption isotherm, while permeability declines mark the define the maximum workable depth.

We assumed 150-m minimum depth cutoff at Centralia as having a reasonable threshold of storage capacity base on the isotherm. Maximum depth is probably in the 1500-m depth range, where permeability is typically minimal. However, Centralia coals are mapped to remain fairly shallow near the power plant, well above above the 1500-m cutoff.

- **Coal Geometry.** For well completion efficiencies, geometrically concentrated coal deposits with fewer thicker seams would be preferred to basins with equal total coal thickness but dozens of thin individual seams.

Fortunately, much of the coal resource at Centralia is concentrated in a half-dozen individual coal seams. We assumed the Big Dirty, Smith, and Mendota seams – being thick, deeper, and higher in rank -- offer the primary targets for CO_2 storage at Centralia.

- **Gas Saturation.** Although methane saturation does not affect CO_2 storage capacity, coal seams that are initially methane saturated have better economic prospects, in terms of more and earlier natural gas production.

No desorbed gas content data are available for deep coal seams at Centralia. CBM testing in other areas of Washington have indicated close to saturated initial conditions. The scoping reservoir simulation, discussed below, included sensitivities for 75% and 100% gas saturation.

Overall, apart from the issue of excessive structural complexity, reservoir conditions look favorable at Centralia for CO_2 storage and enhanced CBM recovery. Structural complexity could be addressed by identifying and selecting areas with few faults and minor folding.

Sorptive Capacity and Isotherms

Coal adsorbs methane, CO_2, and other gases under pressure under a relationship defined by the Langmuir equation ($V_i = P_i * V_L / (P_i + P_L)$), where actual adsorbed volume (V_i) approaches the coal seam's maximum adsorption capacity (V_L) as reservoir pressure (P_i) increases. Unlike conventional gas trapping, the relatively shallow coal seams at Centralia can adsorb significant levels of CO_2 even at shallow depths of 150-500 m.

No sorption isotherms were available for Centralia. Even had they been available, these sorption isotherm curves for surface coal samples would have to be adjusted to reflect the different capacity of deeper CO_2 storage targets, where coal rank is higher and moisture content lower. Instead we used published sorption isotherm data for Washington State and Canada coal samples, selecting the CO_2 and CH_4 curves for Horseshoe Canyon coal in Alberta, which is of comparable sub-bituminous rank (R_o=0.46%; **Figures 33, 34**).[53,54] Should coal rank be found to different in other parts of the Centralia-Chehalis basin, a linear relationship between rank and the sorption equation parameters was defined to allow adjustments (**Figures 35, 36)**.

The isotherms also are useful because there is no direct desorption data for coal seam gas content at Centralia. Coal seam desorbed gases in Washington State typically are high in methane (95-98%), with low CO_2 and other constituents. Thus, we inferred actual methane content for the coal seams based on the sorption isotherms. Absent reservoir pressure data, we further assumed hydrostatic conditions (0.433 psi/foot).

Using these curves, the CO_2 storage capacity at Centralia for coals at a depth of 150 m (500 ft) is estimated to be approximately 11.5 m^3/t (368 scf/ton). The methane storage capacity would be approximately 2.9 m^3/t (94 scf/ton). Note that the ratio of CO_2/CH_4 adsorption at this pressure of about 3.9, which is typically elevated for low-rank coals. Higher-rank coals such as the Fruitland in the San Juan basin tend to have lower CO_2/CH_4 ratio of 2 to 3.[55] This means that low-rank coal reservoirs such as at Centralia actually are more efficient at storing CO_2 than their modest methane content might suggest.

Depth-Prospective Area

Although significant coal resources remain in the deeper parts of the Centralia mine, much of the current mining area is partly to completely mined out. We focused instead on the Centralia syncline area immediately southwest of the Kopiah fault (**Figure 37**). This area is one fault block southwest of and adjacent to the current mining area, close to the Centralia power plant, and contains a large, relatively undisturbed area with coal seams at attractive depth for CO_2 storage (>150 m). It appears this area has not been mined extensively because the Big Dirty seam is deeper and somewhat thinner here than in the Centralia mine area to the northeast.

We obtained lithologic description logs from 53 water and environmental observation wells in the six townships that surround the Centralia region (out of a total 1,000 water wells drilled). Individual coal seams were not specifically named in these logs but often could be identified by their thickness and vertical spacing. The Big Dirty seam, although thinner here than in the mining area, remains the primary target at 5.2 to 11.6 m (17-38 ft) thick. Ten of the wells had penetrated the Big Dirty seam and provided direct data. Twelve other wells penetrated only the upper coal seams, such as the Tono or Thompson beds but the depth to the Big Dirty seam could be inferred from coal seam stratigraphy and spacing.

We mapped out the Big Dirty seam in these water well data points and, following the surface geology trends as well as the structure of the Centralia syncline and adjacent faults, identified an area where the seam appears to be buried at least 150 m (500 ft; **Figure 38**). Maximum depth to the Big Dirty seam along the axis of the Centralia syncline is not known, since the water wells are too shallow, but could be 500 m (1640 ft) or deeper. The west and south edges of this prospective area are less well constrained and rather arbitrarily truncated beyond existing data control. Before a CO_2 injection test takes place at Centralia, we recommend first gathering any proprietary corehole data that may exist in the syncline, shooting seismic data, and drilling exploratory coreholes to further refine the preliminary structural interpretation.

The total area of the high-graded target is 107 km^2. However, internally the area is likely to be more structurally complex that currently mapped, with additional unidentified faults and shallow regions, much like the Centralia coal mining area is broken into individual pits. In addition, the western portion of the target area underlies the city of Centralia and thus may be off limits to CO_2 storage. To compensate for these uncertainties, we assumed three-quarters of the high-graded area would be prospective for CO_2 storage (80 km^2), with the remaining one-quarter not available due to faulting, shallow depth, surface constraints, and other factors.

Outside of the Centralia syncline area, a single isolated water well southeast of the Centralia mine enabled us to infer that the Big Dirty seam is about 177 m (582 ft) deep (**Figure 34**). There are likely to be many additional areas outside of the mapped Centralia syncline in the Centralia-Chehalis basin that have CO_2-prospective deep coal resources. However, these deposits would be further away from the Centralia power plant and were not included in our storage capacity estimate.

CO_2-Prospective Coal Resources and CO_2 Storage Potential

The high-graded CO_2 prospect area within the Centralia syncline, described above, has estimated in-situ coal resources prospective for CO_2 storage of approximately 1.43 million t (**Table 2**). Based on the methane sorption isotherm, we calculate in-situ coalbed methane gas content to range from 4.16 to 5.54 m^3/t (dry, ash-free basis), depending on assumptions of initial gas saturation levels (75% and 100%). Thus, accessible CBM resources are calculated volumetrically to be 7.19 to 9.59 billion m^3 (191-254 Bcf) in place.

Table 2 : Estimated Coal Seam CO_2 Storage Capacity for Centralia Syncline Prospect

Coal Mass	Prospective Area		Depth	Press.	Coal Thickness		Ash	Moisture	Density	Coal Mass Billion daf		
	km^2	acres	m	psi	m	ft	%	%	ton/ac-ft	t	tons	
Total Centralia Syncline Prospect	107	26400	500	725	18	59	12	20	1800	1.73	1.91	
Adjusted Net 75% Area	80	19800	500	725	18	59	12	20	1800	1.30	1.43	
CH_4 and CO_2 Potential	75% Sat.		100% Sat.		100% Sat.		75% Sat		100% Sat.		100% Sat.	
	CH_4 Gas Content (d.a.f.)				CO_2 Content (daf)		CBM Resources				CO_2 Storage Capacity	
	m^3/t	scf/ton	m^3/t	scf/ton	m^3/t	scf/ton	MM m^3	Bcf	MM m^3	Bcf	MM m^3	MM tonnes
Total Centralia Syncline Prospect	4.16	133	5.54	178	21.70	695	7.19	254	9.59	339	37.56	69.82
Adjusted Net 75% Area	4.16	133	5.54	178	21.70	695	5.39	191	7.19	254	28.17	**52.36**
Centralia CO2 Emissions 100%	8.00	million t/yr		6.5	Years storage capacity							
Centralia CO2 Emissions 50%	4.00	million t/yr		**13.1**	**Years storage capacity**							
Sorption Isotherms:	CH4 VL	300	scf/ton daf		CO2 VL	1175	scf/ton					
	CH4 PL	500	/psi		CO2 PL	500	/psi					

Based on the carbon dioxide sorption isotherm, coal seams in the Centralia syncline could store about 21.7 m^3/t of CO_2 (dry, ash-free basis) at 100% gas saturation. CO_2 storage in deep coal seams within the net (again, 75%) prospective Centralia syncline area could total an estimated 52.36 million t. (However, as shown by reservoir simulation in Section 5, actual CO_2 storage likely may be somewhat less than the total capacity due to permeability and well spacing issues.) That equates to approximately 13.1 years of emissions from Centralia, assuming 50% capture. Again, there are likely to be significant additional CO_2-prospective resources outside of the Centralia syncline in the Centralia-Chehalis region, which was selected for detailed study due to its close proximity to the power station.

Scoping CO_2-ECBM Reservoir Simulation

Scoping reservoir simulation was used to examine the likely range of CO_2 storage behavior in deep coal seams at the Centralia syncline area. The reservoir simulator used for the study was the Advanced Resources International COMET3 (binary isotherm – CH_4 and CO_2) model. COMET3 is a finite-difference, fully implicit simulator that is widely used for coalbed methane, enhanced coalbed methane, and CO_2 storage in coals. [56,57]

Given the relative lack of data, a simple five-well injection pattern was constructed for the purpose of scoping reservoir simulation. The model consists of a dual-porosity, single-permeability system where the simulated well is fully bounded, behaving as if it is one well within an infinite field of wells. We assumed 0.16-km^2 (40-acre) well spacing, for both injection and production wells, because permeability at Centralia probably is low (~1 mD). We also modeled tight spacing to maximize the efficiency of injection and storage in what is a fairly small area near the power plant. A five-spot injection pattern was implemented, taking advantage of the pattern's elements of symmetry for efficient model design (10-acre quarter-well model; **Figure 39**).

Figure 40 tabulates input parameters for the simulation model. Average ash (12%) and moisture content (20%) values were assumed (**Table 1**), as well as the methane and CO_2 sorption isotherms previously discussed. The simulated well was assumed to complete the three thickest lower seams, modeled as a single layer, for 18 m of total coal thickness (Big Dirty, Smith, Mendota). Depth to the 18-m single-layer coal reservoir was assumed to be 500 m. For illustrative purposes only, **Figure 41** shows a conceptual pattern of CO_2 injection wells on 40-acre spacing overlain on the Tono coal pit (the best-controlled structure at Centralia), although the model actually used geologic conditions in the less well-controlled Centralia syncline.

Other reservoir parameters, such as coal compressibility and relative permeability, are not known for Centralia, thus were assumed to be similar to those in the better-studied San Juan basin.[58] A standard value of 2 was assumed for differential CO_2 swelling factor. CO_2 solubility in coal seam formation water was assumed to be small and not considered for the purpose of this study.

The simulation model was run for 20 years with CO_2 injection starting on day one. The production well was shut down when produced gas composition reached 50% of CO_2, on the assumption that gas processing costs would no longer be justified by natural gas revenues. The producing well was run at a minimum bottom-hole pressure of 100 psia. Instead of limiting the gas injection rate, injection was conducted on pressure to maximize injected CO_2 volumes. Maximum injection pressure was assumed equal to frac pressure, calculated using a frac gradient of 0.6 psi/ft.

A total of six simulation runs were modeled, with sensitivities to permeability (0.1, 1.0, 10 mD) and initial methane saturation (75%, 100%). Future work might consider other sensitivities, such as well spacing, coal thickness, CO_2 injection rates, etc., but the six runs give a general indication of potential CO_2 behavior in the reservoir. The six cases are summarized as follows:

- **Case 1: 0.1 mD; 75% saturation (Figures 42, 43).** The first sensitivity modeled unfavorably low permeability and initial methane saturation. Very little methane 8,500 m^3 (0.3 MMcf) and little formation water is recovered at the production well. Injected CO_2 totals only 3.7 million m^3 (6,800 t; 130 MMcf) and remains close to the injection well over the 20-year injection period. Clearly, this case would not be economically feasible.

- **Case 2: 0.1 mD; 100% saturation (Figures 44, 45).** Initial methane saturation is more favorable but permeability remains very low. Methane recovery is slightly improved at 140,000 m^3 (5 MMcf) but remains very poor. CO_2 injection totals (4,600 t; 88 MMcf), actually less than for Case 1 which had 25% more initial storage capacity free prior to CH_4 displacement. This case also would be uneconomic.

- **Case 3: 1.0 mD; 75% saturation (Figures 46, 47).** Performance improves markedly with medium permeability. Although delayed for 6 years due to undersaturation, methane recovery rises to 7.1 million m^3 (0.25 Bcf), about comparable to a below-average Powder River basin well. CO_2 injection increases dramatically to 38 million m^3 (70,000 t; 1.33 Bcf) with the higher permeability. After 20 years CO_2 becomes more evenly distributed throughout the reservoir but does not break through to the production well.

- **Case 4: 1.0 mD; 100% saturation (Figures 48, 49).** Considered the most likely case, with medium permeability and full initial methane saturation. CO_2 does not break through over the 20-year period. Methane recovery totals 9.7 million m^3 (0.34 Bcf), similar to an average Powder River basin well. CO_2 storage is distributed quite uniformly throughout the reservoir, totaling 34 million m^3 (63,000 t; 1.19 Bcf).

- **Case 5: 10 mD; 75% saturation (Figures 50, 51).** High permeability markedly increases injectivity and flow but also causes rapid breakthrough to the production well, only about 2.7 years in this scenario. The production well reaches the 50% CO_2 level after 3 years and is shut in. Even still, with the higher permeability conditions methane recovery is fairly good (10 million m^3; 0.35 Bcf). CO_2 production continues until year 8, when injection pressure approaches the fracture gradient and coal matrix swelling becomes more severe. Even ceasing injection at year 7.6, the injected CO_2 volume totals 64 million m^3 (120,000 t; 2.25 Bcf), the highest of the six cases. Wider well spacing would probably better suit this high level of permeability.

- **Case 6: 10 mD; 100% saturation (Figures 52, 53).** CO_2 takes slightly longer to break through (3.1 years), after which the production well is shut in. Injection pressure approaches the frac gradient and injection ceases at year 8. High permeability and initial methane saturation allows excellent ECBM recovery (10 million m^3; 0.47 Bcf). CO_2 storage is essentially the same as for Case 5 at 64 million m^3 (120,000 t; 2.25 Bcf). This case also would improve with wider spacing.

The reservoir simulation helps define the possible outcomes of CO_2 injection at Centralia. However, an injection test pilot ultimately would be needed to establish initial conditions and allow a more confident assessment of the feasibility.

Saline Aquifer CO_2 Storage Capacity

One recently developed concept that may have application at Centralia is the “Stacked Storage” model. The Southeast Regional Carbon Sequestration Partnership (SECARB) is employing this strategy in the Central Appalachian region.[59] Coal seams here are relatively thin while the adjacent sandstones are low in permeability. However, defining a stack of multiple injection targets makes CO_2 storage more feasible. It also helps to increase the surface area available for chemical reactions and permanent storage of CO_2 through mineralization within the thin intervals. This approach seems very relevant to Centralia.

There are four main storage mechanisms for CO_2 operate in saline aquifer rocks.[60] These are:

- **Structural and Stratigraphic Trapping.** Migration of CO_2 in response to its buoyancy and/or pressure gradients within the reservoir is prevented by low permeability barriers (caprocks) such as shale.

- **Residual saturation trapping.** Capillary forces and adsorption onto the surfaces of mineral grains within the rock matrix trap some of the injected CO_2 along its migration path.

- **Dissolution Trapping.** Injected CO_2 dissolves and becomes trapped within the reservoir brine.

- **Geochemical Trapping.** Dissolved CO_2 reacts with pore fluids and minerals in the rock matrix of the reservoir, slowly forming reaction products as solid carbonate minerals over hundreds to thousands of years.

For the purposes of a first-order capacity estimate, we calculated structural and stratigraphic trapping in the estimated pore space. Residual saturation and dissolution trapping were not considered, due to lack of reservoir data at this early stage. Geochemical trapping was considered to be too slow to be significant over the time frame of an injection project (20-40 years) but would be significant over a much longer period.

Compared with the deep coal seams, reservoir data for the potential saline aquifer sandstones at Centralia are much less available. Data are limited to detailed petrographic descriptions including texture and mineralogy for core and outcrop samples from the Eocene Skookumchuck and Oligocene Lincoln Creek Formations. These two units, which comprise the injection and storage reservoirs at the Jackson Prairie underground gas storage field, also appear to be the most promising candidates at Centralia. The Skookumchuck and Lincoln Creek sandstones are stratigraphically adjacent to the coal targets and thus could be efficiently targeted under a “Stacked Storage” type of injection strategy.

Up to 1 km thick, the Skookumchuck generally includes a lower and upper sandstone units separated by a westward-thickening siltstone unit in between. **Figure 28** shows a typical stratigraphic interval of well-developed sandstone totaling about 45 m thick in several beds within the Skookumchuck coal section at Centralia. As discussed in Section 3, these sandstones generally are massive cross-bedded and thinly laminated sandstones which, along with interbedded siltstones, reflect shallow-water deposition. They are inter-tongued with marine, fine-grained sandstones and siltstones. The sandstone is fine- to medium-grained, micaceous and carbonaceous (coaly), basaltic and andesitic, and locally contains fine tuff. Poorly sorted generally, the more massive beds (such as the 25-m thick sand beneath the Lower Thompson and Big Dirty seams) can be better sorted.

The sandstone beds have lenticular geometry but some may be traced out for several kilometers. Mostly friable, they are cemented with calcite, iron oxide, and silica derived from volcanic glass. They consist mainly of feldspar, quartz, muscovite, biotite, and lithic fragments. Clastic grains account for 50-80% of the rock. Matrix and cement comprise the remaining 20-50%, consisting of calcite, clay minerals, chlorite, and altered volcanic glass.

Laboratory analysis shows Skookumchuck sandstones range from 5.3 to 35.2% porosity, while permeability ranges from 1.42 to 3,506 mD. The thicker, more massive beds generally have better reservoir characteristics. For a base case, we assumed average 20% porosity for the 45-m thick sandstone column shown in Figure 28. We further assumed that CO_2 saturation could reach 40%, with the remaining pore space filled with residual water and/or natural gas.

For a high case, we increased sandstone thickness 5-fold to 225 m, based on a reasonable extrapolation of sandstone occurrence in the 1,000-m thick Skookumchuck and 600-m thick Lincoln Creek Formations. We also increased porosity to 25%, assuming the massive, better-sorted sandstones with better-than-average porosity are the main target. Finally, we increased CO_2 saturation to 50%.

Table 3 shows potential storage capacity in saline aquifer sandstones at the Centralia syncline. The base case CO_2 storage calculation totals 37.5 million t, equivalent to 9.4 years of power plant emissions (50% capture). The high case would total 293 million t, equivalent to 73 years of emissions (@ 50%). Adding together the deep coal and saline aquifer potential give a total storage capacity of 90 to 346 million t, equivalent to 22 to 86 years of emissions at 50% capture. This assumes that all of the volume could be contacted, which is probably optimistic.[61]

Table 3 : Estimated Deep Coal and Saline Aquifer Storage Capacity at the Centralia Prospect

Coal Mass	Prospective Area		Depth	Press.	Coal Thickness		Ash	Moisture	Density	Coal Mass Billion daf	
	km^2	acres	m	psi	m	ft	%	%	ton/ac-ft	t	tons
Total Centralia Syncline Prospect	107	26400	500	725	18	59	12	20	1800	1.73	1.91
Adjusted Net 75% Area	80	19800	500	725	18	59	12	20	1800	1.30	1.43

CH_4 and CO_2 Potential	75% Sat.		100% Sat.		100% Sat.		75% Sat		100% Sat.		100% Sat.	
Deep Coal Storage Potential	CH_4 Gas Content (d.a.f.)				CO_2 Content (daf)		CBM Resources				CO_2 Storage Capacity	
	m^3/t	scf/ton	m^3/t	scf/ton	m^3/t	scf/ton	MM m^3	Bcf	MM m^3	Bcf	MM m^3	MM tonnes
Total Centralia Syncline Prospect	4.16	133	5.54	178	21.70	695	7.19	254	9.59	339	37.56	69.82
Adjusted Net 75% Area	4.16	133	5.54	178	21.70	695	5.39	191	7.19	254	28.17	**52.36**

Centralia CO2 Emissions 100%	8.00	million t/yr	6.5	Years storage capacity
Centralia CO2 Emissions 50%	4.00	million t/yr	**13.1**	**Years storage capacity**

Sorption Isotherms:	CH4 VL	300	scf/ton daf	CO2 VL	1175	scf/ton
	CH4 PL	500	/psi	CO2 PL	500	/psi

Saline Aquifer Storage Potential	Prospective Area		Depth	Press.	Sand Thickness		Rock Volume	Por-osity	Pore Volume	CO2 Sat.	CO2 Density	CO2 Capacity
	km^2	acres	m	psi	m	ft	km3		km3		kg/m^3	MM t
Base Case	80	19800	500	725	45	148	3.61	20%	0.72	40%	130	37.50
High Case (5 * h)	80	19800	500	725	225	738	18.03	25%	4.51	50%	130	292.97

Centralia CO2 Emissions 100%	8.00	million t/yr	4.7	Years storage capacity	Base Case
Centralia CO2 Emissions 50%	4.00	million t/yr	**9.4**	**Years storage capacity**	Base Case
Centralia CO2 Emissions 100%	8.00	million t/yr	36.6	Years storage capacity	High Case
Centralia CO2 Emissions 50%	4.00	million t/yr	**73.2**	**Years storage capacity**	High Case

Total Coal and Saline Aquifer Potential							CO2 Capacity MM t
Centralia CO2 Emissions 100%	8.00	million t/yr	11.2	Years storage capacity	Base Case		89.86
Centralia CO2 Emissions 50%	4.00	million t/yr	**22.5**	**Years storage capacity**	Base Case		89.86
Centralia CO2 Emissions 100%	8.00	million t/yr	43.2	Years storage capacity	High Case		345.34
Centralia CO2 Emissions 50%	4.00	million t/yr	**86.3**	**Years storage capacity**	High Case		345.34

CO_2 Storage Test Corehole Program

The next step for a potential CO_2 capture and storage project at Centralia would be to design and implement a reservoir testing program consisting of approximately 3 to 5 coreholes in the targeted Centralia syncline. Other high-potential deep coal and sandstone targets in the area that subsequently may be identified could also be tested. This section outlines the basic strategy for such a well test program. Should the project move forward, there would need to be a more detailed site selection, drilling design and cost estimation, and reservoir testing program performed for each of the selected locations.

The main objectives of the drilling program would be to confirm the presence of thick coals and reservoir-quality sandstone saline aquifers in the Centralia Syncline. The coal reservoir characterization would need to measure the following parameters : coal thickness, depth, quality, maceral composition, rank, gas content & composition, sorption isotherm (both methane and CO2), and absolute permeability. The main techniques would be on-site desorption for gas content and composition; injection/falloff well testing for in-situ permeability and stress; and laboratory measurement of sorption isotherm, coal proximate analysis, vitrinite reflectance, and coal petrography for maceral composition.

The saline aquifer characterization would need to measure the following parameters: sandstone stratigraphy, geometry, porosity, permeability, mineralogy, texture, natural fracturing, fluid composition, pressure, and temperature. The main techniques would coring; logging (porosity, permeability; mineralogy); and laboratory analysis (gas composition, permeability, porosity).

Once the data from the coreholes has been collected, it would be necessary to perform a comprehensive reassessment of the storage potential and reservoir properties at Centralia. This would involve more detailed GIS geologic mapping, including construction of cross-sections, detailed structure and depth mapping, and 3D analysis of individual coal seams and sandstones. Following the mapping, a more detailed reservoir simulation analysis would be needed to evaluate the deep coal and saline aquifer reservoirs (preferably within one model).

The costs for such a test program would depend on a number of variables, such as permitting requirements, total depth, hole diameter, casing program (fewer the better at this stage), core lengths, logging program, number of laboratory analyses, as well as the number of coreholes (there are certain economies of scale). We assume that seismic reflection data would not be needed for the corehole program, but would be essential for a CO_2 injection pilot.

Based on the somewhat elevated drilling and operations costs in the Pacific Northwest, we estimated the costs of the corehole delineation program (**Table 4**): The corehole test program as defined would provide the necessary data to permit a more complete evaluation of the CO_2 storage capacity and reservoir properties at Centralia, sufficient to reach a decision on whether to proceed with an injection pilot demonstration.

Geologic and Manmade Hazards

Injecting and storing CO_2 in deep coal seams at Centralia, like any underground storage project, would involve risks of unplanned leakage out of the injection zone or to the surface. During the past decade, methodologies and technologies have been developed to quantify and mitigate such risks.[62] Prior to conducting a CO_2 storage project at Centralia, there should be a more formal evaluation of the geologic and manmade risks, including their consequences and probability. Briefly, there appear to be two major risks: seismicity in the tectonically active Pacific Northwest region, and leakage to surface caused by poorly completed or abandoned wellbores in the injection area at Centralia.

Table 4 : Estimated Costs for Reservoir Testing Corehole Program at Centralia

Activity	Corehole	No.	Total
Permitting	5000	3	15000
Drilling	150000	3	450000
Coring	30000	3	90000
Supervision	20000	3	60000
Well Testing	30000	3	90000
Lab Work	25000	3	75000
Geology	20000	3	60000
Simulation	20000	3	60000
Management	20000	3	60000
Total			**$960,000**

Seismicity. The Centralia area is located within the seismically active Pacific Northwest region, where earthquakes occur related to active subduction of the Kula plate beneath North America. However, the subduction rate here is relatively slow and large earthquakes in onshore western Washington are thought to be infrequent. The modern seismic record shows that the largest earthquakes recorded in this region been in the range of 4.0 to 5.0 magnitude.

No earthquakes larger than 4.0 magnitude have occurred during the past 100 years in the central Washington area near Centralia (**Figure 25**). There have been a few recent events within the Centralia coal mine area, but these have been smaller than 3.0 magnitude (**Figure 26**). It is possible that some of the identified faults at Centralia are seismically active, such as the Doty fault which may represent a transform-type fault related to active subduction.[63]

Earthquakes are unlikely to cause release of CO_2 stored in deep coal seams. This is because the storage mechanism is adsorption of CO_2 onto the coal under pressure, with is transmitted by hydrostatic forces. Fault slip of several meters would not change the reservoir pressure conditions at depth and thus cannot cause CO_2 to escape. Only a sudden drop in hydrostatic pressure could cause that but it is unlikely that seismicity could be such a cause.

Wellbore Leakage. A more likely potential source for leakage would be poorly completed or poorly abandoned wellbores in the Centralia syncline area. Fortunately, there are few petroleum wells in the area. Most of the water wells were shallow and did not penetrate the Big Dirty, Smith, and Mendota coal seams; these wells would not be at risk of contacting the CO_2 injection zone. **Figure 37** shows that only a handful of water wells in the Centralia syncline penetrated the Big Dirty seam; none of these are known to have penetrated the deeper Smith and Mendota seams. However, any wellbore that penetrates the target seams would need to be protected with cemented casing or properly abandoned (cement to surface).

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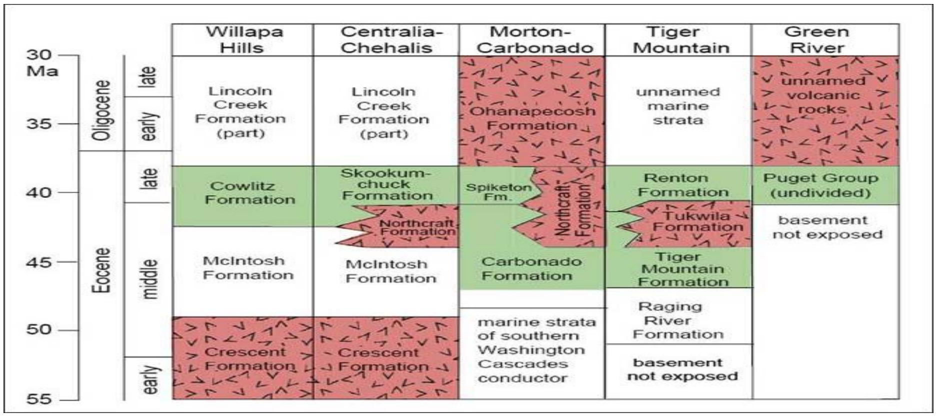
CENTRALIA (WASHINGTON STATE) GEOLOGIC FORMATION
CO_2 STORAGE ASSESSMENT FIGURES

Scott Stevens
Advanced Resources International, Inc.

DOE Contract No.: DE-FC26-05NT42593
Contract Period: October 1, 2005 - May 11, 2011

Figure 1 : Generalized stratigraphic chart for coal fields in the state of Washington.



Source : From Brownfield, et al, 1994
(Tertiary Coals of Western Washington)

Figure 2 : Coal areas in Oregon and Washington with CO_2 storage potential include the Bellingham, Puget Sound (including Centralia), and Coos Bay region.

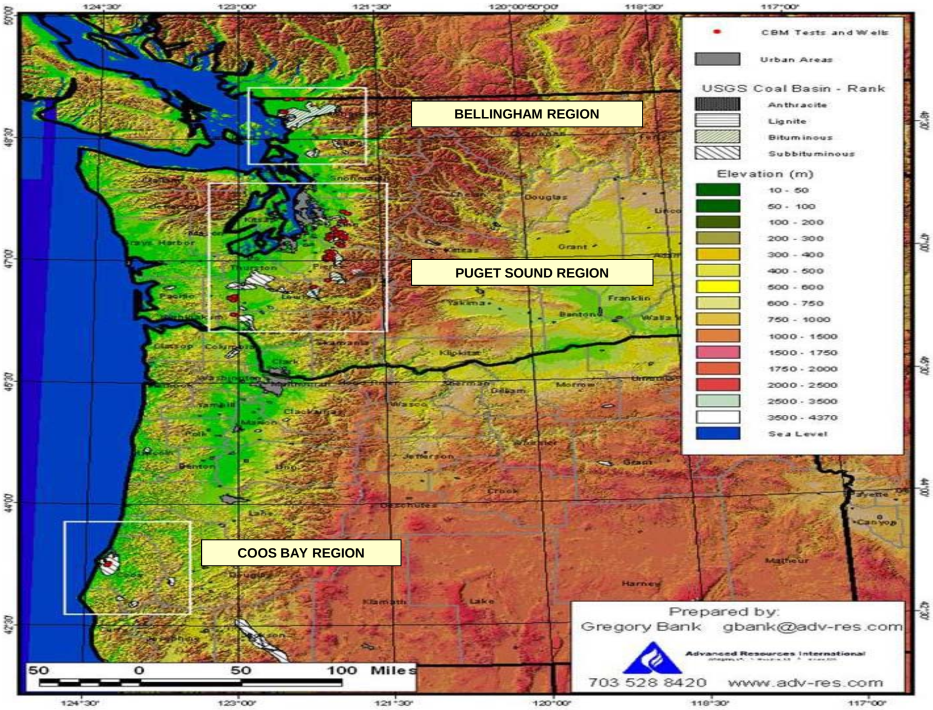


Figure 3 : TransAlta's 1,404-MW thermal power plant at Centralia is equipped with advanced SO_2 and NO_x scrubbers, making it one of the cleanest coal-fired plants in the US.

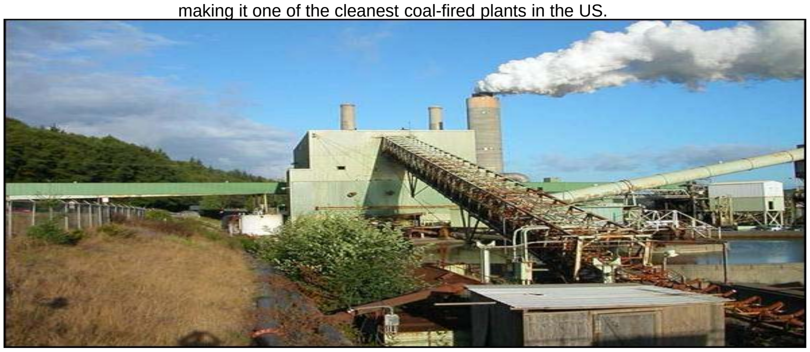


Figure 4 : Wireline coring rig (800-ft max) targeting the Big Dirty Seam at the Centralia mine.

Figure 5 : Mining operations in the Smith seam, central Packwood pit, Centralia coal mine.

Figure 6 : Reclaimed hillside after mining and prior to reforestation, Centralia coal mine.

Figure 7 : Regional map of southwestern Washington State showing the Centralia coal mine, Jackson Prairie gas storage field, Mist gas field, CBM wells, and deep Shell well

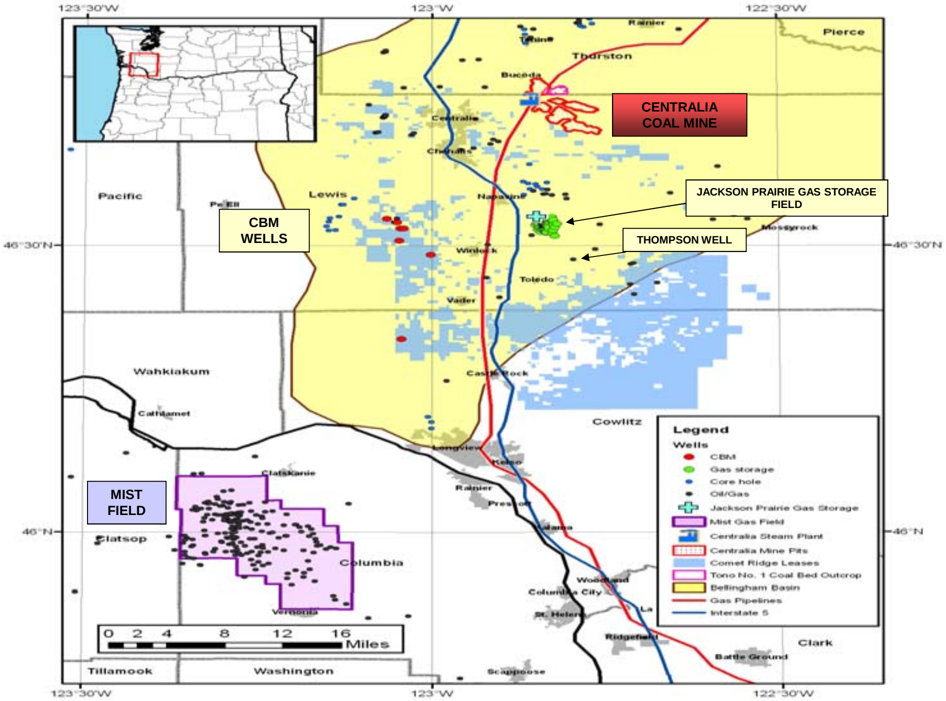


Figure 8 : Geomorphic map of Centralia-Chehalis basin showing Centralia coal mine, cities, power plant, major structural features, and significant petroleum wells.

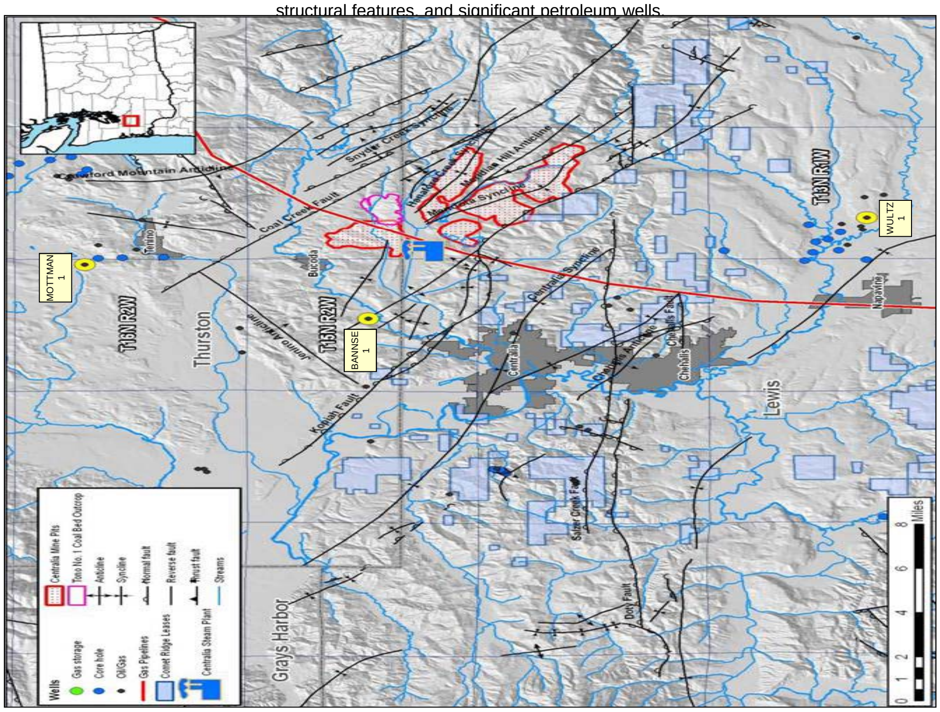


Figure 9 : Coalbed methane exploration wells in west-central Washington State.

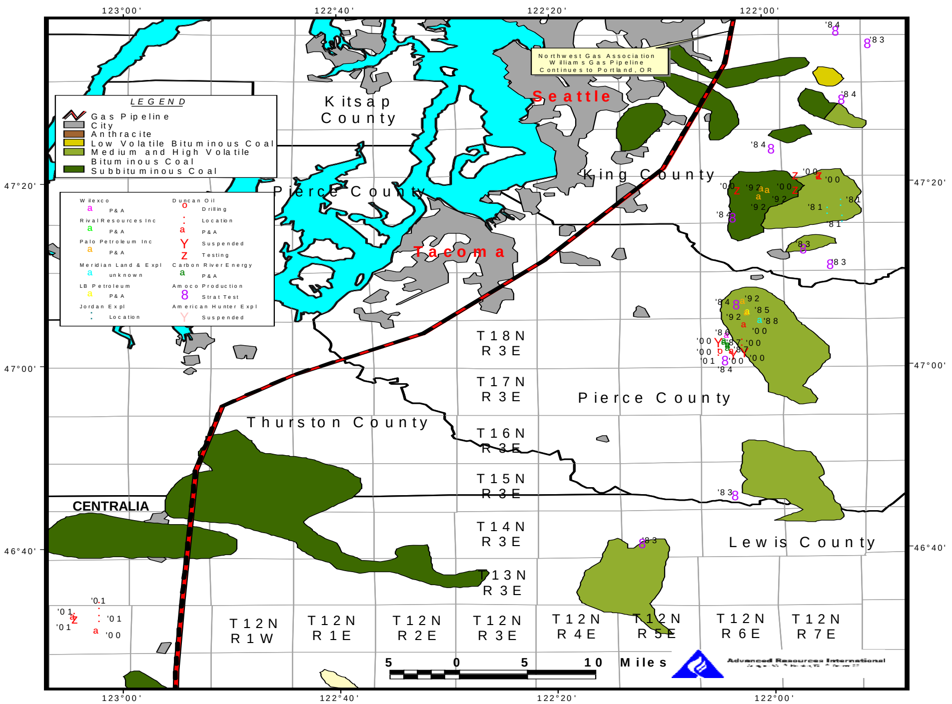


Figure 10a : Well log from Duncan Oil #3 coalbed methane exploration well (28-18N-6E, Pierce County, Washington). A total of 19 seam were penetrated for nominal 37 m (120 ft) of coal. Coal seam dips ranged from 15-80º (avg 34º), making true coal thickness 30 m (99 ft).

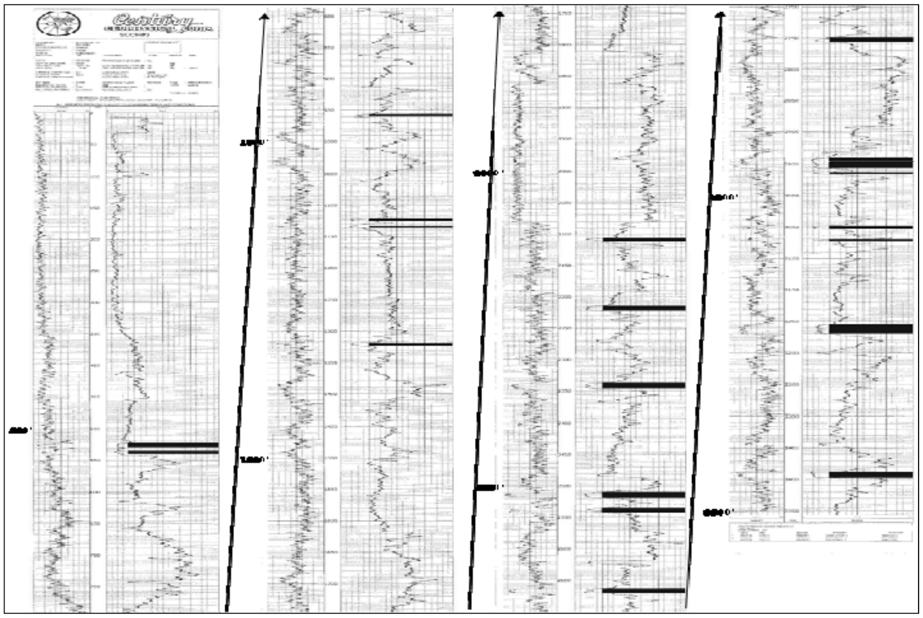


Figure 10b : Well log from Duncan Oil #3 coalbed methane exploration well (28-18N-6E, Pierce County, Washington). A total of 19 seam were penetrated for nominal 37 m (120 ft) of coal. Coal seam dips ranged from 15-80º (avg 34º), making true coal thickness 30 m (99 ft).

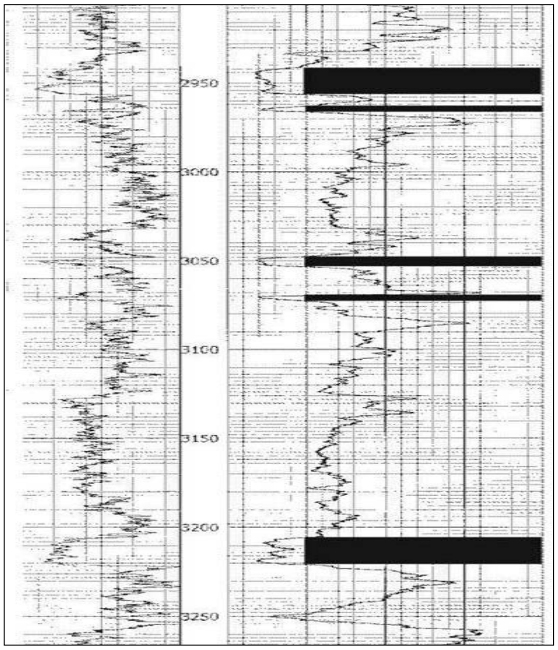


Figure 11 : Coalbed methane well operations, El Paso Inc. Carbonado pilot area.

Source : McHenry et al., 2003

Figure 12 : Coalbed methane completed wellhead, El Paso Inc. Carbonado pilot area.

Source : McHenry et al., 2003

Figure 13 : Coalbed methane wells in Coos Bay basin, Oregon

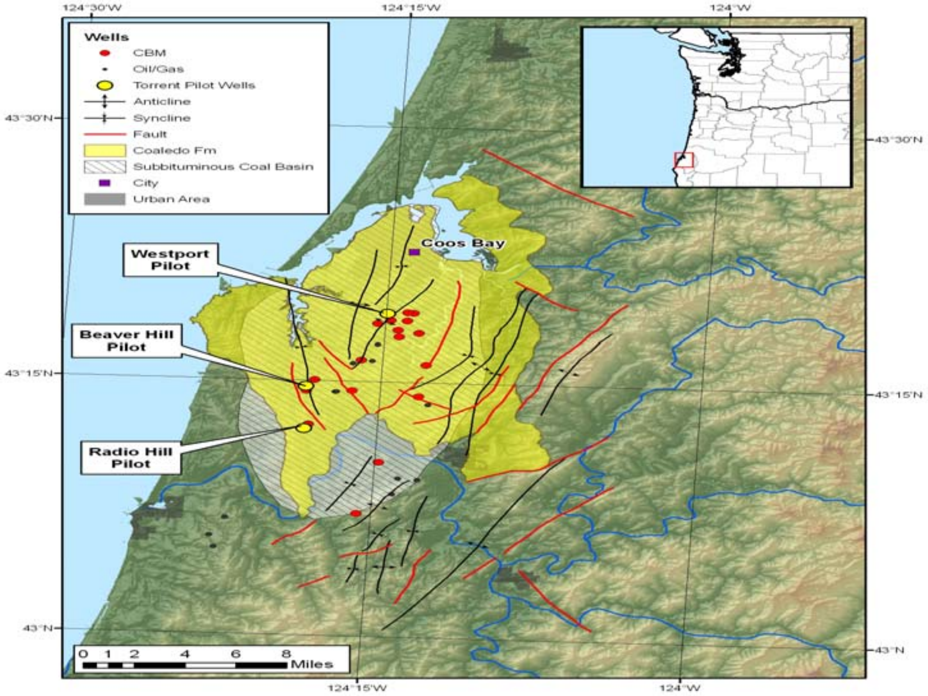
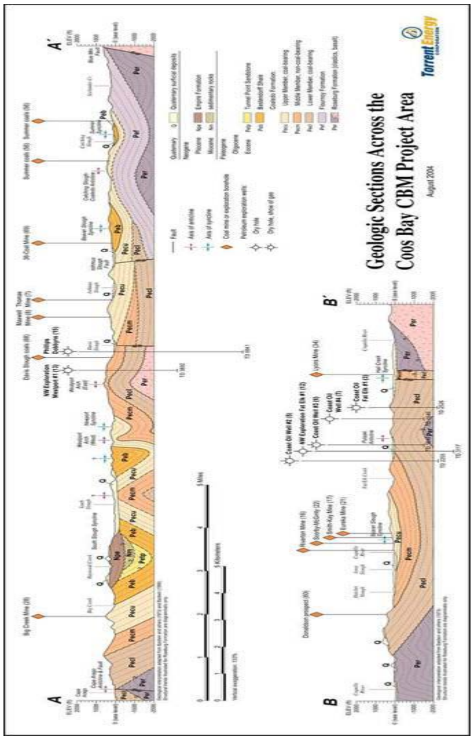
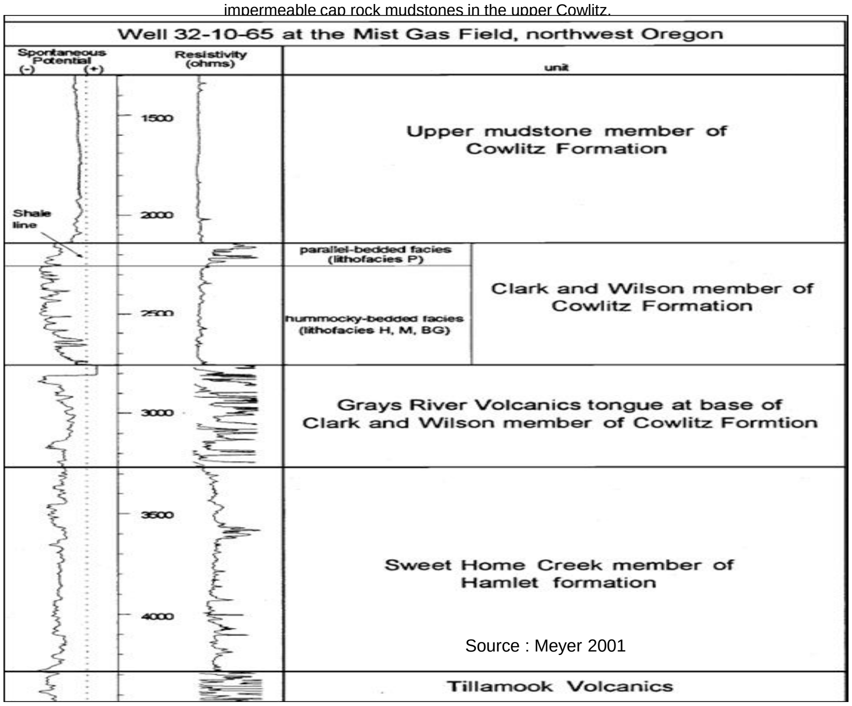


Figure 14 : Geologic cross-section across Torrent Energy's Coos Bay CBM project, Oregon.



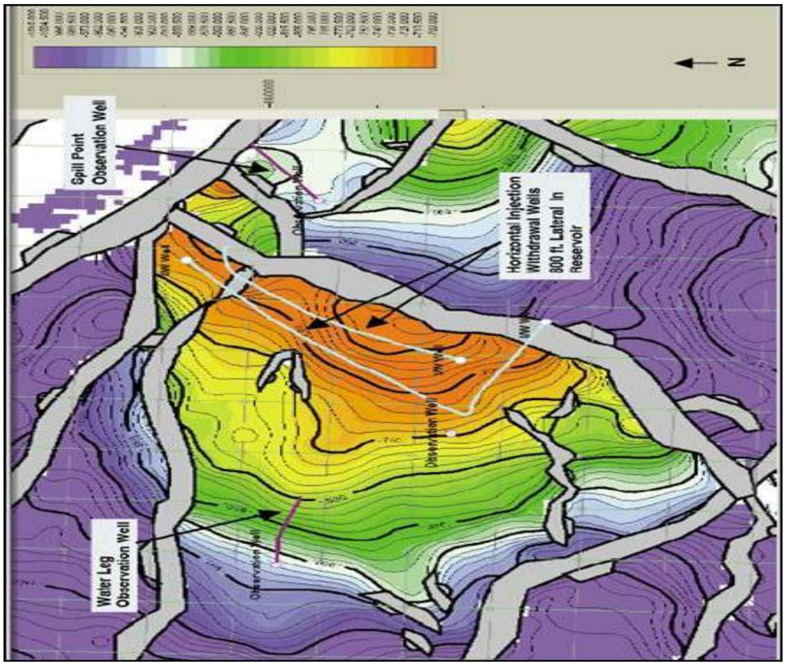
Source : Torrent Energy

Figure 15 : Well log from Mist gas field, Oregon, showing porous Clark/Wilson reservoir sandstones, Eocene Cowlitz Fm, overlain by impermeable cap rock mudstones in the upper Cowlitz.



Source : Meyer 2001

Figure 16 : Structural contour map on the structurally complex reservoir sandstone in the Eocene Cowlitz Formation at Mist gas storage field, Oregon. Storage targets in sandstones and coal seams at Centralia are expected to have comparable structural complexity.



Source : Meyer 2001

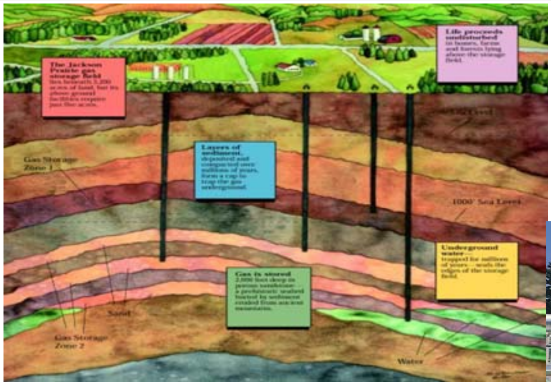


Figure 17 : Jackson Prairie underground gas storage field :

a) diagrammatic cross section

b) Aerial view of the field

c) Natural gas facilities

Source : Puget Sound Energy, 2008

Figure 18 : Detailed structure map of Tono basin, Centralia coal mine, showing surface geology, many small faults, and underground coal gasification coreholes (yellow).

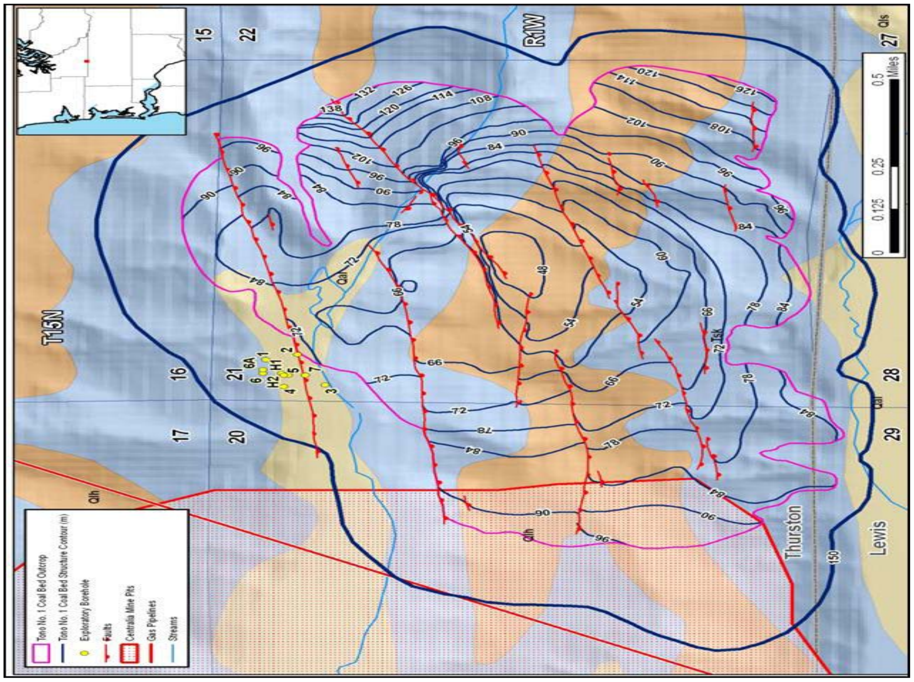


Figure 19 : Surface geology, structure, wells in the Centralia-Chehalis coal basin

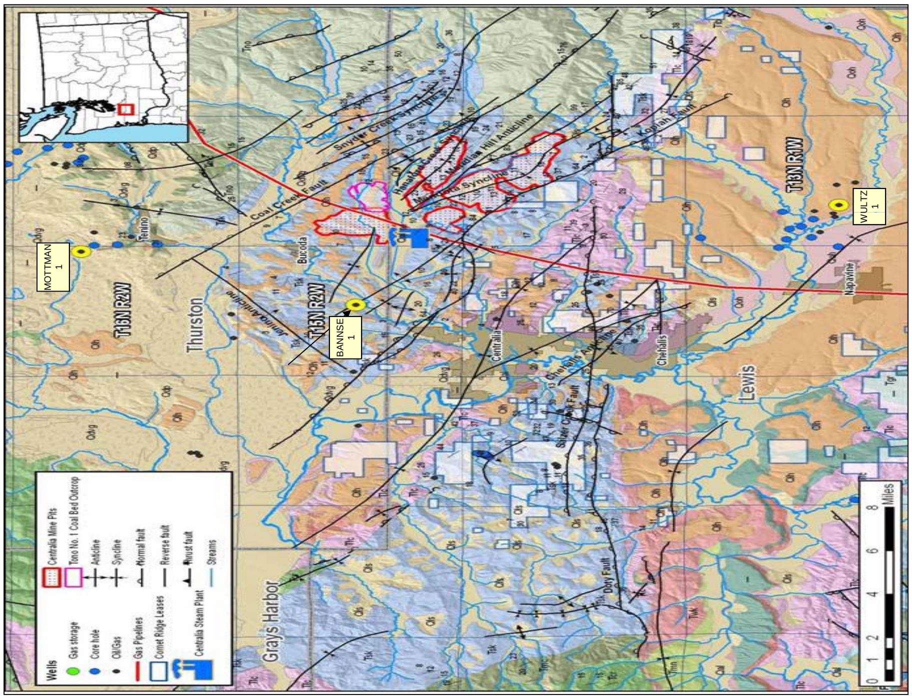
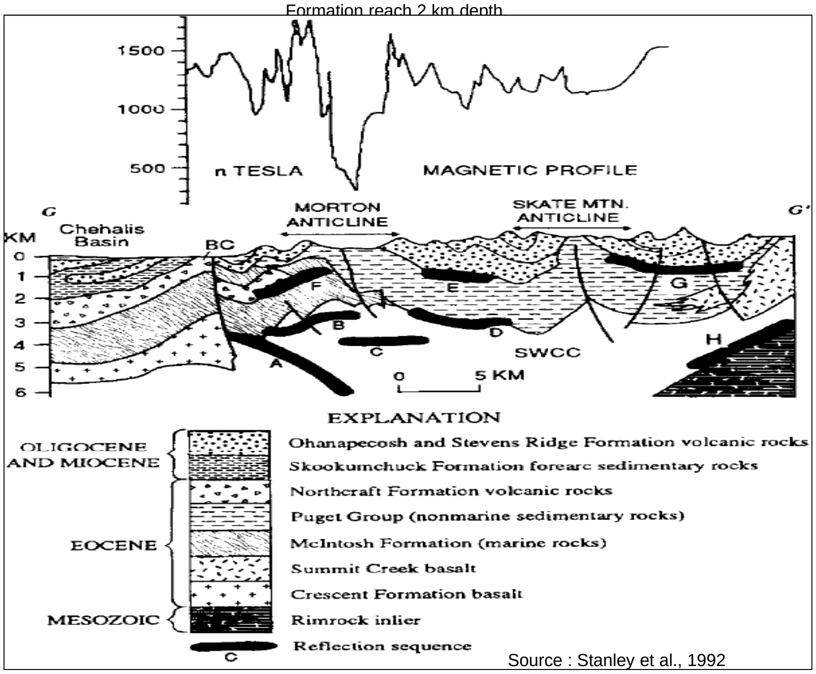


Figure 20 : Regional cross section interpretation based on electromagnetics, showing a total 3-5 km of sedimentary rocks resting on basaltic basement in the Chehalis basin. Coal seams and saline aquifers in the Skookumchuck Formation reach 2 km depth.



Source : Stanley et al., 1992

Figure 21 : Comparison of Centralia (red) with a typical developed CBM basin (San Juan basin; blue), illustrating Centralia's smaller relative size and greater structural complexity.

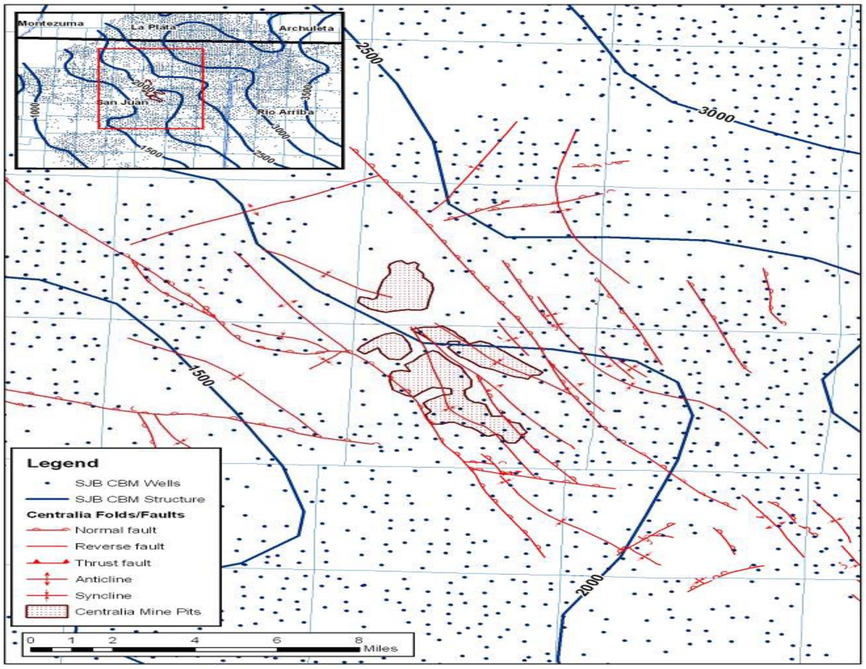


Figure 22 : Surface geology and structural features of the Centralia coal mine area.

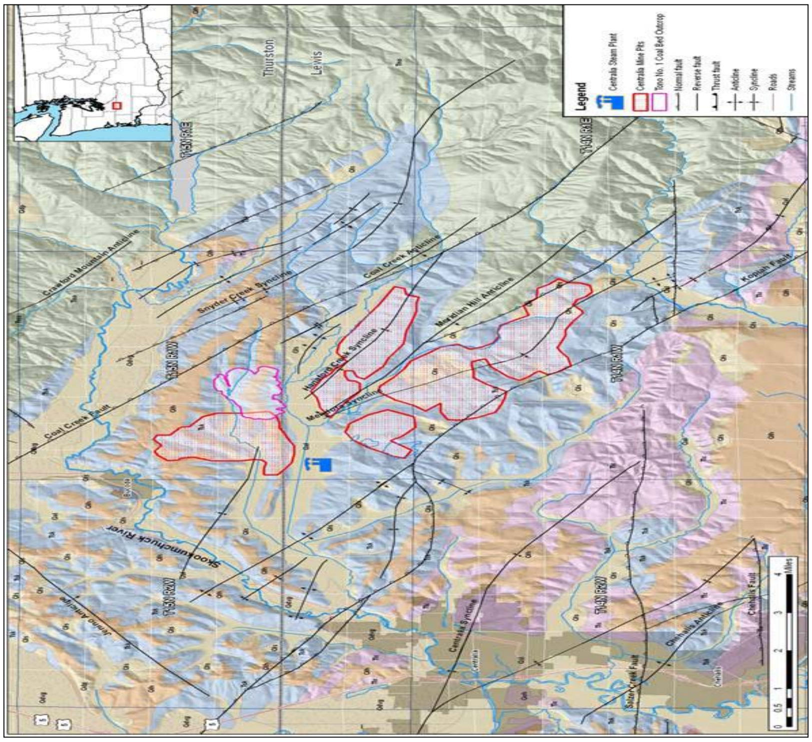
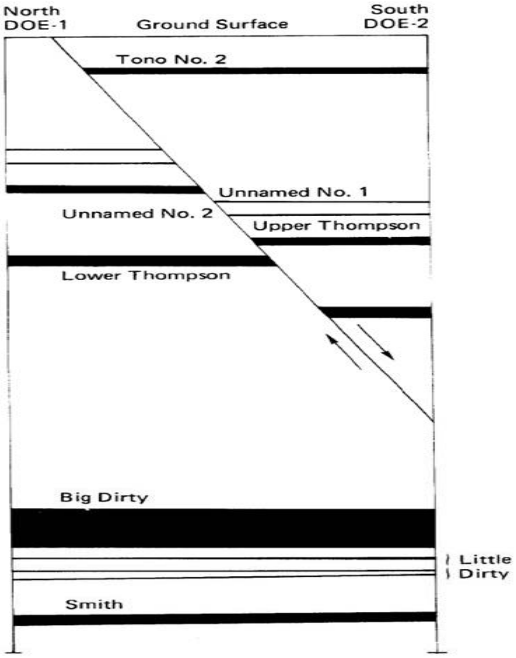
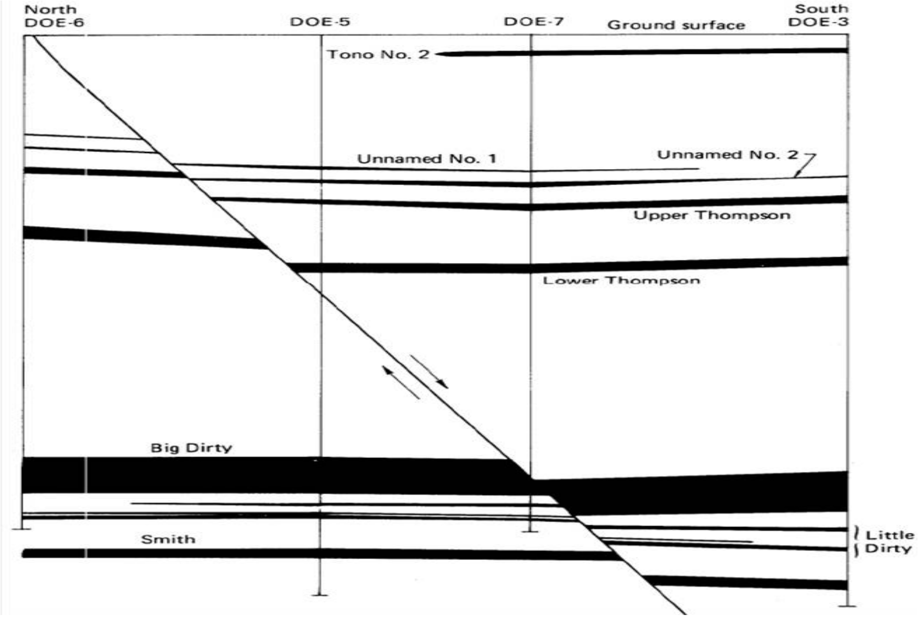


Figure 23 : Normal fault between boreholes DOE-1 and -2 at the Tono pit, Centralia coal mine. The fault was not identified by surface seismic or other geophysical methods.



Source : Bartel and Love, 1981

Figure 24 : Normal fault through boreholes DOE-6, -5, -7, and -3 at the Tono pit, Centralia coal mine. The fault was not identified by surface seismic or other geophysical methods.



Source : Bartel and Love, 1981

Figure 25 : Earthquake distribution map of Washington. Centralia is a fairly inactive area.

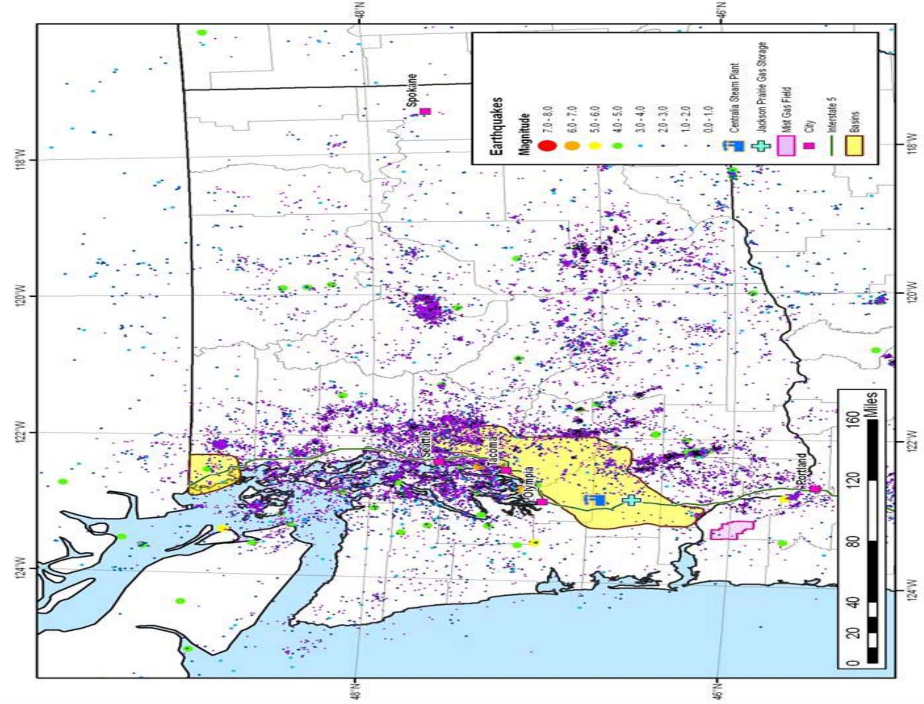


Figure 26 : Earthquake distribution map of central Washington. A few small (mag 2-3) events have occurred near the Centralia coal mine, with more activity 30 km SE near the Cascades.

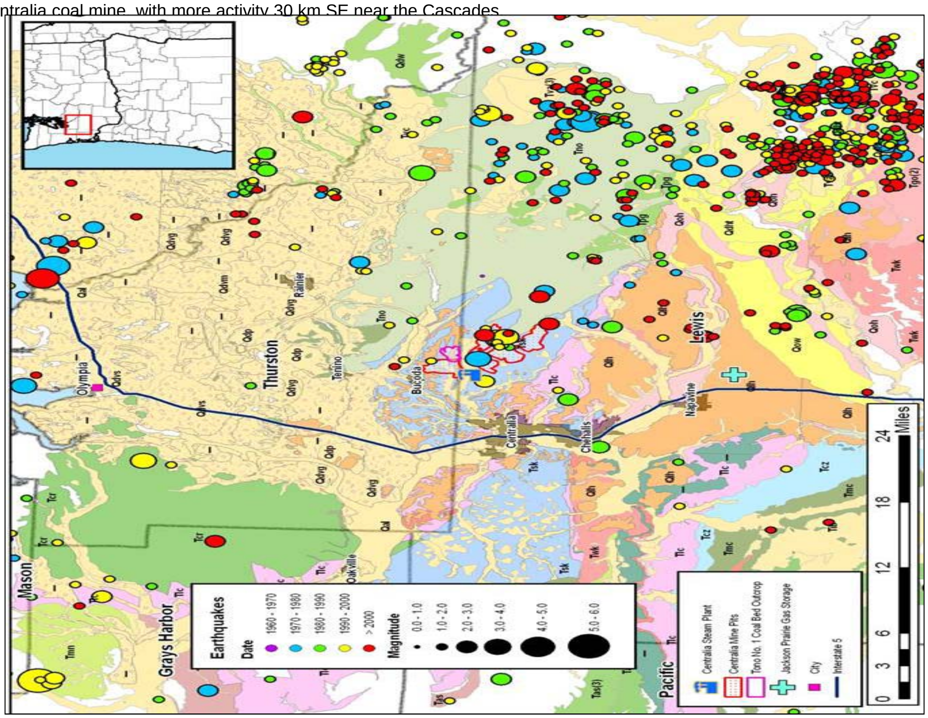


Figure 27 : Generalized tratigraphic chart for coal fields in the state of Washington, showing the primary target for CO_2 storage – the Big Dirty seam.

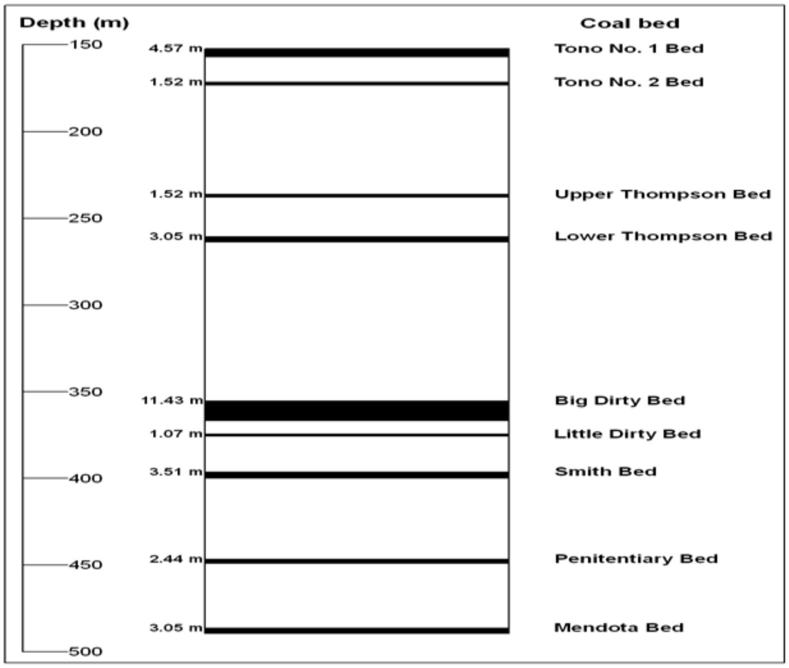
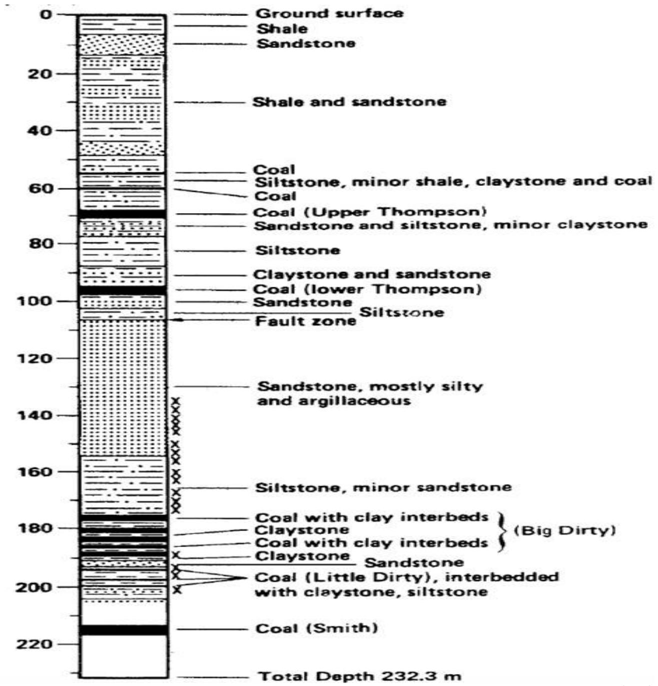
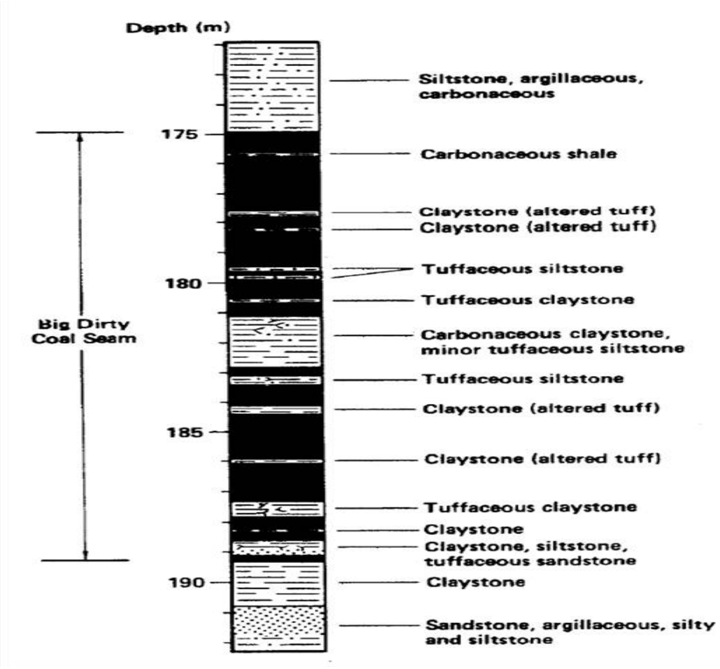


Figure 28 : Stratigraphic section for borehole DOE-5 at the Tono pit, Centralia coal mine.



Source : Bartel and Love, 1981

Figure 29 : Detailed stratigraphy of the Big Dirty seam, borehole DOE-5, Tono pit, Centralia coal mine.



Source : Bartel and Love, 1981

Figure 30 : 3-m thick Lower Thompson Seam at the Centralia mine.

Figure 31 : 15-m thick Big Dirty Seam at the Centralia mine, with white bentonite tuff parting.

Figure 32 : Aerial photo of Centralia coal mine showing the extent of surface mining and individual seam outcrops. The mine is currently being refilled and reforested.

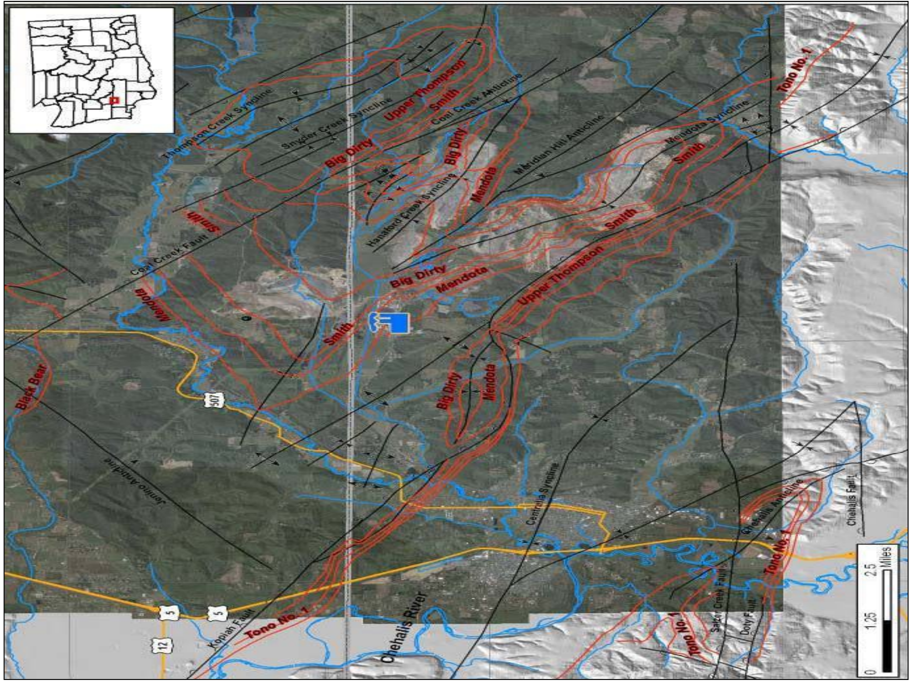
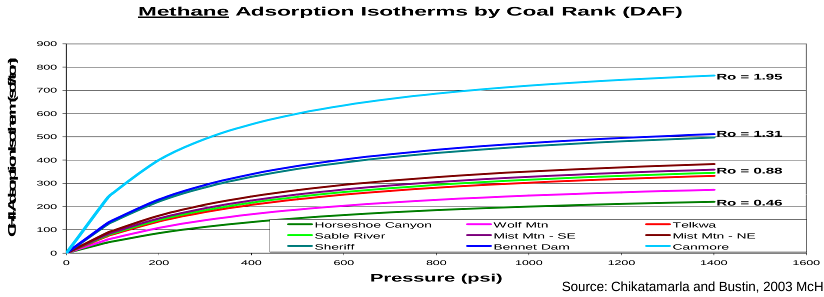
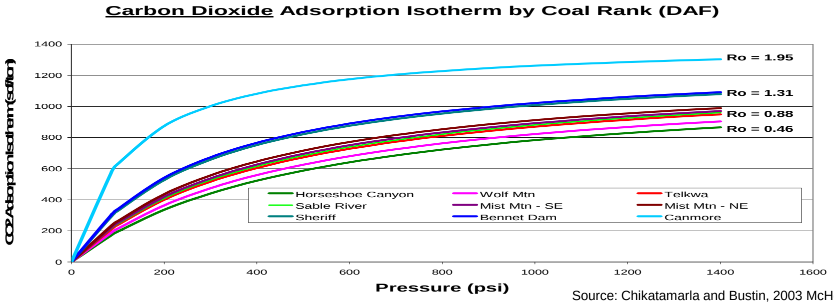


Figure 33 : Methane adsorption isotherms for coals in Washington state and British Columbia. The low-rank (R_o=0.46%) Horseshoe Canyon coal is the closest analog to the Big Dirty seam at Centralia.



Source: Chikatamarla and Bustin, 2003 McHenry et al., 2003.

Figure 34 : Methane adsorption isotherms for coals in Washington state and British Columbia. The low-rank (R_o=0.46%) Horseshoe Canyon coal is the closest analog to the Big Dirty seam at Centralia.



Source: Chikatamarla and Bustin, 2003 McHenry et al., 2003.

Figure 35 : Methane adsorption increases with rank for coals in Washington state and British Columbia. Both Langmuir Volume (V_L) and Langmuir Pressure (P_L) vary linearly with vitrinite reflectance (R_o).

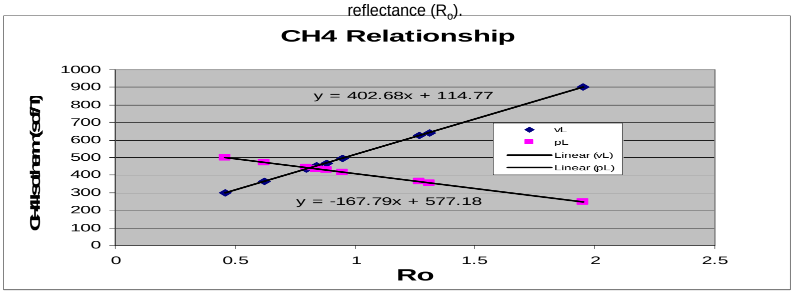


Figure 36 : CO_2 adsorption increases with rank for coals in Washington state and British Columbia. Both Langmuir Volume (V_L) and Langmuir Pressure (P_L) vary linearly with vitrinite reflectance (R_o).

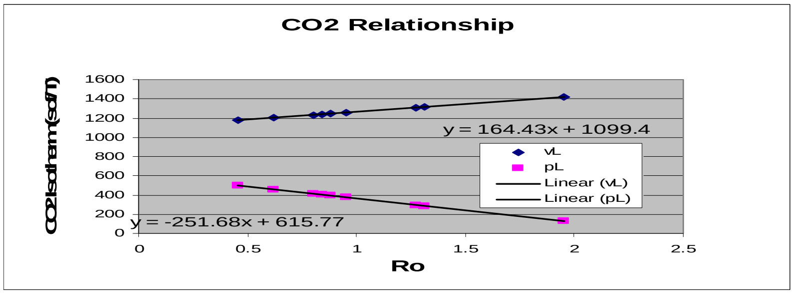


Figure 37 : Thickness and depth of Big Dirty seam near Centralia coal mine based on water well logs. The Big Dirty seam is deeper than 150 m (500 ft) and about 10 m (33 ft) thick in the Centralia syncline west of the coal mine.

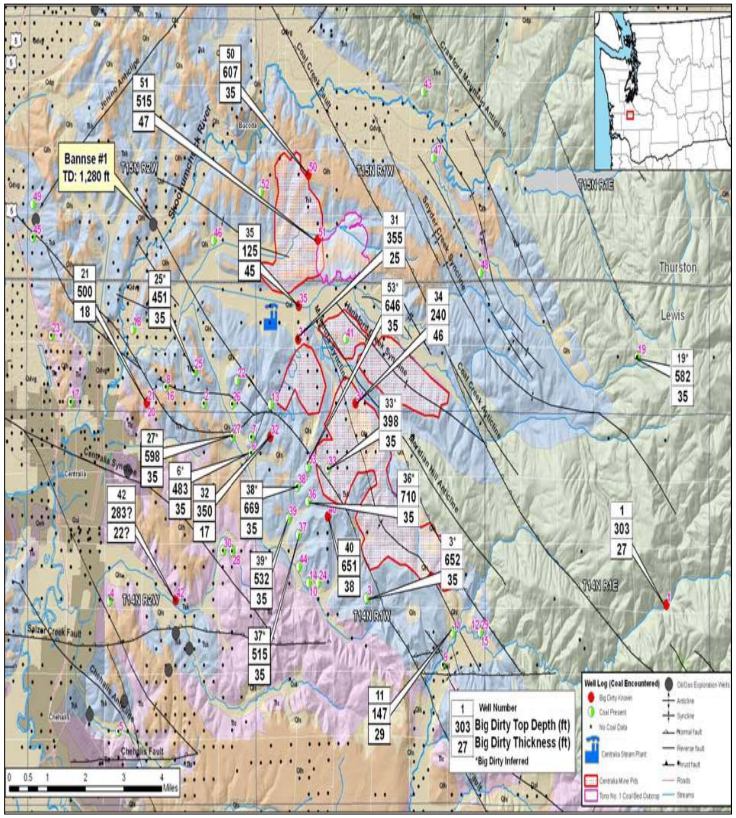
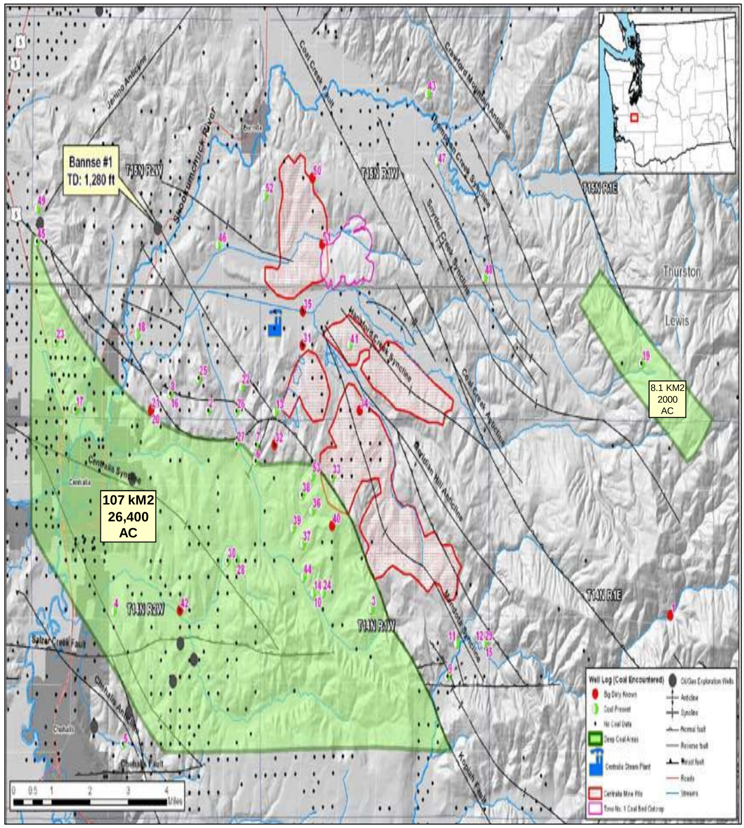


Figure 38 : Centralia coal field and adjacent areas (green) where the Big Dirty seam may be deeper than 150 m (500 feet), based on water well logs, and prospective for CO_2 storage.



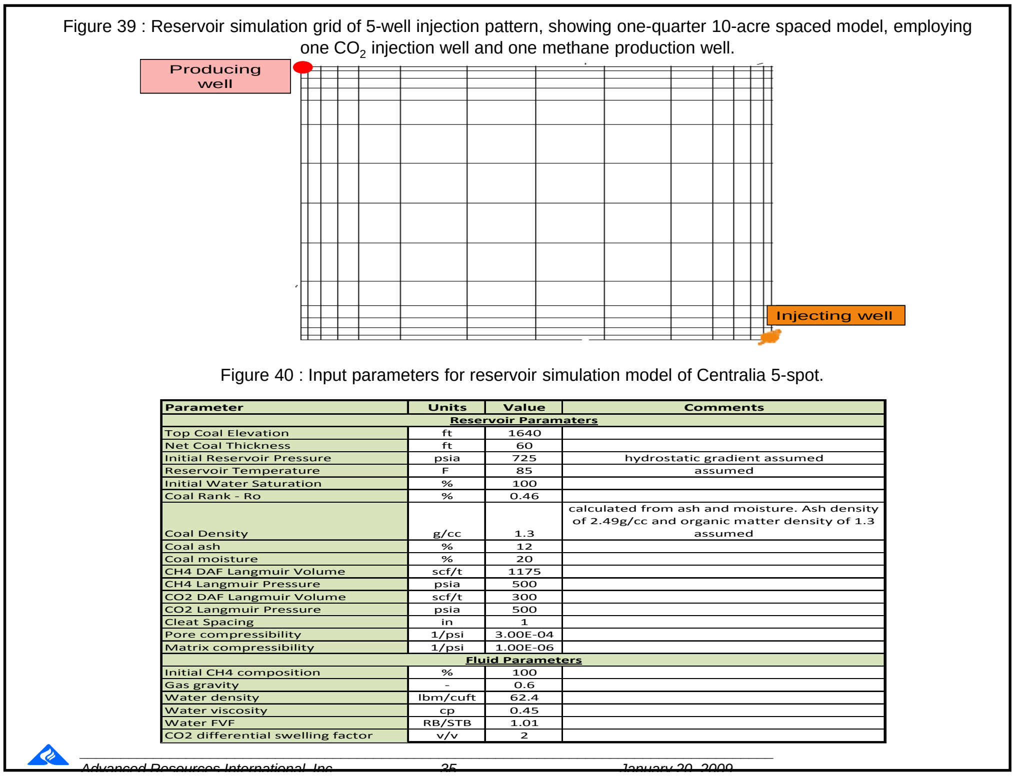


Figure 39 : Reservoir simulation grid of 5-well injection pattern, showing one-quarter 10-acre spaced model, employing one CO_2 injection well and one methane production well.

Figure 40 : Input parameters for reservoir simulation model of Centralia 5-spot.

Parameter	Units	Value	Comments
Reservoir Paramaters			
Top Coal Elevation	ft	1640	
Net Coal Thickness	ft	60	
Initial Reservoir Pressure	psia	725	hydrostatic gradient assumed
Reservoir Temperature	F	85	assumed
Initial Water Saturation	%	100	
Coal Rank - Ro	%	0.46	
Coal Density	g/cc	1.3	calculated from ash and moisture. Ash density of 2.49g/cc and organic matter density of 1.3 assumed
Coal ash	%	12	
Coal moisture	%	20	
CH4 DAF Langmuir Volume	scf/t	1175	
CH4 Langmuir Pressure	psia	500	
CO2 DAF Langmuir Volume	scf/t	300	
CO2 Langmuir Pressure	psia	500	
Cleat Spacing	in	1	
Pore compressibility	1/psi	3.00E-04	
Matrix compressibility	1/psi	1.00E-06	
Fluid Parameters			
Initial CH4 composition	%	100	
Gas gravity	-	0.6	
Water density	lbm/cuft	62.4	
Water viscosity	cp	0.45	
Water FVF	RB/STB	1.01	
CO2 differential swelling factor	v/v	2	

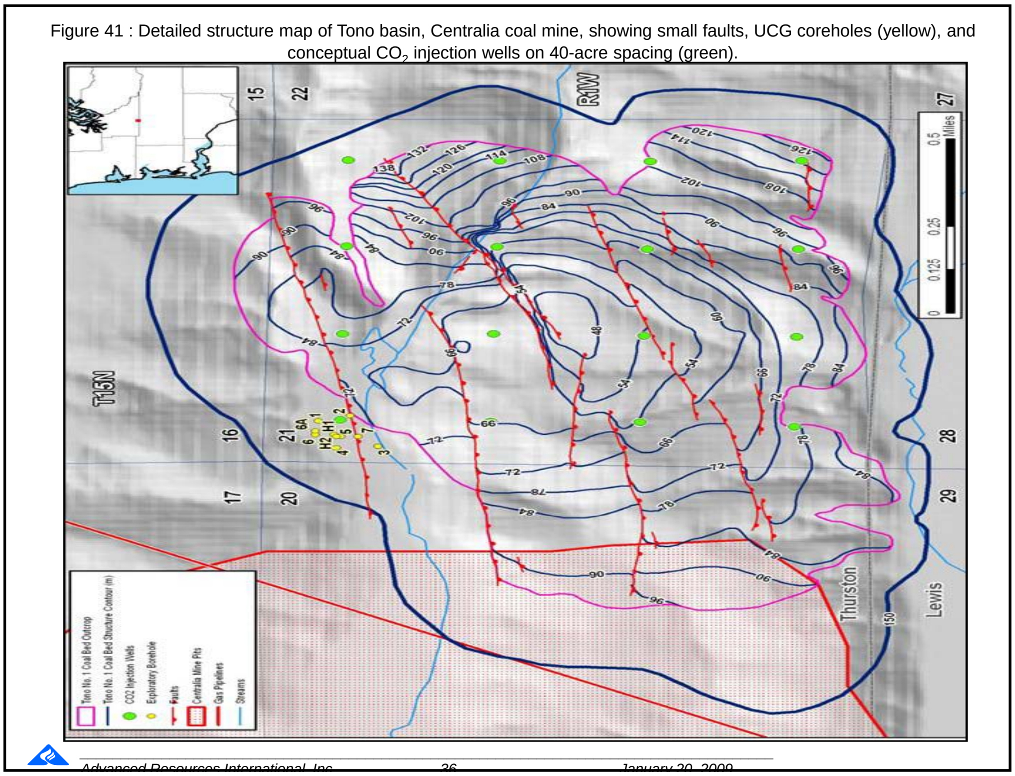


Figure 41 : Detailed structure map of Tono basin, Centralia coal mine, showing small faults, UCG coreholes (yellow), and conceptual CO_2 injection wells on 40-acre spacing (green).

Figure 42 : Methane production for 0.1 mD / 75% gas saturation case. Low permeability results in low and declining gas and water production under this scenario.

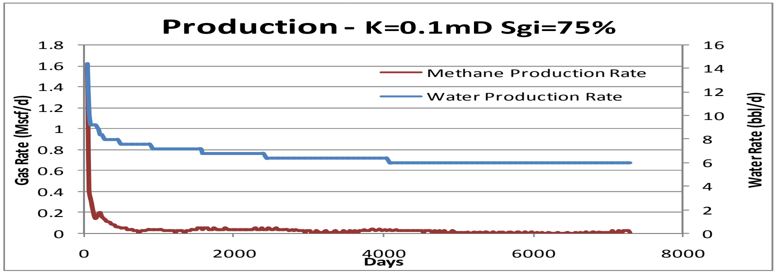


Figure 43 : CO_2 storage for 0.1 mD / 75% gas saturation case. Low permeability results in minimal CO_2 movement and storage under this scenario.

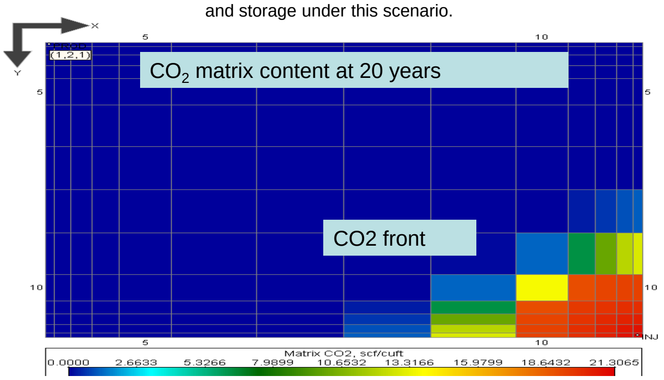


Figure 44 : Methane production for 0.1 mD / 100% gas saturation case. Low permeability results in low and declining gas and water production under this scenario.

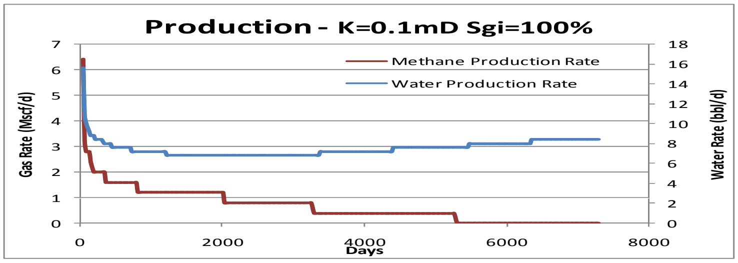


Figure 45 : CO_2 storage for 0.1 mD / 100% gas saturation case. Low permeability results in minimal CO_2 movement and storage under this scenario.

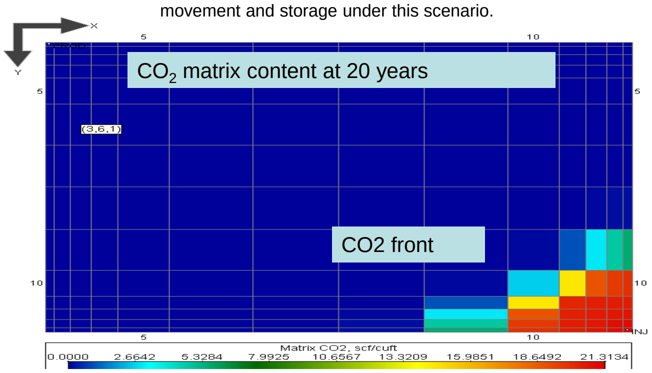


Figure 46 : Methane production for 1.0 mD / 75% gas saturation case. Undersaturation delays gas production but medium permeability eventually allows gas to exceed 50 Mcfd (1500 m^3/day) at year 10.

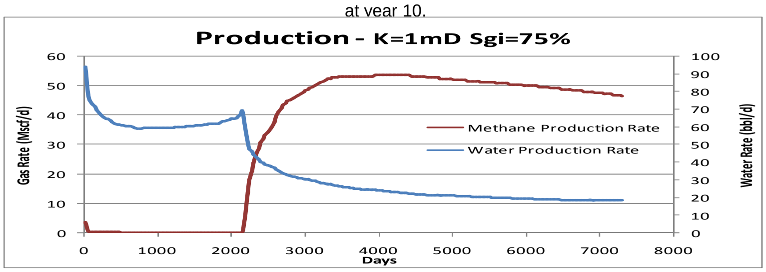
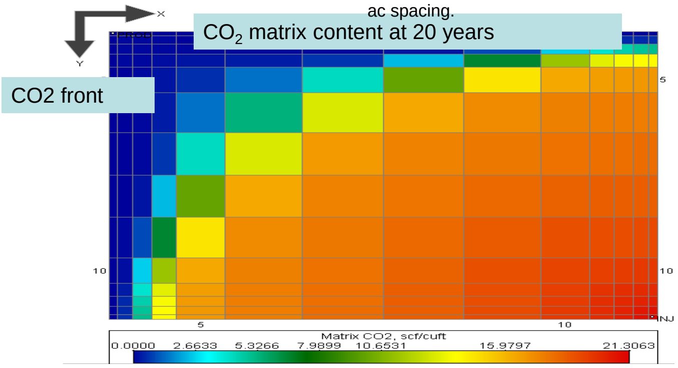


Figure 47 : CO$_2$ storage for 1.0 mD / 75% gas saturation case. Undersaturation and medium permeability aids CO2 storage, resulting in efficient CO$_2$ movement and storage under this scenario appropriate for 40-ac spacing.



CO$_2$ matrix content at 20 years

CO2 front

Figure 48 : Methane production for 1.0 mD / 100% gas saturation case. Medium permeability results in fairly slow dewatering and peak gas production of 65 Mcfd (1800 m^3/day) at year 6.

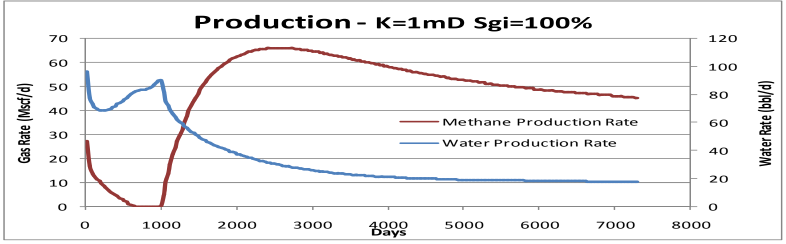
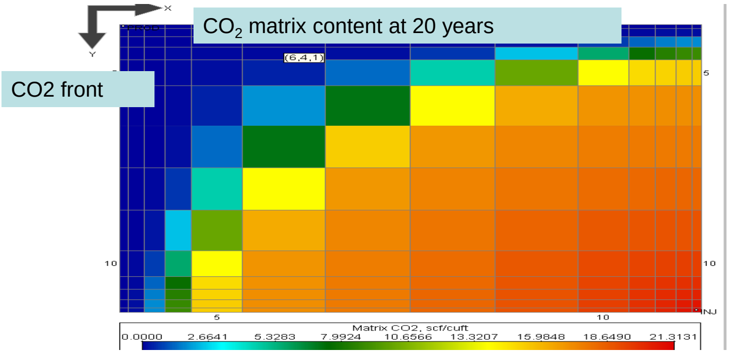


Figure 49 : CO$_2$ storage for 1.0 mD / 100% gas saturation case. Medium permeability results in efficient CO$_2$ movement and storage under this scenario appropriate for 40-ac spacing.



CO$_2$ matrix content at 20 years

CO2 front

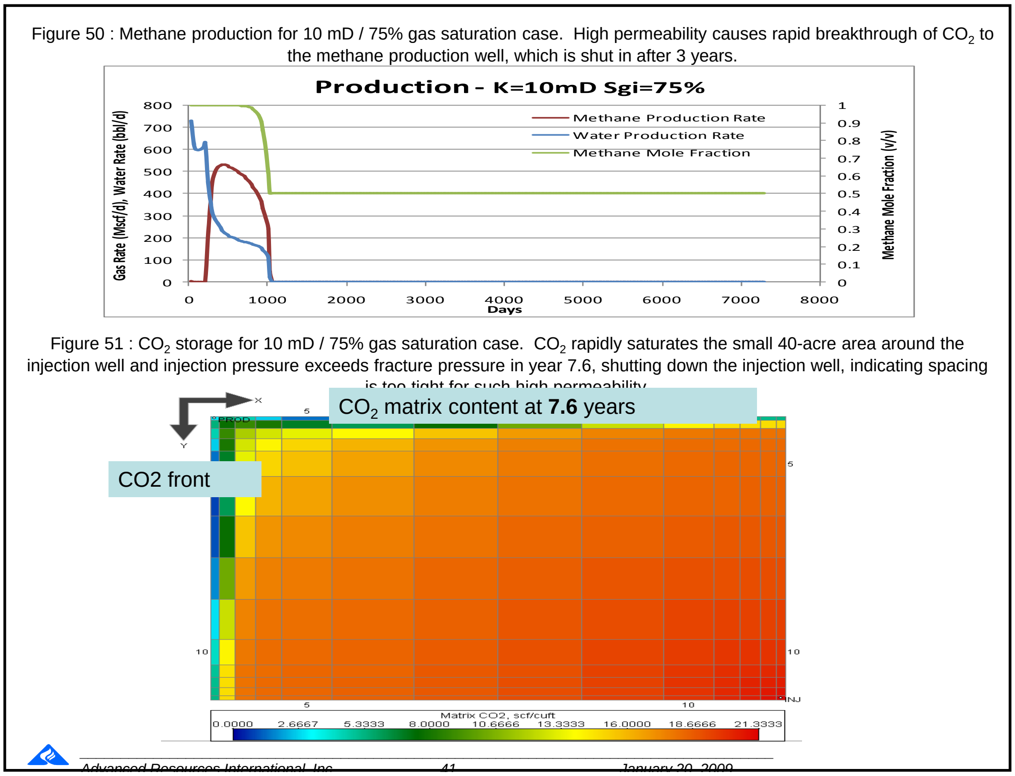


Figure 50 : Methane production for 10 mD / 75% gas saturation case. High permeability causes rapid breakthrough of CO_2 to the methane production well, which is shut in after 3 years.

Figure 51 : CO_2 storage for 10 mD / 75% gas saturation case. CO_2 rapidly saturates the small 40-acre area around the injection well and injection pressure exceeds fracture pressure in year 7.6, shutting down the injection well, indicating spacing is too tight for such high permeability.

CO_2 matrix content at **7.6** years

CO2 front

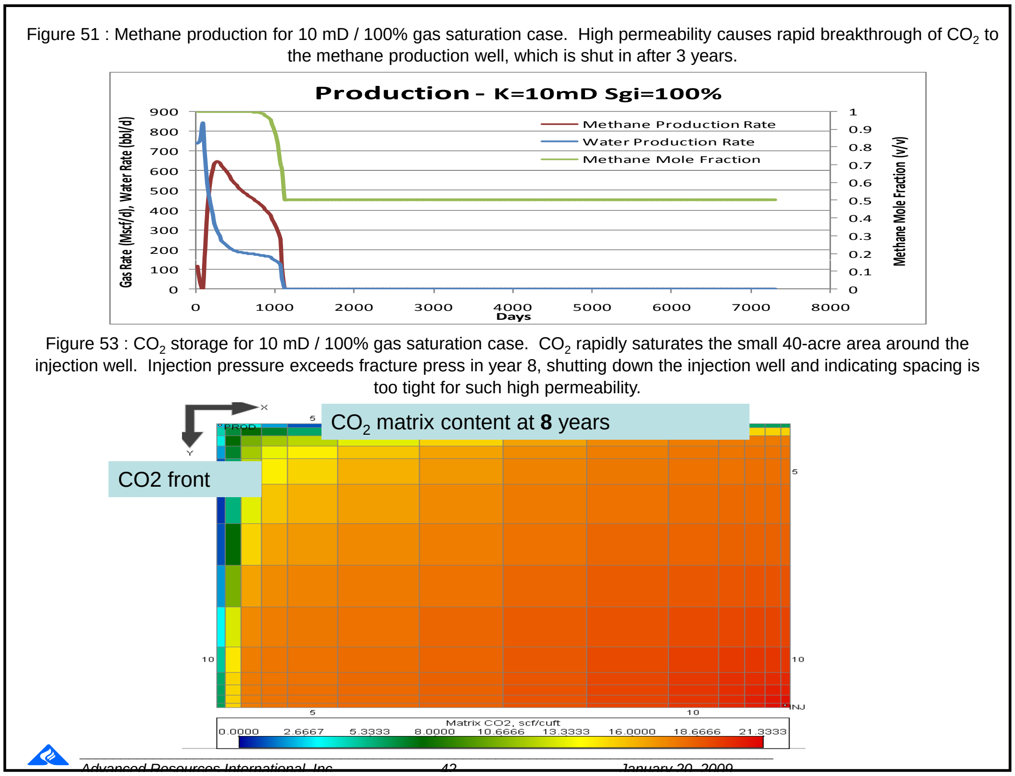


Figure 51 : Methane production for 10 mD / 100% gas saturation case. High permeability causes rapid breakthrough of CO_2 to the methane production well, which is shut in after 3 years.

Figure 53 : CO_2 storage for 10 mD / 100% gas saturation case. CO_2 rapidly saturates the small 40-acre area around the injection well. Injection pressure exceeds fracture press in year 8, shutting down the injection well and indicating spacing is too tight for such high permeability.

CO_2 matrix content at **8** years

CO2 front

Figure 53 : CO_2 storage and methane production for deep coal project at Centralia, with sensitivity to initial methane saturation and permeability.

	Permeability (mD)					
	0.1		1		10	
	Saturation (%)		Saturation (%)		Saturation (%)	
	75	100	75	100	75	100
Cumulative Methane Production (MMcf)	0.3	5	250	341	353	470
Cumulative CO2 injected (MMcf)	130	88	1,333	1,192	2,252	2,247
Cumulative CO2 produced (MMcf)	0	0	0.1	0.02	14	11
Cumulative Water produced (MSTB)	48	55	262	247	304	301
Methane Recovery Factor (%)	0.1	1	66	69	93	95

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EMISSIONS AND POTENTIAL EMISSION REDUCTIONS FROM HAZARDOUS FUEL TREATMENTS IN THE WESTCARB REGION

Pearson, TRH, K. Goslee, and S. Brown.
Winrock International

DOE Contract No.: DE-FC26-05NT42593
Contract Period: October 1, 2005 - May 11, 2011

Arnold Schwarzenegger
Governor

EMISSIONS AND POTENTIAL EMISSION REDUCTIONS FROM HAZARDOUS FUEL TREATMENTS IN THE WESTCARB REGION

PIER PROJECT REPORT

Prepared For:

California Energy Commission
Public Interest Energy Research Program

Prepared By:

Winrock International

July 2010
CEC-XXX-XXX-XXX

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Commission Work Authorization No. MR-045

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Acknowledgements

We would like to thank the following people for their assistance with this research: Nick Martin, Nancy Harris and Silvia Petrova of Winrock International; Olga Krankina of Oregon State University; Mark Harmon of the Oregon State University; Dave Saah of SIG; Max Moritz & Berkeley Labs; Sam Sandberg; Jim Cathcart of the Oregon Department of Forestry; Mark Nechodom & Bruce Goines of USFS; Western Shasta Resource Conservation District; Bob Rynearson of W.M. Beaty and Associates.

Thanks also to those would reviewed a draft version of this report and provided comments: Jim Cathcart, Bruce Goines, Olga Krankina, Max Moritz, Bob Rynearson, Dave Saah, and Sam Sandberg.

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Please cite this report as follows:

Pearson, TRH, K. Goslee, and S. Brown. 2010. *Emissions and potential emission reductions from hazardous fuel treatments in the WESTCARB region.* California Energy Commission, PIER. CEC-500-XXXX-XXX.

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission) conducts public interest research, development, and demonstration (RD&D) projects to benefit the electricity and natural gas ratepayers in California. The Energy Commission awards up to $62 million annually in electricity-related RD&D, and up to $12 million annually for natural gas RD&D.

The PIER program strives to conduct the most promising public interest energy research by partnering with RD&D organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally Preferred Advanced Generation
- Energy-Related Environmental Research

This *Final Report on WESTCARB Fuels Management Pilot Activities in Shasta County, California* is a report for the West Coast Regional Carbon Sequestration Partnership – Phase II (contract number MR-06-03L, work authorization number MR-045), conducted by Winrock International. The information from this project contributes to PIER's Energy-Related Environmental Research program.

For more information on the PIER Program, please visit the Energy Commission's Web site at www.energy.ca.gov/pier or contact the Energy Commission at (916) 654-5164.

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Abstract

This report summarizes efforts by Winrock International and the WESTCARB Fire Panel to develop a methodology for estimating greenhouse gas (GHG) benefits of project activities to reduce emissions from wildland fires in low to mid elevation mixed conifer forests. These efforts focused on low to mid elevation mixed conifer forests and included a conceptual framework developed to aid in determining the full impacts of hazardous fuels treatments, four workshops with carbon and fire experts, numerous consultant activities, and field measurements of hazardous fuels treatments in Shasta County, California and Lake County, Oregon. The task of developing a rigorous methodology to quantify baseline emissions from wildland fires and emission reductions attributable to fuel reduction is complex due to the methodological challenges of modeling fire behavior and emissions, the relatively low annual risk of fire for any given potential project location, and the emissions resulting from fuels treatments. Given (current hazardous fuel removal technologies and) the low probability of fire on any given acre in any given year, hazardous fuel reduction treatments in the forest types addressed in this report cannot directly generate offsets. However, careful design of fuel treatments building from the methodology employed in this analysis can minimize risks to lives and property while also minimizing emissions. Integration of fire and an avoided emissions framework with other ecosystem services will go even further toward a sustainable approach to ecosystem management.

Keywords: *Carbon, sequestration, emission, forest, hazardous fuel reduction, California, wildland, fire, wildfire, greenhouse gas*

Executive Summary

Introduction

The West Coast Regional Carbon Sequestration Partnership (WESTCARB), led by the California Energy Commission, is one of seven US Department of Energy regional partnerships working to evaluate, validate and demonstrate ways to sequester carbon dioxide and reduce emissions of greenhouse gases linked to global climate change. Emissions from fire were identified in WESTCARB Phase I as the single largest source of GHG emissions from land use. Thus the focus of this research was to determine if GHG emissions from wildfire could be reduced and provide a potential opportunity for landowners to generate a new type of carbon mitigation or "offset" activity. For such activities to yield GHG offsets, rigorous measurement, monitoring and verification (MMV) methodologies and reporting protocols must be developed to meet the standards of voluntary and regulated markets for high-quality GHG reductions. Fire suppression and hazardous fuel accumulation are concerns primarily in low to mid elevation mixed conifer forests that prehistorically experienced frequent and low severity fires; we therefore focused our analysis and findings on these ecosystems.

Purpose

The aim of this research was to determine whether a methodology could be developed for use by developers of potential carbon projects to quantify their baseline emissions, project emissions with activities to reduce hazardous fuels, and estimate the associated project carbon benefit.

Project Objectives

The overall goal of WESTCARB Phase II is to validate and demonstrate the region's key carbon sequestration opportunities through pilot projects, methodology development, reporting, and market validation. WESTCARB research will facilitate informed decisions by policymakers, communities, and businesses on how to invest in carbon capture and storage technology development and deployment to achieve climate change mitigation objectives. The opportunity presented here is decreasing wildland fire emissions through hazardous fuel treatment, combined where feasible with fuel removal to a biomass energy facility.

Project Methodology

A conceptual framework was developed to determine the net impact hazardous fuel treatment activities have on the total quantity of greenhouse gases in the atmosphere? This framework incorporated the critical elements of fuel treatments and wildfire as they relate to net CO_2 emissions:

1. **Annual Fire Risk**
2. **Emissions as a Result of Treatment**
3. **Emissions as a Result of Fire**
4. **Removals from forest Growth / Regrowth**
5. **Retreatment**
6. **Shadow Effect**

The following framework was used to estimate losses and gains in stored carbon with and without treatments (with and without "project") and fire:

Gain from *decreased* intensity or spread of fire due to fuel treatment within the treatment and shadow area * annual fire probability

+ Loss from biomass removed during treatment

+ Gain /Loss from substitution of fuels for energy generation

+ Gain from long term storage as wood products from removed biomass during fuels treatment

+ Loss from decomposition of additional dead wood stocks created through fuels treatment

+ Gain /Loss from growth differences between with and without treatment and with and without fire

+ Loss from fires occurring in with project case (with treatment) * annual fire probability

+ Loss from retreating stands through time

A positive net result indicates increased carbon storage as a result of the with-treatment project, while a negative net result indicates a net loss in carbon storage and increased emissions as a result of the with-treatment project.

The individual elements of this framework were quantified to determine their overall impact on net emissions/removal, and on-the-ground projects were implemented to test the overall validity of the framework.

Project Outcomes

Fire represents a significantly more complex opportunity than traditional land use greenhouse gas reduction activities such as afforestation, changes in forest management, and forest protection. This is because a fuel reduction project compares emissions that would have occurred from fires without any treatment on the landscape, which necessarily requires a complex fire baseline modeling effort, against emissions that did occur through fuel treatment. For this purpose it was necessary to examine the risk of a fire burning through a particular location or fireshed in a given year and the emissions that would occur if such a fire did occur.

The reality is that fire risk in any given location on the landscape considered in this report is relatively low (< 0.76% per year), and consequently amortized baseline emissions are low. This reality must be balanced with the emissions that occur when a catastrophic fire does occur. While emissions from fire in the baseline scenario are relatively low, emissions from fuel treatment in the project scenario are not insignificant in that they occur across a relatively broad area in order to intersect with an unknown future fire location.

Substantial emissions occur in the event of a wildfire but significant greenhouse gas emissions still occur on treated sites. In addition regrowth of a healthy forest means that sites have to be retreated with accompanying emissions on a regular schedule (likely <20 years). The impact of growth is complex but in the absence of wildfire growth modeling for these projects show that the treated stands as a whole will store less carbon than the untreated stands – the opposite is true in the event of a wildfire but such a fire is a low probability event.

Consolidating across the conceptual framework we can reached the following conclusions:

- Fire risk is very low (<0.76%/yr)
-Treatment emissions are relatively high and are incurred across the entire treated area
-Treatment never reduces fire emissions by more than 40% and on average across five sites only reduced emissions by 6%
-In the absence of fire, treatment reduces sequestration
-Retreatment will have to occur with accompanied emissions
-A positive impact of treatment beyond the treated area is not guaranteed and is unlikely to ever be large enough to impact net greenhouse gas emissions

So low fire probability is combined with high emissions and low sequestration in the absence of a fire and relatively few emissions reductions in the event of fire.

Conclusions

Reducing emissions from fire could be an important contribution to reducing CO_2 emissions overall, yet the inherent reduction of carbon stocks in hazardous fuels treatments, combined with the low annual probability of fire on a given acre of land prevent the development of a workable carbon offset methodology for such treatments. It may be possible that specific treatments, removing a minimum amount of small diameter ladder fuels in certain forest ecosystems can yield an overall emission reduction. Furthermore, low-emissions technologies to be developed in the future may yield increased emission reductions. In the case of the standard fuels treatments for mixed conifer forests in Northern California and Southern Oregon, which served as the field test for this research, treatments led to increased net emissions over the 60-year modeling period. However, reducing the risk of fire is a critical activity for many other reasons, including enhancing forest health, maintaining wildlife habitat, and reducing risk to life and property, and so hazardous fuel treatments must go ahead and should be planned to minimize net emissions.

In today's world where actions to curb atmospheric greenhouse gas concentrations are growing more urgent, an accurate accounting is important of all emission sources (and sinks) at national, regional and local scales. The work completed here allows a better understanding of the relative emissions that arise from hazardous fuel treatments and wildfires in low to mid elevation mixed conifer forests. While our results show that, in the absence of wildfire, fuels treatments did not lead to net emission reductions at these demonstration sites, it is important for planners to understand relative greenhouse gas emissions in order to be able to design treatments in a way that minimizes emissions while maximizing non-greenhouse gas benefits.

1.0 Introduction

1.1 Background and overview

The West Coast Regional Carbon Sequestration Partnership (WESTCARB), led by the California Energy Commission, is one of seven US Department of Energy regional partnerships working to evaluate, validate and demonstrate ways to sequester carbon dioxide and reduce emissions of greenhouse gases linked to global warming. Terrestrial (forestry and land use) sequestration options being investigated include afforestation, improved management of hazardous fuels to reduce emissions from wildfires, biomass energy, and forest management. Shasta County, California and Lake County, Oregon were chosen for WESTCARB Phase II terrestrial sequestration pilot projects because of the diversity of land cover types present, opportunities to implement the most attractive terrestrial carbon activities identified in Phase I, and replication potential elsewhere in the WESTCARB region.

Fire was identified as the single largest source of emissions from forestland in California (Brown et al 2004). In California an estimated 1.83 MMTCO$_2$e are emitted per year due to fires on forests and rangelands (Pearson et al. 2009). For Oregon the value is 1.03 MMTCO$_2$e/yr, for Washington 0.18 MMTCO$_2$e/yr and for Arizona 0.47 MMTCO$_2$e/yr (Pearson et al. 2007 a,b,c). Policy mechanisms and/or incentives to decrease these emissions could therefore have profound effects on GHG emissions at the state and regional levels.

All carbon project activities work through interventions that lead to a decrease in emissions or an increase in removals (sequestration) relative to a reference or baseline case. In this situation, a carbon project developer would need to estimate the emissions from fire that are likely to occur within defined project boundaries without the implementation of project activities, and how the implementation of project activities would decrease these emissions. Therefore, the substantial challenge is to define the risk of fire and the emissions associated with that risk and to quantify how fuels treatments can diminish these emissions. A good deal of anecdotal evidence exists suggesting that fuels treatments in particular locations have appeared to reduce the intensity, spread, or emissions from fires, and/or slow the progress of fires enough to make suppression feasible. The challenge in this effort is to move from anecdotal evidence to a rigorous scientific methodology, quantifying in a transparent and replicable way the GHG benefits attributable to fuel treatments.

1.2 Project Objectives

The overall goal of WESTCARB Phase II is to validate and demonstrate the region's key carbon sequestration opportunities through pilot projects, methodology development, reporting, and market validation. WESTCARB will produce methodologies, plans, data, technical papers, and reports that facilitate informed decisions by policymakers, communities, and businesses on how to invest in carbon capture and storage technology development and deployment to achieve climate change mitigation objectives. This report focuses on one of those opportunities, creation of a methodology to track wildfire emissions reductions attributable to fuel treatments.

1.3 Report Organization

The report is organized in six key sections. In Section 2 the literature background is given together with the process undertaken: a straw-man method and the fire panel and work with fire experts. In Section 3 the analyses and results from work by fire experts are discussed. In Section 4 details and results are given from the parallel pilot studies that were undertaken under WESTCARB in Shasta County, California and Lake County, Oregon. In Section 5 the results from the consultancies and the field projects are integrated and conclusions made on the possibility of developing a methodology. In Section 6 literature that contrasts with our findings is reviewed in order to identify the sources for the different conclusions. Finally in Section 7 conclusions and recommendations are made addressing the implications of these findings and future opportunities.

2.0 Literature Background, a Straw-man and the Fire Panel

2.1 Current Status of Knowledge on Fire, Fuels Treatments and Greenhouse Gases

Calculating potential offsets from removal of hazardous fuel requires properly addressing all of the expected changes in carbon stocks and emissions that result from treatments. Past studies have addressed change in carbon stocks as a result of fire suppression policies, emissions from wildfire, and the effectiveness of treatments. More recently, a few researchers have addressed the impacts of hazardous fuels treatments on carbon stocks. However, these studies did not produce consistent results and did not always fully address all possible carbon stocks and sources of emissions. Much of this past research has considered emissions from fire as a given or has assumed that 100% of biomass removed in treatments will be utilized and none is emitted due to inefficiencies or decomposition. We explored existing research to identify which factors were considered when calculating the carbon balance of hazardous fuels treatments and to determine the most comprehensive methodology for such calculations.

2.1.1 Effects of fire suppression on carbon storage

Forest ecosystems in the U.S. provide a carbon sink that is estimated to be between 0.17 Pg C/yr and 0.37 Pg C/yr (Pacala et al. 2001). While some research has found that present day forests have lower live-tree carbon stocks than under historic active-fire conditions (North *et al*. 2009, Fellows and Golden 2008), numerous studies have found that 100 years of fire suppression has led to an increase in carbon stored in forests. Findings indicating an increase in sequestered carbon range in scope from the entire U.S. carbon sink (Houghton *et al*. 2000, Hurtt *et al*. 2002) to specific ecosystems such as oak savannah (Tilman *et al*. 2002) and Sierra mixed conifer forests (Bouldin 2009). With an increase in overall biomass, there is the potential for wildfires to release an increased amount of carbon to the atmosphere, especially as they become crown fires rather than simply surface fires, and it is important to have an understanding of the relationship between increased sequestration and increased wildfire emissions.

2.1.2 Pyrogenic CO_2 emissions

While wildfires where they occur may produce a high level of emissions, and may turn a forest from a carbon sink into a carbon source in the short-term, their impact over the long term is likely to be far less than anthropogenic emissions. A study of wildfires in the Metolius watershed in Oregon over two years found that emissions were equal to 2.5% of the statewide emissions of CO_2 from fossil fuel use and industrial processes during the same period (Meigs *et al.* 2009). Dore *et al.* (2008) found that after a stand-replacing fire, carbon losses may continue due to the slow recovery of gross primary production. However, Meigs *et al.* point out that most fires are not stand-replacing, and so it is important to account for the emissions from low to moderate severity fires. Campbell *et al.* (2007) found that over 60% of the emissions in a large wildfire in Oregon came from surface fuels, which would decompose over a period of 10 to 20 years in the absence of a fire, and would for the most part be emitted into the atmosphere anyhow.

Wiedinmyer and Neff (2007) address the variability of CO_2 emissions from fires across the U.S. that they say produce, on average, 4-6% of anthropogenic emissions. They state that wildfires have a near neutral effect on atmospheric CO_2 over the course of multiple decades when regrowth is allowed and factored into the equation. They also point out that fire presents one of the greatest risks to stored terrestrial carbon in the short term, and this risk introduces a high level of uncertainty in projecting forest carbon storage, particularly with changes in fire frequency. However, the effects of such changes are ecosystem-dependent. In looking at the case study of the Yellowstone fires, Kashian *et al.* (2006) found that with the long fire return intervals and relatively rapid regeneration that occurs in that ecosystem, landscape-level carbon storage is not significantly changed as a result of changes in fire frequency because these forests regenerate at such a rapid rate.

2.1.3 Effectiveness of fuels treatments

The basis for hazardous fuels treatments is that they reduce the intensity and extent of subsequent wildfires. It is reasonable to imagine that different fuels treatments yield different results in terms of reducing the severity and extent of wildfires. Agee and Skinner (2005) discuss a three-part objective for fuels treatments: reducing surface fuels, reducing ladder fuels, and reducing crown, and note that these goals can be accomplished using prescribed fire and thinning. However, they caution that not every forest is a high priority candidate for treatment. Lippke *et al*. (2007) found that treating the stand for a target basal area led to decreased wildfire hazard for 45 years, while removing all of the trees under 9 inches diameter at breast height (dbh) or over 12 inches dbh had little or no effect on wildfire intensity and extent. North *et al.* (2009) also found that removing overstory trees did not significantly improve fire resistance. Hurteau and North (2009) looked at eight types of treatments in Sierra Nevada mixed conifer forests and found that those that created a stand with lower tree density of primarily large, fire resistant pines were most successful at protecting the stand. Similarly, Lenart *et al*. (2009) note that after the Rodeo-Chediski fire in Arizona, those stands that had been thinned of smaller diameter trees sustained less damage than unthinned stands.

The success of treatments also depends on the forest ecosystem. Pollet and Omi (2002) show that while fuels treatments are often successful in forests with short fire-return intervals, they are less cost-effective in stands with longer fire-return intervals, and placement of treatments should be balanced with the risk of loss from a fire in urban interface areas. Schoennagel *et al*. (2004) show that while fuel load has the greatest impact on fire behavior in some areas, climatic factors are more significant in other areas where thinning may not significantly impact wildfire behavior.

It is also important to note that different types of treatments will lead to different levels of biomass reduced and carbon emitted. Lippke *et al*. (2007) note that all treatments reduce carbon storage, while not all reduce wildfire severity. The treatments that Stephens and Maghaddas (2005) and Zald *et al.* (2008) found to be most successful at reducing the severity of fires incorporate understory thinning and prescribed burning to reduce surface fuels. In a prescribed burn, the majority of the treated material is an immediate emission, although Narayan *et al*. (2007) found that prescribed fire can have reduced emissions when compared to wildfire, depending on the fire return interval. In the case of understory thinning, in many areas there are no mechanisms to use small diameter wood, and most or all of the biomass removed in such treatments will be emitted to the atmosphere as CO_2 in a relatively short time frame. North *et al*. (2007) suggest that historic forest conditions may be best adapted to resisting stand replacing fires, but they found that thinning alone did not return stands to these conditions; understory thinning combined with prescribed fire was the treatment that most closely resulted in forests that approximated 1865 conditions.

2.2 Conceptual Framework

The aim of this research was to produce a methodology that could be used by potential carbon projects to quantify their baseline emissions, project emissions with activities to reduce hazardous fuels, and estimate the associated project carbon. To that end we developed a general conceptual framework under which a detailed conceptual model could be tested to determine the full impacts of hazardous fuels treatments on wildfire and greenhouse gas emissions. The basic question is-

What net impact do hazardous fuel treatment activities have on the total quantity of greenhouse gases emitted to the atmosphere?

The general conceptual framework includes the approach for estimating the emissions in the baseline case (without fuel treatment) and the approach for the project case (with fuel treatment) as follows:

The baseline case is estimated as:

> The area that would have burned in the absence of project activities multiplied by the emissions that would be expected per unit area burned.

The project case is equal to:

> The estimated emissions from removal of hazardous fuels less any carbon stored in long-term wood products or reduced emissions from bioenergy substitutions, plus

emissions per unit area burned from any fires that occur on the project land through time after fuel treatment.

The detailed conceptual model includes the following factors:

1. **Annual Fire Risk**: The occurrence, spread, and intensity of forest wildfires are unpredictable and, for any specific area of forest, relatively rare. Given this nature of forest wildfires, the application to fuel treatments projects would need to examine the likelihood of fire occurring on any given acre across the project area in any given year. In this model, a performance standard function for fire is needed that is referred to here as an annual fire risk (or probability) distribution. This fire risk distribution would be applied in both with and without project scenarios.

2. **Emissions as a Result of Treatment**: Fuels treatments lead to reductions in carbon stocks in the treated stands as fuels are cut to the ground and/or removed. These fuels enter the atmosphere via one of 5 pathways –
    a. Decomposition over time of the treatment-produced dead material on the forest floor
    b. Prescribed under burn with associated CO_2 and non-CO_2 greenhouse gas emissions
    c. Piling and burning with associated CO_2 and non-CO_2 greenhouse gas emissions
    d. Extraction for wood products with subsequent emissions due to milling inefficiency and product retirement (and burning/decomposition)
    e. Extraction for the production of energy with associated emissions from combustion balanced to a given extent by offsetting the displaced fossil fuel emissions from energy production

3. **Emissions as a Result of Fire**: If a fire occurred in a forest stand, emissions will clearly differ depending on whether or not treatment has occurred and on climatic conditions. Given the complexity of fire behavior, invariably fire emissions must be modeled based on input data on stocks and stand composition.

4. **Forest Growth / Regrowth**: Forest growth must also be considered in both the project and baseline case. Fuels treatments may lead to either an increase or decrease in growth rates relative to the baseline:
    a. Removing hazardous fuels will provide more growing space for the remaining trees, allowing them to grow at a faster rate, possibly removing additional carbon from the atmosphere.
    b. Alternatively, removing hazardous fuels removes trees that in the baseline would have been sequestering carbon from the atmosphere thus leading to a net decrease in growth in the project case relative to the baseline.

5. **Retreatment:** As a result of forest growth, there will likely be a need to retreat forests periodically to maintain the benefits of reduced emissions from wildfire.

6. **Shadow Effect**: The baseline and project must also account for the "shadow effect" of fuel treatments—that is an area that is not treated, but, because of treatments there is a reduced risk of fires and/or reduced fire emissions as a result of treatment. This may be because the fire is more easily extinguished or because the fire will have decreased to the forest floor and will not immediately climb back into the canopy.

The impact of the project on gains and losses of carbon is summarized as follows:

> **Gain** from *decreased* intensity or spread of fire due to fuel treatment within the treatment and shadow areas * annual fire probability
>
> \+ **Loss** from biomass removed during treatment
>
> \+ **Gain** /**Loss** from substitution of fuels for energy generation
>
> \+ **Gain** from long term storage as wood products
>
> \+ **Loss** from decomposition of additional dead wood stocks created through fuels treatment
>
> \+ **Gain** /**Loss** from growth differences between with and without project treatment and with and without fire
>
> \+ **Loss** from fires occurring in with project case * annual fire probability
>
> \+ **Loss** from retreating stands through time

A positive net result indicates increased carbon storage or decreased emissions as a result of the project, while a negative net result indicates decreased carbon storage or increased emissions as a result of the project.

2.3 Creation of a "straw man" methodology

Considering the complexity of the task and absence of any comparable effort to use as a starting point for the effort, the decision was made to create an initial simplified methodology that could be presented to a panel of fire experts and serve as the basis for discussions, critiques and progress forward:

Brown et al. 2006, *Protocol for monitoring and estimating greenhouse gas benefits from hazardous fuels management in Western U.S. forests. Report for the West Coast Regional Carbon Sequestration Partnership Phase II.*

Winrock took the approach of a 10-year moving window of fire probability based on data for northern California defining the risk of the project area burning in the baseline. The straw man methodology is included in **Appendix A**.

2.4 WESTCARB Fire Panel

Fire experts from the WESTCARB region were identified and invited to join a WESTCARB Fire Panel for GHG methodology development[1]. Four meetings were held with various members of the Fire Panel participating.

The full Fire Panel was convened in October 2006, to begin the task of methodology development with Winrock's "straw man" methodology as a starting point. The workshop brought together fire scientists, carbon scientists and fuels management experts for discussion of approaches to quantifying baseline emissions from wildfires, estimating emission reduction/sequestration benefits of fuel reduction, and developing measuring, monitoring and verification protocols to qualify these projects for carbon reporting and/or markets. The desired outcome of the workshop was to identify areas of agreement and issues requiring further research, as well as to clarify roles and potential contributions of Fire Panel members in ongoing protocol development. Fire Panel members were reminded that the desired outcome of the WESTCARB fire methodology task was a methodology that is cost-effective, practical and transparent for landowners/land managers to use, conservative in its GHG estimates, and has sufficient scientific credibility ultimately to qualify these activities for carbon market recognition.

Workshop participants included:

- California Department of Forestry and Fire Protection: Elsa Hucks, Doug Wickizer
- California Air Resources Board: Neva Sotolongo
- Lake County Resources Initiative: Bill Duke
- Oregon Department of Forestry: Jim Cathcart
- Oregon State University: Olga Krankina
- Sylvan Acres LLC: Brent Sohngen
- University of California at Berkeley - Center for Fire Research and Outreach: Max Moritz
- USDA Forest Service - Pacific Northwest Research Station - Pacific Wildland Fire Sciences Laboratory: Sam Sandberg
- USDA Forest Service - Pacific Southwest Research Station - Redding Silviculture Laboratory: Bob Powers
- USDA Forest Service - Pacific Southwest Research Station – Sierra Nevada Research Center: Mark Nechodom
- USDI National Park Service - Whiskeytown NRA: Tim Bradley
- W.M. Beaty and Associates: Bob Rynearson
- Western Shasta Resource Conservation District: Leslie Bryan, Jack Bramhall
- Winrock International: Sandra Brown, Tim Pearson, Nancy Harris, Silvia Petrova, Nick Martin, John Kadyszewski

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[1] While the members of the fire panel were instrumental in discussing issues related to hazardous fuels treatments, fire risk, and methodology development, the panel did not reach a final consensus, and the ultimate findings of this report are the conclusions of the authors, rather than the full fire panel.

An expert subgroup met in May 2007 to discuss, in a smaller group setting, key methodological issues that had been identified in the full Fire Panel meeting as needing further discussion or alternative approaches. In preparation for this meeting, Winrock asked Panel members Sam Sandberg of the PNW Research Station, and Scott Stephens and Max Moritz of the University of California at Berkeley, to work on developing alternative baseline methodologies for estimating emissions and area burned, respectively. Progress and results to date on alternative approaches were presented, followed by open discussion and consideration of next steps.

Meeting participants included:

- University of California at Berkeley - Center for Fire Research and Outreach: Max Moritz, Eric Waller, Scott Stephens
- USDA Forest Service - Pacific Northwest Research Station - Pacific Wildland Fire Sciences Laboratory: Sam Sandberg (Emeritus Physical Scientist)
- USDA Forest Service - Pacific Southwest Research Station – Sierra Nevada Research Center: Mark Nechodom
- TSS Consultants: David Ganz
- Spatial Informatics Group: David Saah
- Winrock International: Sandra Brown, Tim Pearson, Nancy Harris, Silvia Petrova, Nick Martin

The subgroup met again in March 2008 to review the current status of the various separate efforts, determine if and how these efforts could be unified, and identify gaps that needed to be addressed. Participants at this meeting included:

- University of California at Berkeley - Center for Fire Research and Outreach: Max Moritz
- USDA Forest Service - Pacific Northwest Research Station - Pacific Wildland Fire Sciences Laboratory: Sam Sandberg (Emeritus Physical Scientist)
- USDA Forest Service - Pacific Southwest Research Station – Sierra Nevada Research Center: Mark Nechodom
- TSS Consultants: David Ganz
- Spatial Informatics Group: David Saah
- Oregon Department of Forestry: Jim Cathcart
- Oregon State University: Olga Krankina
- Winrock International: Sandra Brown, Tim Pearson, Nancy Harris, Nick Martin, Katie Goslee

A final meeting took place in April 2010, when the researchers still actively involved met to determine final commonalities in their respective findings and discuss the overall potential for reducing greenhouse gas emissions through hazardous fuels reductions. Participants at this meeting included:

- University of California at Berkeley - Center for Fire Research and Outreach: Max Moritz
- Spatial Informatics Group: David Saah
- Oregon Department of Forestry: Jim Cathcart
- Winrock International: Sandra Brown, Tim Pearson, Katie Goslee

3.0 Consultancies with fire experts and additional fire analyses

After the full WESTCARB Fire Panel workshop in October 2006, it was determined that expert fire modelers would be required to create a credible fire emissions reduction methodology. Two teams were contracted: Dr. Sam Sandberg, Emeritus Physical Scientist representing the USDA Forest Service - Pacific Northwest Research Station - Pacific Wildland Fire Sciences Laboratory, and Drs. Max Moritz, Scott Stephens and Eric Waller of the University of California at Berkeley - Center for Fire Research and Outreach. Two existing WESTCARB partners also conducted complimentary fire analyses – Oregon State University and the Oregon Department of Forestry.

3.1 Fire risk and firesheds

The UC Berkeley team focused on developing baseline fire risk (probability of an area being burned in a given year) for Shasta County, California, where fuel treatments were implemented in the WESTCARB terrestrial pilot locations.

Following the spring 2008 fire panel meeting, the work of the Center for Fire Research and Outreach was extended, and a consultancy with Dr. David Saah of the Spatial Informatics Group was added to incorporate the concept of firesheds and their relevance to fuels treatments.

The UC Berkeley team focused on developing alternate approaches to quantify baseline fire risk (i.e. probability of an area being burned in a given year) across the regions of northern California where WESTCARB fuel reduction pilot activities are being monitored. . The group reached final conclusions that reinforced the findings of the initial Winrock work (in the straw man methodology) that modeled fire return intervals were between 120 and 300 years for mixed conifer forest types in Shasta County giving annual fire probabilities of less than 0.8% (0.008) (Figure 1).

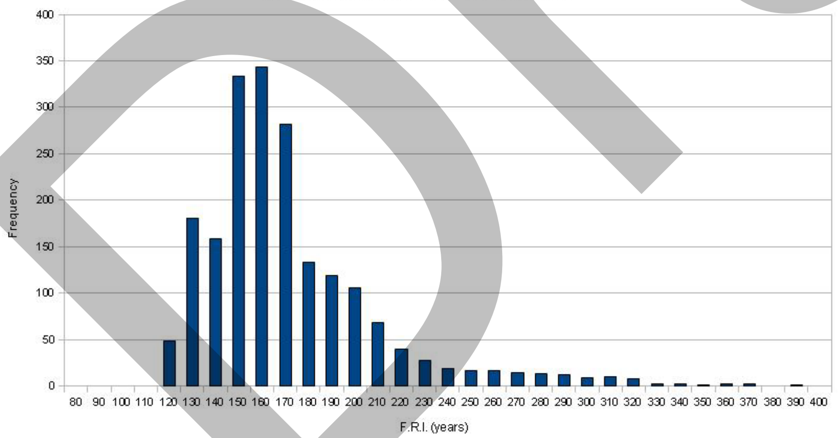

Figure 1: Histograms of fire return intervals for Sierra mixed conifer. Fire return intervals are calculated based on transformation of relative fire probabilities and historical burning rates for Shasta County over 2001-2007

The Berkeley team produced a map showing how this value varies across the northern Californa landscape and across vegetation types (Figure 2).

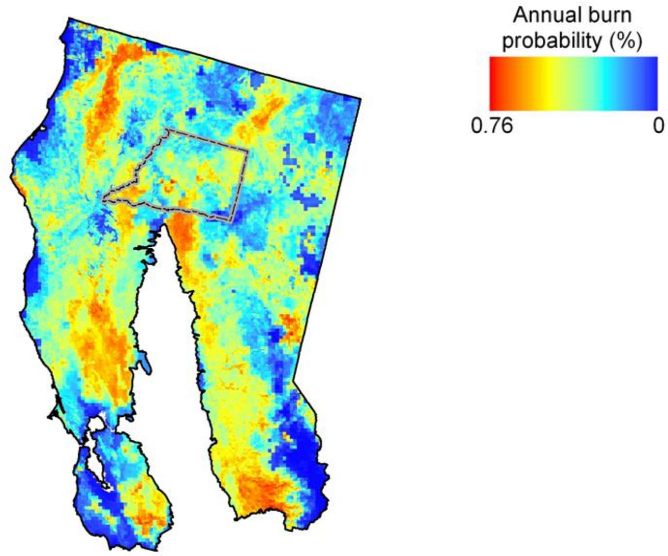

Figure 2: Annual burn probability as calculated by the UC Berkeley fire team (led by Max Moritz)

Within Shasta County ,firesheds were delineated based on five main factors: the "fire behavior triangle" (fuels, weather and topography), barriers to fire spread (both natural and anthropogenic), potential fire behavior (under a "near-worst case" weather scenario), fire occurrence probability patterns, and fire history (Figure 3). For each fireshed a full set of attributes were defined (Table 1).

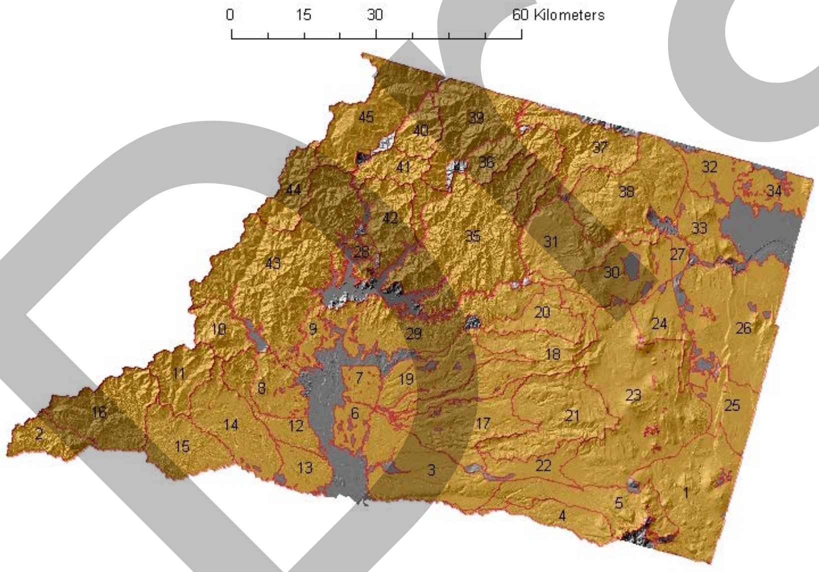

Figure 3: Firesheds delineated for Shasta County, California. Areas not enclosed by a fireshed are non-wildland/non-burnable, i.e. water, urban, agricultural, or barren (Saah *et al.* 2010).

Table 2: Summary of fireshed attributes for Shasta County, California. NLCD indicates the land cover type code from the National Land Cover Database, 2001 (42 is evergreen forest, 43 is mixed forest, 52 is shrub, 71 is grassland/herbaceous). Area indicates the total number of acres in the fireshed. Fire probability values range between 0 and 1 and listed wind speed values are those expected under near-worst case scenarios. Surface flame length is listed in meters, surface fire line intensity is kW/m. Low, medium and high crown fire activity are classified as 1, 2, and 3 respectively.

Fireshed	NLCD Cover Type	Area (Acres)	Fire Probability	*Fire Probability Standard Deviation*	Windspeed (mph)	Topographic Roughness Index	Surface Flame Length	Surface Fire Line Intensity	Crown Fire Activity Class
1	42	85,157	0.261	*0.054*	23.53	1.019	27.88	42,526	3
2	42	24,859	0.389	*0.061*	21.9	1.081	20.95	37,143	1
3	71	73,845	0.461	*0.050*	24.25	1.006	7.89	9,219	1
4	42	25,997	0.447	*0.103*	22.8	1.015	37.1	58,395	3
5	42	56,444	0.339	*0.140*	23.65	1.029	30.45	47,855	3
6	71	14,817	0.392	*0.018*	23.86	0.999	3.66	3,995	1
7	71	13,811	0.433	*0.014*	23.85	1	2.84	2,494	1
8	52	27,656	0.551	*0.045*	24.02	1.021	7.59	10,514	1
9	43	21,696	0.538	*0.058*	23.76	1.026	9.25	12,346	1
10	42	25,386	0.454	*0.065*	23.36	1.08	22.89	39,623	3
11	42	31,825	0.409	*0.061*	23.63	1.086	21.48	37,845	1
12	52	29,314	0.49	*0.046*	23.93	1.031	11.72	16,694	1
13	71	21,114	0.427	*0.024*	24.28	1.002	5.51	5,939	1
14	52	53,956	0.464	*0.041*	23.57	1.013	7.01	9,993	1
15	71	45,640	0.478	*0.030*	23.66	1.025	4.16	6,489	1
16	52	62,906	0.45	*0.056*	23.22	1.084	12.12	22,309	1
17	52	58,341	0.49	*0.040*	23.51	1.015	11.02	13,856	1
18	42	68,791	0.473	*0.071*	23.73	1.022	23.53	37,999	3
19	71	48,316	0.466	*0.055*	24.02	1.012	6.01	6,777	1
20	52	27,252	0.498	*0.077*	23.32	1.02	16.49	22,853	1
21	42	72,889	0.456	*0.073*	23.22	1.029	39.64	65,216	3
22	42	23,030	0.478	*0.032*	23.76	1.005	38.32	59,289	3
23	42	159,183	0.343	*0.051*	23.32	1.017	38.94	63,243	3
24	42	27,912	0.378	*0.031*	22.3	1.016	21.14	28,548	3
25	52	31,802	0.353	*0.038*	22.55	1.009	8.9	8,312	2
26	42	105,654	0.39	*0.029*	22.84	1.008	7	6,056	2
27	42	6,335	0.4	*0.014*	22.64	1.004	2.13	1,335	1
28	52	9,045	0.579	*0.016*	24.15	1.058	5.5	6,261	1
29	42	70,176	0.537	*0.044*	24.01	1.037	6.34	7,902	1
30	42	47,571	0.395	*0.044*	23.41	1.016	11.89	13,756	2
31	42	53,530	0.472	*0.049*	23.22	1.036	20.87	33,088	1
32	42	25,018	0.425	*0.007*	22.65	1.001	14.86	18,262	2
33	42	31,906	0.418	*0.015*	23.63	1.021	9.36	11,660	1
34	42	25,027	0.409	*0.014*	22.37	1.003	4.38	3,221	2
35	42	133,539	0.5	*0.030*	23.88	1.106	14.8	21,026	1
36	42	45,897	0.48	*0.050*	24.06	1.099	30.32	46,920	3
37	42	53,928	0.405	*0.084*	22.59	1.081	25.48	36,514	3
38	42	83,237	0.401	*0.054*	23.76	1.041	31.85	50,594	3
39	42	60,599	0.505	*0.043*	22.88	1.108	24.31	36,169	3
40	42	20,114	0.534	*0.028*	23.32	1.108	20.82	31,915	1
41	42	29,433	0.521	*0.036*	23.25	1.123	14.88	20,581	1
42	42	37,955	0.575	*0.039*	24.12	1.093	9.7	12,673	1
43	42	163,176	0.506	*0.051*	23.3	1.101	12.79	20,239	1
44	42	29,424	0.449	*0.061*	25.12	1.096	34.54	58,901	3
45	42	67,736	0.414	*0.102*	22.79	1.073	22.68	30,693	3

The final report of the UC Berkeley team is included in **Appendix B**.

3.2 Fire Fuelbeds and Baseline Emissions

Dr. Sam Sandberg was tasked with developing estimates of emissions to be paired with the baseline rate of fire.

Sam Sandberg used the USFS fire model - Fuel Characteristic Classification System (FCCS). He proposed a process that could be used on a specific land ownership to estimate future carbon emissions for managed and unmanaged (i.e. baseline) scenarios: 1) predict into the future what harvest and fuel treatment strategies would be applied to a management unit; 2) customize fuelbeds to represent each of the future time periods and management options; 3) calculate the probability of wildfire on each fuelbed before and after treatment based on adjustments to the baseline algorithm using fire potentials; 4) calculate the carbon release from prescribed fire treatments and expected wildfire area. The adjusted annual fuel risk by different fuelbeds in the Shasta County region is shown in Figure 4, and the average emission from a fire in each fuelbed type by different moisture conditions in Figure 5. The final report of Sam Sandberg can be found in **Appendix C**.

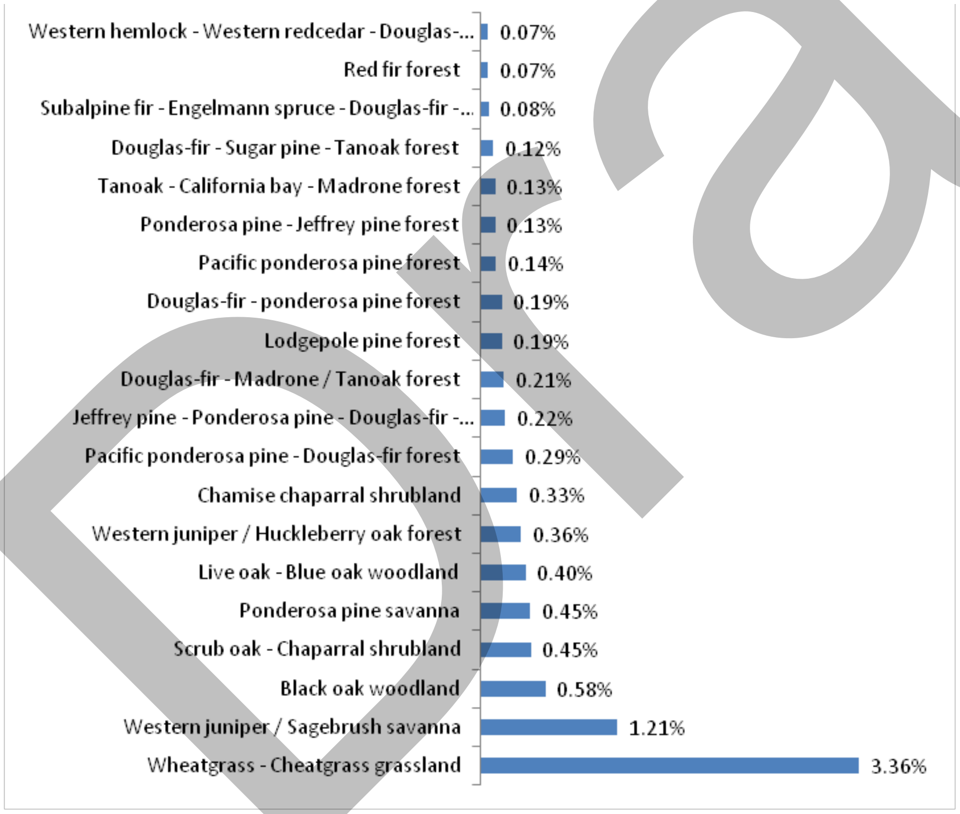

Figure 4 Historic annual fire risk for FCCS fuelbeds in ecosystem province M261 (Sierran Steppe – Mixed Forest – Coniferous Forest – Alpine Meadow). The individual fire risk are assumed to be the same for any Project Area (including Shasta County) in the Province

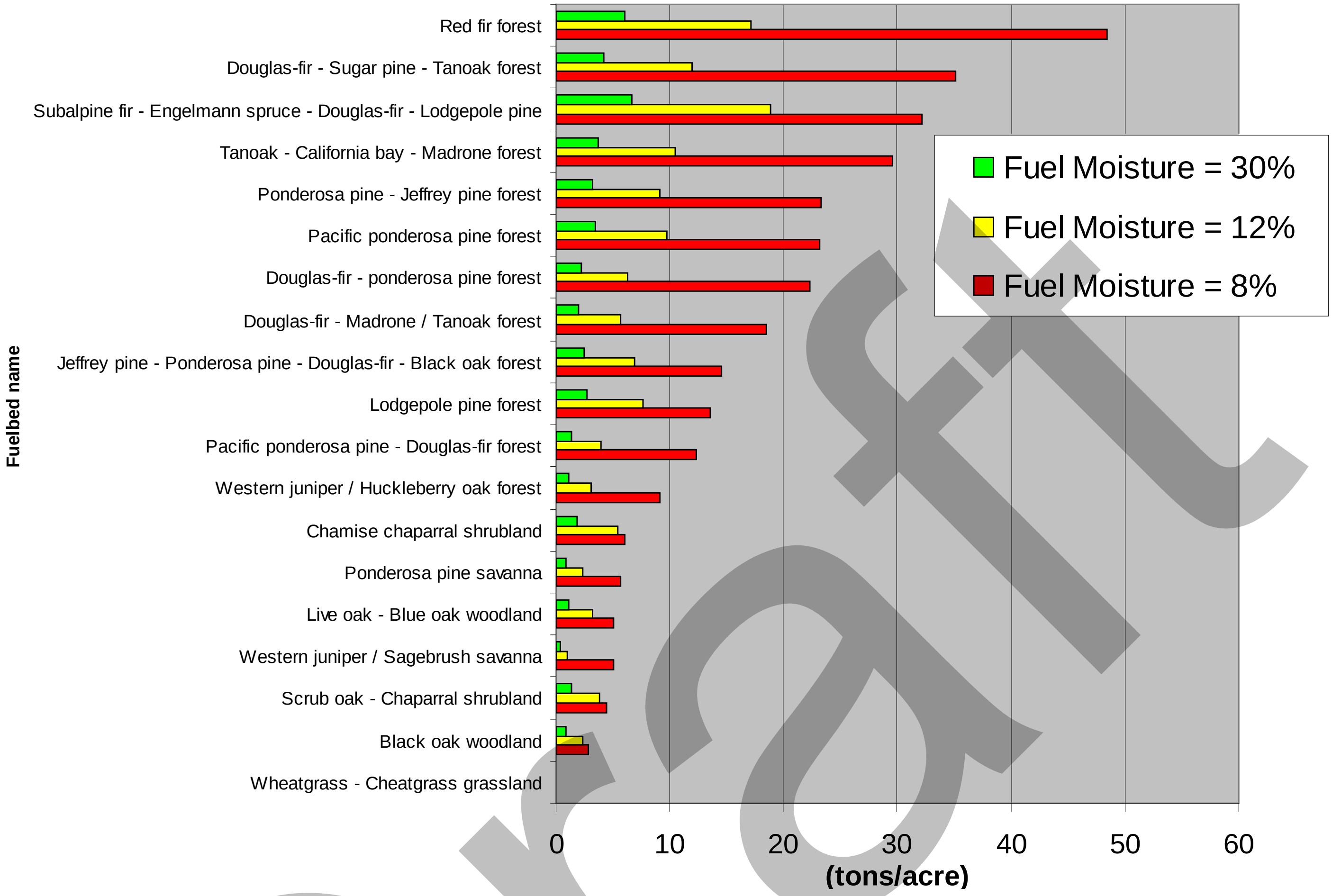

Figure 12. Carbon emissions (tons/acre) for FCCS fuelbeds in Oregon/California at three 1000-hr moisture content profiles. The "8%" moisture profile represents an average wildfire; 12% and 30% represents a range in emissions expected from prescribed fire in each fuelbed.

3.3 Impact of Fuel Treatments on Stand Growth

Oregon State University completed literature and analyses of data on rates of decomposition of woody debris. OSU also examined the impact of fuel treatments on stand growth and carbon sequestration using the STANDCARB model. The reference data for model calibration was obtained from the US Forest Service – Forest Inventory and Analysis database, and model settings were adjusted to represent realistically the regional patterns (in Southern Oregon) of live tree biomass accumulation with age of forest stands for one forest type (Ponderosa pine). The team developed a set of thinning and fire scenarios to be simulated. Preliminary model outputs suggest that after 200 years of application of aggressive thinning (e.g., 35% removal every 15 years or 50% removal every 25 years) carbon stores in live biomass and total biomass declined by about 20 and 30 t C/ha respectively, with smaller losses for moderate thinning regimes. This loss represents 15-20% of the baseline scenario, though use of harvested wood could reduce this loss. On average, over 200 years of applying these thinning schedules the losses of live biomass ranged from 4 to 14 t C/ha compared to a no-thin scenario. The effect of thinning on the average C store in forest fuels was small; moderate thinning had virtually no effect; more aggressive thinning reduced forest fuel load on average by 0.5-1.9 t C/ha or 1-4% of the forest fuel load in baseline scenario. For thinning to be effective as a measure to reduce carbon emissions from fires, the emission reduction has to be greater than the estimated losses of biomass caused by thinning. OSU's reports are included in **Appendix D**.

3.4 Case Study Simulation of Fuel Treatments and Wildfire Emissions – Lake County, OR

The Oregon Department of Forestry conducted separate research that addressed the question—does fuels treatments result in an overall carbon benefit from reduced wildfire emissions – through a case study simulation analysis of fuel treatments and wildfire emissions (Cathcart *et al*, In Press). The case study addressed the 169,200 acre Drews Creek watershed in Lake County, Oregon that is comprised of agricultural lands, juniper woodland, dry ponderosa pine forests, and mixed conifer forests. Within the watershed, 9,500 acres have burned over the last 50 years. The researchers modeled the effects of the anticipated large "problem fire," to be avoided through the Fremont-Winema national Forest's fuel treatment planning effort. The problem fire is a blow-up event under sever fuel moisture and weather conditions that burns 11,000 acres over an 8-hour afternoon burn period. Fuels treatments were modeled by thinning from below and under-burning a total of 12,825 acres, 9.1% of the watershed's forestland. Using ArcFuels software, wildfires under extreme fuel moisture and weather conditions were simulated over the 8 hour burn period with 10,000 random ignitions for both the treated (with project) and untreated (baseline) watershed. Conditional probabilities, both for wildfire reaching a given stand and for its intensity once it reached the stand, were calculated for the treated and untreated landscapes. The effect of the fuel treatments on wildfire risk were based on the treatments lowering both the conditional probability of wildfire reaching a stand, and the probability of higher severity fires once fire reached treated stands. The conditional burn probabilities averaged 2.2% (0.0022) for the untreated watershed and 1.7% (0.0017) for the treated watershed; the effect of the fuel treatments only reducing the average conditional burn probability by 0.05% (0.0004). As seen in the other studies, the predominate simulation for a given stand was that no wildfire occurred – averaging 97.9% of the time for the treated watershed.

The study design explicitly simulated the shadow effect of the treatments by calculating the avoided wildfire emissions in untreated stands as a result of the treatments. The area of the shadow effect was assumed to be the watershed boundary. The results showed that the likelihood of fire reaching untreated stands decreases with treatment. Carbon stocks lost in thinning and under-burning were estimated to be -271,333 tons of carbon (-21.2 tons per treated acre). In comparison, only an expected 3,700 tons (0.21 tons per acre) of avoided carbon loss from wildfire accrued to the project as a result of the treatment's effect of reducing both the likelihood and intensity of wildfire. The avoided emissions from the treatment shadow effect was an additional 3,087 tons of expected avoided carbon loss (0.025 tons per untreated acre) as a result of the treatment's effect of reducing the likelihood of wildfire in untreated areas. The total avoided emissions benefit from treatment was 6,787 tons of expected carbon loss avoided (0.048 tons per forested acre). This low expected avoided emissions is again due to the infrequent probabilistic nature of wildfire. The net offset from avoiding the chance of a problem fire from a given ignition within the watershed under severe fuel moisture and weather was -264,546 tons (-1.9 tons per forested acre). Given these emissions, and the one-time investment of fuels treatments to avoid a “problem fire,” if there were five ignitions per year under severe weather conditions (dry conditions with relatively high wind speeds), the break even shelf life (the time the treatment’s carbon losses are recouped from avoided wildfire emissions spanning several years following treatment) is nine years.

4.0 Field Data and Modeled Fuels Treatment Projects

4.1 The Purpose of Measurement and Modeling Activities

To gather real-world data for an assessment of fuel treatment project methodologies, pre- and post-fuel treatment carbon stock measurements were conducted by Winrock International and its WESTCARB partners on several treated areas. The purpose of the measurements was to provide ground data from real treatments as input into a model of a hypothetical greenhouse gas emission reduction projects. Measurements identified the carbon stocks before and after treatment, the direct impacts of fuel treatments on carbon stocks in different carbon pools (e.g. increases in dead wood, decreases in dense growth), and the fuel removed from the forest for biomass energy or wood products during treatment. Two hazardous fuel treatment projects were identified in Lake County, Oregon and three in Shasta County, California.

These measurements were used to determine the carbon stocks before and after treatment and before and after a potential wildfire, for each project area. Growth modeling was conducted with the Forest Vegetation Simulator for both with and without treatment stands. Emissions from a potential fire were modeled in both with- and without-fuels treatment scenarios using both the Fuel Characteristic Classification System (FCCS) and the Forest Vegetation Simulator fire and Fuels Extension (FVS-FFE). FVS was also used to project growth on burned stands, incorporating the impacts of fire on the future stand.

More information on the fuels treatment and results can be found in the full pilot study reports:

Goslee, K., T. Pearson, S. Grimland, S. Petrova, and S. Brown. 2010. *Final Report on WESTCARB Fuels Management Pilot Activities in Shasta County, California.* California Energy Commission, PIER. CEC-500-XXXX-XXX.

And

Goslee, K., T. Pearson, S. Grimland, S. Petrova, and S. Brown. 2010. *Final Report on WESTCARB Fuels Management Pilot Activities in Lake County, Oregon.* California Energy Commission, PIER. CEC-500-XXXX-XXX.

4.2 Summary of Results

The initial stocks of forests in the five sites were between 51 and 82 t C/ac dropping to between 34 and 72 t C/ac after treatment with an average decrease of 12 t C/ac (Table 2). Decreases in stocks due to wildfire were estimated at between 8 and 12 t C/ac in the absence of treatment and between 7 and 13 t C/ac if a treatment had occurred.

Table 2: Carbon stocks (in t C/ac) for each of the five treatment locations before and after treatment and modeled with and without an immediate wildfire.

		Pre-Treatment		Post-Treatment	
		No fire	Wildfire	No fire	Wildfire
Oregon	Bull	82	70	72	59
	Collins	55	47	34	25
California	Davis	51	41	48	39
	HH	64	53	55	45
	Berry	70	58	51	44

On a percentage basis (Table 3) treatment led to an average of 19% reduction of stock (range 6-38%). Wildfires led to a reduction in stocks of 17% on average where no treatment had occurred or 19% with fuel treatment.

Table 3: The percentage change in stocks at each of the five treatment locations as a result of treatment and in response to a wildfire with and without a treatment

		Reduction due to treatment	Reduction due to fire	
			No Treatment	With Treatment
Oregon	Bull	12%	15%	18%
	Collins	38%	15%	26%
California	Davis	6%	20%	19%
	HH	14%	18%	18%
	Berry	27%	17%	14%

In all cases treatment led to a decrease in carbon removals (sequestration) in the absence of wildfire (Table 4). In every case the situation was reversed where a wildfire occurred.

Fuel treatment reduced wildfire emissions by an average of 6%. However, the ratio varied from a decrease of 38% to an increase of 16% (Table 4). This variation is likely related largely to the intensity of treatment and the size composition of the stand prior to treatment.

Table 4: The impact of fuel treatment and wildfire on carbon removals through forest growth (over 60 years), emission resulting from wildfire and net emissions considering all input factors, handling of fuels and risk of fire for each of the five locations. A negative indicates a net emission, a positive indicates a net removal

		Growth				**Fire Emissions**		**NET EMISSIONS**	
	Treatment	**No**	**Yes**	**No**	**Yes**	**No**	**Yes**		
	Wildfire	**No**	**No**	**Yes**	**Yes**	**Yes**	**Yes**	**Short Term**	**Long Term**
					t CO_2/ac				
Oregon	Bull	14	29	106	72	-43	-47	-47	-37
	Collins	92	62	-36	-26	-29	-33	-108	-113
California	Davis	212	184	55	69	-37	-34	-39	-60
	HH	205	180	57	94	-40	-35	-84	-91
	Berry	172	129	6	99	-43	-26	-83	-116

Short term = 10 years; Long term = 60 years

The net emissions incorporated regrowth following fire and following treatment plus the risk of fire occurring. Risk of fire was derived from the work of UC Berkeley and was equal to 0.64% for the sites in Shasta County and 0.60% for the sites in Lake County. Using the full accounting methodology, a proportion of biomass extracted as timber is accounted as a permanent removal. However, for biomass energy the extracted biomass serves to displace fossil fuels burned for power generation. In California, new power is generated by burning natural gas and natural gas produces fewer greenhouse gas emissions per megawatt hour of power production than burning biomass. Thus, all biomass extracted during treatment for energy production results in a net emission (albeit lower than if the stocks had been burned on site).

Many interpret the fact that biomass is replaceable (in the way that fossil fuels are not) to mean that all biomass burned has no net impact on the atmosphere. But burning biomass does increase greenhouse gases resident in the atmosphere. Burning biomass might prevent emissions from fossil fuels, but this is by no means permanent. In this debate about use of biomass for power production, it is critical to focus on the atmosphere, i.e. does the project cause an increase or decrease in the concentration of carbon dioxide in the atmosphere? In the case of burning biomass rather than natural gas, the net result is an increase in CO_2 in the atmosphere because natural gas burns more cleanly than biomass. If coal were displaced instead of natural gas the savings would be greater while if the displacement is of electricity generated by nuclear power, solar, wind or hydro power then the result is an emission with no net saving.

If the stand is not treated the fuels are available in the forest to be emitted to the atmosphere through wildfires, and as shown above in the CA and OR region this risk is very low. However, this should not be considered under the biomass energy calculations. If it is then we would be counting the baseline fire emissions twice. The baseline fire risk multiplied by the stock gives the baseline emission from wildfires, which is the emission from fuels in the absence of fuel treatment.

Considering the disposition of biomass and the risk of fire, the analyses at the five pilot sites showed net emissions of between 47 and 108 t CO_2e/ac within ten years and between 37 and 116 t CO_2e/ac after 60 years have passed (Table 4).

This analysis integrates a risk of fire based on the measured fire return interval. Thus if a fire actually occurs then the result would be a net removal but in reality the balance of probabilities indicates that a fire will not occur and in this case the net emission would be yet higher.

This analysis integrates a risk of fire based on the measured fire return interval. Thus if a fire actually occurs then the treatments reduce emissions sufficiently to result in a net removal. However, it is far more likely that a fire will not occur on the landscape, in which case, the net emission would be yet higher due to the removal of carbon stocks in the treatment.

More details are found in the two pilot study reports.

5.0 Integration and Offset Methodology Conclusions

The results of the analyses and measurements are strongly conclusive:

- The annual fire risk does not exceed 0.76% in any of the forest types examined in parts of CA and OR.
- Fuels treatment leads to reductions in stocks of 10 to 40% with corresponding emissions
- Fuels treatments must be conducted across a wide area due to the unpredictability of fire occurrence
- Fuels treatments must be repeated to maintain efficacy
- Fuels treatments undoubtedly make a fire more easy to control and thus save lives, however, the measured treatments only led to a 6% reductions in emissions from a wildfire occurring immediately after treatment in the five sites examined

The net result is an increase in emissions, as a result of treatments, of between 30 and 120 t CO_2-e/ac. In addition, this value cannot be decreased through using fuels for biomass energy for these project areas (at least given current extraction technologies and equipment fuel efficiencies).

Ultimately, for fuels reduction to be a credible offsets project, it would be necessary to be able predict exactly where fires are going to occur and implement well designed fuels treatments in those locations. In reality this is of course impossible given current modeling capabilities.

5.1 Revisiting the Conceptual Framework

1. **Annual Fire Risk**: Multiple studies under this task identified annual fire risks of less than 1%. Based on ten-year moving average, Winrock estimated annual burn risks of 0.12% for private lands and 0.33% for public lands in Northern California. The more detailed analysis of the UC Berkeley team determined a mean annual fire probability of 0.64% for mixed conifer forests in Shasta County, California and 0.60% for mixed conifer forests in Lake Country, Oregon. In no case were probabilities higher than 0.76%/year.

Thus there is a less than 1 in 130 chance of a fire at any site in any given year and for some sites it is 1 in 300 or more.

2. **Emissions as a Result of Treatment**: Across the five measurement sites in California and Oregon hazardous fuel treatment led to reductions in stocks of between 6 and 38% (average – 19%).
Where timber was extracted, between 25.5% (in CA) and 30.9% (in OR) of the extracted biomass can be considered permanently sequestered in wood products. The remaining ~70% is emitted to the atmosphere over time.

Where biomass is extracted for power generation there is a net emission of 1.334 t CO_2/ton of biomass burned where the displaced fossil fuel is natural gas (as in California) or as low as 0.833 t CO_2/ton of biomass where the displaced fossil fuel is coal.

Any treated biomass not extracted from the forest will be emitted to the atmosphere – the only difference being if fire is used (underburn or pile) then non-CO_2 gases will also be emitted. Methane has an atmospheric impact 23 times that of carbon dioxide and nitrous oxide has an impact that is 310 times that of carbon dioxide.

3. **Emissions as a Result of Fire**: Across the five measurement sites in California and Oregon fuel treatment led to changes in emissions from subsequent wildfires of between a 16% increase[2] in emissions and a 38% reduction in emissions. On average emissions were reduced by 6%.

4. **Forest Growth/Regrowth**: Across the five measurements sites growth modeling showed a higher rate of sequestration after 60 years in stands with no treatment compared to treated stands in the absence of wildfire (on average 17% lower sequestration). Where a wildfire occurs the relationship is reversed with the total sequestration higher where treatment had occurred (on average 63% higher sequestration).

5. **Retreatment**: Hazardous fuels regrow rapidly. No analysis was conducted on this component of the conceptual framework, however, it is considered likely that retreatment will be needed every 10 to 20 years. Over a twenty year period even assuming the highest fire risk there is only a 15% chance that a fire will have occurred.

6. **Shadow Effect**: Analysis of the shadow effect by the UC Berkeley/SIG team revealed that no simple relationship or assumption can be derived. The size of the shadow effect will depend on the level of hazardous fuels in surrounding forests, the climatic conditions, the access to the site and the relative presence of fire fighters and firefighting equipment. The shadow effect may be zero where no immediate effort is possible at extinguishing the fires and where the fuel and climatic conditions are favorable for rapid reclimbing into the canopy. Dr Sam Sandberg estimated that the shadow area would not exceed five times the treated area. The Oregon Department of Forestry simulation assumed that the

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[2] Increases in emissions following fuels treatments were primarily the result of an increase in 1- and 10-hour fuels.

boundary of the shadow effect coincided with the watershed boundary, and modeled emission avoidance occurring in the shadow area explicitly. In this instance, accounting for the shadow effect doubled the calculated gross emission avoidance benefits from a single random emission, but that was still much lower than the initial carbon cost of the treatments themselves.

Consolidating across the conceptual framework we can reach the following conclusions:
- Fire risk is very low
-Treatment emissions are relatively high and are incurred across the entire treated area
-Treatment never reduces fire emissions by more than 40% and on average across five sites only reduced emissions by 6%
-In the absence of fire, treatment reduces sequestration
-Retreatment will have to occur with accompanied emissions
-A positive impact of treatment beyond the treated area is not guaranteed and is unlikely to ever be large enough to impact net greenhouse gas emissions

So low fire probability is paired with high emissions and low sequestration in the absence of a fire and relatively few emissions reductions in the event of fire.

5.2 Supporting Literature

Related research on the Mendocino National Forest in Shasta County (Pearson *et al*. 2010) showed similar results. This study looked at the effects on wildfire emissions of fuels treatments done under a Forest Service Stewardship Contract. In this case, the treatments did not reduce the risk of fire, nor did they decrease emissions from fire, and the reduction of carbon stocks lead to a large net gain in overall emissions.

Our conclusions are supported by a recent study that addressed the uncertain probability of fire (Mitchell *et al.*, 2009) and the long-term carbon impacts of fire on three ecosystems in the Pacific Northwest: east Cascades ponderosa pine forests, west Cascades western hemlock-Douglas-fir forests, and Coast Range western hemlock-Sitka spruce forests. The study found that hazardous fuel reduction projects more often than not reduce more carbon than they allow the stand to store with an increased resistance to wildfire. One of the reasons for this is that much of the carbon that is stored in the forest is not immediately consumed even in high-severity fires. The authors of this study recommend that while fuel reduction projects may be the best management option in high risk forests near urban areas, other forests may be best used for their ability to sequester carbon, and not treated for fuel reduction.

6.0 Contrasting Literature

Given the conclusion of our work here that there is currently no opportunity for fuels reduction as a greenhouse gas emission offset category, it is perhaps surprising that many studies have come out demonstrating a positive greenhouse gas impact of fuels treatments. It should be noted that the majority of these studies had different purposes to our own so it is not surprising that inconsistencies exist. However, for our full atmospheric accounting purposes, the conclusions in these studies have omitted certain aspect of carbon accounting that we find to be essential. Here we take each study showing a positive impact and discuss where we feel that omissions occurred:

Finkral and Evans (2008)

The effects of a thinning treatment on carbon stocks in a northern Arizona ponderosa pine forest.

Publication Conclusion: The authors state that the thinning treatment resulted in net emissions of 3,114 kg C/ha (4.8 t CO_2-e/ac), though if the wood removed had been used in longer lasting products, the net carbon storage (relative to without thinning) would have been around 3,351 kg C/ha (1.9 t C/ac). So that thinning for treatment of fuels with storage in long term products results in a net emission reduction of 6.97 t CO_2-e/ac.

Forest type: Northern Arizona ponderosa pine

Treatments: pre-settlement restoration

Stocks: pre-treatment: 48.88 tons/ha; post-treatment: 36.42 tons/ha

Fire risk: 2.8%

Wildfire emissions: wildfire was modeled using FVS, and emissions were estimated at about 20% of carbon stocks for both treated and untreated

Emissions from prescribed fire: N/A

Emissions from treatment: 0.091 tons/ha emitted from equipment use for harvest and transport.

Utilization: firewood, because markets for longer-lived products were not available

Reassessment Conclusions: The authors assumed that a fire takes place and the emissions from fire are a given in their calculations. Accounting for the potential for fire (multiplying emissions by the 2.8% risk of fire), if wood is used as firewood, the treatment emissions are 5,457 kg C/ha (8.1 t CO_2-e/ac). In addition, in accounting for the net storage or release of carbon if the wood is used for longer lasting products, the authors did not incorporate mill inefficiencies. Incorporating both inefficiencies and risk of fire for longer lasting products, net carbon emission due to fuel treatment is 1.8 t CO_2-e/ac (1,131 kg C/ha) as opposed to the net emission reduction as a result of fuel treatment calculated in the paper of 7.0 t CO_2-e/ac (a difference of 8.8 t CO_2-e/ac) . This value does not account for the rate of turnover/retirement of the wood products – using USFS defaults for the Rocky Mountain region 63.3% of the extracted material is emitted to the atmosphere within 100 years

North, Hurteau, and Innes (2009)

Fire suppression and fuels treatment effects on mixed-conifer carbon stocks and emissions

Publication Conclusion: The authors conclude that forests with large trees, approximating 1865 active fire stand conditions, act as fire-resistant carbon sinks, storing high levels of carbon, and that such stands could be achieved with minimal reductions in existing carbon pools.

Forest types: Sierra Nevada mixed conifer

Treatments: 6 types: no thinning, understory thinning, and overstory thinning, each with and without prescribed burning

Stocks: Range of 66 Mg C/ha in most intensive treatment, overstory thin and burn, to 250 Mg C/ha in control. The percent change from pretreatment mean was as follows: burn only, -6.8%; understory thin, -28%; understory thin and burn, -34%; overstory thin, -56%, overstory thin and burn, -65%.

Fire risk: does not address risk of wildfire

Wildfire emissions: does not address emissions from wildfire

Emissions from treatment: Emissions sources included prescribed burn, equipment releases, trucking to the mill, and milling waste, with milling waste being the highest emission and prescribed burning being the second highest. (Only equipment and trucking are not accounted for in stocks above.) Carbon storage in long-lived wood products was not addressed.

Reassessment Conclusions: The study did not model fire, only discussed basic fire principles, such as fuel loads and crowning index and how these were affected by treatments. Thinning increased crowning index and prescribed fire reduced loading in most fuel classes. Without knowing the potential wildfire emissions after each treatment type, it is difficult to assess the actual carbon balance of the treatments using our framework.

USDA Forest Service (2009)

Biomass to Energy: Forest Management for Wildfire Reduction, Energy Production, and Other Benefits

Publication Conclusion: The authors conclude that the treatments provide a net benefit for total energy consumption and reduced emissions.

Forest types: Sierra Nevada mixed conifer

Treatments: 13 prescriptions, including clear cutting, pre-commercial thinning, commercial thinning, salvage logging, select harvest, and restrictive thinning, with use of underburning

Stocks: N/A (compared treatment emissions and risk of fire, rather than calculating stocks)

Fire risk: chose discrete ignition points at locations across the landscape

Wildfire emissions: reference case: 17,000,000 tons CO_2-e;
test case: 14,000,000 tons CO_2-e;
Net *reduction* in emission due to fuel treatment:
3,000,000 tons CO_2-e.

Emissions from treatment: equipment: 1,220,000 tons CO_2-e; underburning: 1,700,000 tons CO_2-e

Utilization: biomass energy, wood products.

However, the model did not account for:

- emissions from sawlog production or
- any potential emissions or credits for offsetting natural gas

These could be calculated, respectively, as net emissions of:

- 37,603,847 tons CO_2-e for wood products (based on wood retirement rate of 64.5% over 100 years), and
- 27,613,800 tons CO_2-e for emissions from biomass energy (based on offsetting natural gas)

Reassessment Conclusions: When emissions from sawlog utilization and retirement and biomass efficiency are incorporated, the test case has more than five times higher emissions than the reference case:

Reference case: 17,000,000 tons CO_2-e;
Test case: 14,000,000 + 37,603,847 + 27,613,800
= 79,217,647 tons CO_2-e;
Net *increase* in emissions due to fuel treatment:
62,217,647 tons CO_2-e.

Hurteau, Koch, and Hungate (2008)

Carbon protection and fire risk reduction: toward a full accounting of forest carbon offsets

Publication Conclusion: The authors state that their "'back of the envelope' calculations indicate that massive CO_2 emissions from wildfire are avoidable in forests that have historically been characterized by frequent, low-severity fire."

Forest types: Ponderosa pine and mixed conifer forests in AZ, CO, OR, and CA

Treatments: Looked at four large forest fires (Rodeo-Chediski in AZ, Hayman in CO, Biscuit in OR and CA, and McNally in CA), and modeled the effects that treatments prior to fire would have had. Hypothetical treatment was a thin from below, removing the majority of small diameter trees.

Stocks: N/A (compared treatment and fire emissions, rather than calculating stocks)

Fire risk: 100%, as the study addressed fires that had occurred

Wildfire emissions: 4.2-6.1 $MMTCO_2e$ from live tree emissions, across the four fires; modeled treatment could have reduced the emissions more than 90%

Emissions from treatment: Modeled thinning removed 3.9 $MMTCO_2e$ across the four fires; study did not account for emissions from thinning and transportation

Utilization: not included, as thinned material was non-merchantable, though biomass energy may be an option

Reassessment Conclusions: The study looked at major stand replacing fires that had occurred. In reality as we have shown the risk of fire is relatively low and the risk of a large-scale crown fire is lower still. Emissions could have been reduced by more than 90%, however, the risk of fire is very unlikely to exceed 3% per year (and is likely to be less than 1% as we found in Oregon and California). When these factors are integrated in the analyses it is unlikely that a net emission reduction could result from treatment.

Wiedinmyer and Hurteau (2010)

Prescribed fire as a means of reducing forest carbon emissions in the Western United States

Publication Conclusion: The study concludes that prescribed burning could reduce fire emissions in the western U.S. by 18-25%.

Forest type: Western forests – multiple forest types

Treatments: Emissions from prescribed burning were modeled on western forests that historically had fairly frequent fire return intervals and low or mixed severity effects.

Stocks: N/A

Fire risk: 100%, as the study addressed fires that had occurred

Wildfire emissions: Annually averaged state-wide wildfire emissions ranged from 1-18 $MMTCO_2$/yr from 2001-2001 across 11 western states.

Emissions from prescribed fire: Annually averaged state-wide prescribed fire emissions ranged from 1-14 $MMTCO_2$/yr from 2001-2008 across the same states.

Emissions from treatment: same as above, as treatment consisted entirely of prescribed burning

Utilization: N/A

Reassessment Conclusions: The findings are based on the replacement of wildfire with prescribed fire, presupposing that the location of wildfires could be predicted accurately before their occurrence, allowing for management with prescribed fire only in locations that would otherwise burn in a wildfire. Modeling techniques do not yet allow us to know exactly where fires will occur, necessitating large areas of treatment in order to capture future uncertain area of wildfire. If the prescribed fire emissions are multiplied by a 20-200 factor to reflect the additional area that would have to be treated in order to be confident of capturing future wildfires (reflecting a fire risk of between 0.5 and 5% / yr) then the emissions from prescribed fires would range between 20 and 2,800 $MMTCO_2$/yr (clearly exceeding the emissions from wildfires)[3].

Robards and Wickizer (2010)

Demonstration of the Climate Action Reserve Forestry Protocols at LaTour Demonstration State Forest, WESTCARB Final Report

Publication Conclusion: This study shows a total expected emission reduction of 12,387.3 tC (47,070 t CO_2-e) over the life of the project (100 years)

Forest type: Ponderosa pine, mixed conifer, white fir, red fir

Treatments: Creation of a shaded fuel break, retaining a post-harvest basal area of 50 ft^2/ac, and reducing ground and ladder fuels.

Stocks: 98,616.9 tons of carbon across entire project area

Fire risk: 3% (assumed not calculated)

Wildfire emissions: 30% loss of carbon stocks in extreme fire conditions, 20% loss in high severity weather conditions, 10% loss in moderate severity weather conditions (assumed not calculated)

Emissions from prescribed fire: N/A

Emissions from treatment: 2,109.4 tons of carbon across fuel break (8,031 t CO_2-e).

Utilization: N/A

Reassessment Conclusions: The study relies on highly optimistic assumptions:

- First, the study uses a fire risk that is significantly higher than commonly accepted annual burn probabilities including burn probabilities calculated independently by UC Berkeley, Winrock and Dr Sam Sandberg in the course of this study. LaTour State Forest is in Shasta County so we can be confident that the actual fire risk is <0.75%/yr;
- Second, it is assumed that installation of a fuel break prevents fire from even reaching half of the project area. Essentially this states that a 300 ft wide fuel break will prevent the passage of any wildfire;
- Third, it is assumed that there is no regrowth of trees whatsoever following a wildfire.

The report states that, even with these assumptions with regard to decrease in fire incidence due to the fuel break and the lack of regrowth, there is a break even in terms of emissions in baseline and project cases with an annual fire risk of 0.44% (close to what might be expected for the region).

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[3] If such large-scale prescribed burning were undertaken then through time the benefit would grow as all areas would be treated within the first years and ultimately reduced emissions would result from wildfires in the absence of additional treatment emissions (or at least just with the diminished treatment emissions that arise with retreatment).

7.0 Summary and Recommendations

Discussion/Conclusions

Reducing emissions from fire could be an important contribution to reducing CO_2 emissions overall, yet the reduction of carbon stocks in hazardous fuels treatments, combined with the low annual probability of fire on a given acre of land in the study region of northern California and southern Oregon prevent the generation of viable carbon offsets from such treatments. In the case of the standard fuels treatments for mixed conifer forests in northern California and southern Oregon which served as the field test for this research, treatments clearly led to significant increased net emissions.

Our conclusions may be subject to change in the future if new technologies are developed for fuel removal, energy generation through fuel combustion or enhanced modeling techniques are developed for predicting the location of future wildfires.

Our findings should in no way be read as an argument for halting fuel treatments. Reducing the risk of fire is a critical activity for many other reasons, including enhancing forest health, maintaining wildlife habitat, and reducing risk to life and property, and as such is an activity that must continue though unfortunately without financial support from greenhouse gas emission reduction offsets.

It may be desirable to return forests to a condition that more closely resembles pre-suppression forests. Such forests are likely to experience fewer high severity fires, and therefore release less carbon dioxide in the event of a wildfire. However, achieving these conditions will likely require the short term release of carbon dioxide currently stored as forest biomass. Therefore, it is not likely that this type of management presents a carbon offset project type, but rather a desirable overall management strategy that may lead to lower but more stable carbon stocks.

In addition, in today's world where actions to curb atmospheric greenhouse gas concentrations are growing more urgent, an accurate accounting of all emission sources at national, regional and local scales is important. The work completed here allows a better understanding of the relative emissions that arise from hazardous fuel treatments and wildfires. This may become increasingly important as fire risk is California has been projected to increase between 12 and 53 percent by the end of the century (Westerling and Bryant, 2008). Even though current technologies make it difficult for fuels treatments to lead to net emission reductions, it is important for planners to understand relative greenhouse gas emissions to be able to design treatments in a way that minimizes emissions while maximizing benefits to local populations and forest health and habitats.

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Appendix A:

Brown et al. 2006, *Protocol for monitoring and estimating greenhouse gas benefits from hazardous fuels management in Western U.S. forests*.

See separate attachment.

Appendix B:

Saah, D, T. Moody, E. Waller, E. Newman, M. Moritz. 2010. *Developing and Testing a Framework for Estimating Potential Emission Reduction Credits: a pilot study in Shasta County, California, USA.* Submitted to Winrock as WESTCARB deliverable.

See separate attachment.

Appendix C:

Sandberg, DV (Sam). 2008. *Draft Protocol for Baseline Fire Emissions.* Submitted to Winrock as WESTCARB deliverable.

See separate attachment.

Appendix D:

Oregon State University reports:

Harmon, Mark E., Carlos A. Sierra, and Olga N. Krankina. 2007. *Rates of Decomposition o fWoody Debris in WESTCARB Region.* Department of Forest Science, Oregon State University. Submitted to Winrock as WESTCARB deliverable.

Krankina, Olga N., Carlos A. Sierra, and Mark E. Harmon. 2007. *Modeling Study of Carbon Dynamics for Selected Treatments of Forest Fuels in Southern Oregon.* Department of Forest Science, Oregon State University. Submitted to Winrock as WESTCARB deliverable.

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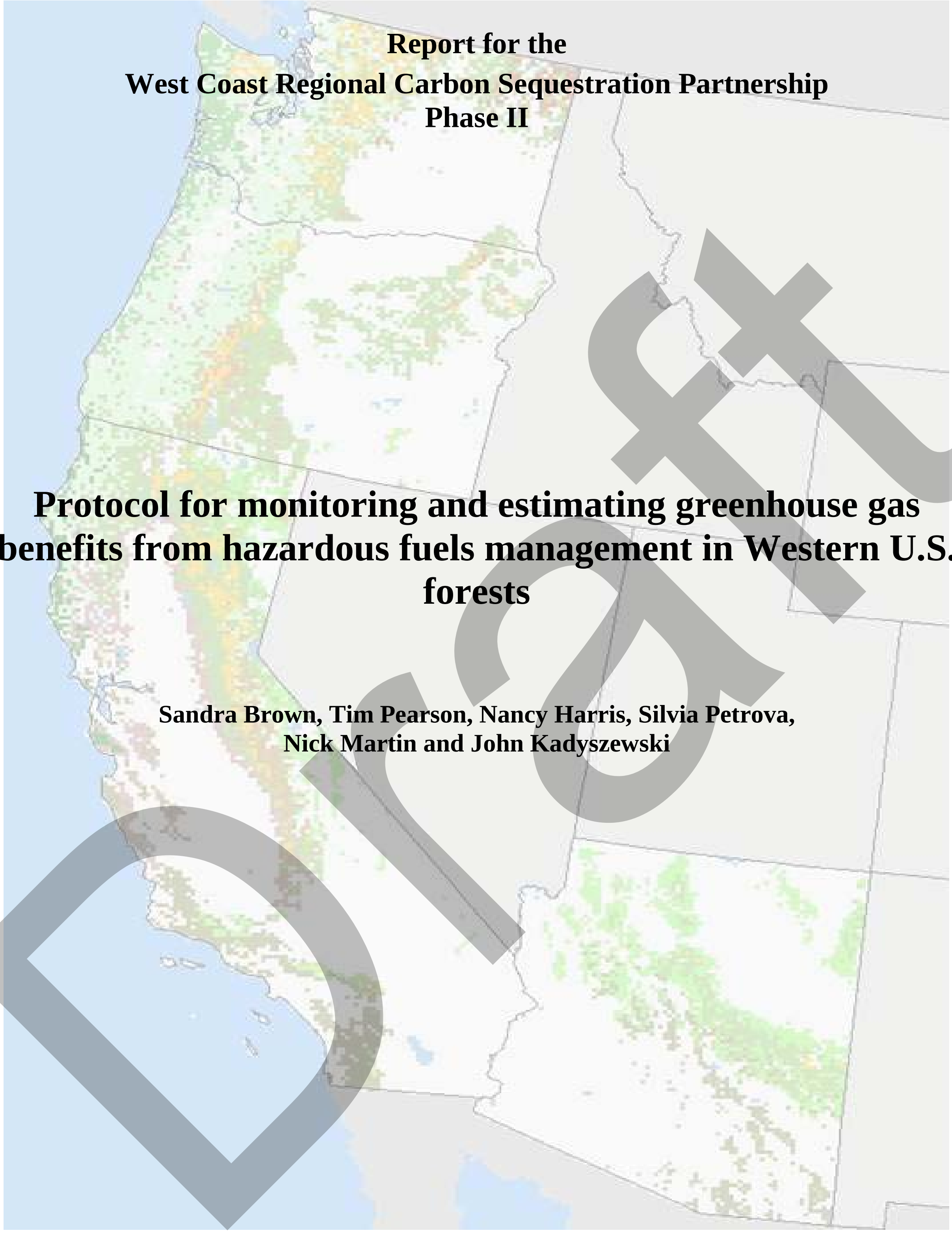

Report for the
West Coast Regional Carbon Sequestration Partnership
Phase II

Protocol for monitoring and estimating greenhouse gas benefits from hazardous fuels management in Western U.S. forests

**Sandra Brown, Tim Pearson, Nancy Harris, Silvia Petrova,
Nick Martin and John Kadyszewski**

Submitted by
Sandra Brown and John Kadyszewski, Co-Principal Investigators
Winrock International

Table of Contents

Overview

This paper introduces key concepts and provides an approach for developing baseline, measuring and monitoring methodologies as part of a protocol for estimating potential greenhouse gas benefits from improved fuel management programs in western U.S. forests. First, we outline what is needed and provide our preliminary approach and calculations. We then discuss the specific factors involved in our approach, and introduce several ***key questions and uncertainties*** that will guide discussions at the WESTCARB Fire Workshop (Redding, October 24-25, 2006).

Tables

Figures

SECTION 1: General Approach

1.1 What is needed and why?

Our goal is to develop a **cost-effective, practical, transparent protocol** for estimating, to acceptable levels of accuracy and precision, the carbon benefits associated with improved management of hazardous fuels in forests susceptible to wildfires. We assume that fuels management activities would be executed by private or public landowners as specific "projects" that would occur over finite areas while remaining embedded in the larger surrounding landscape.

Developing protocols for project activities that are designed to **reduce or avoid emissions** of greenhouse gases present several major challenges, the main one being the baseline. The reason for this challenge is that the baselines for such projects, by their very nature, are projections into the future of what would happen, and generally what would happen in the future is based on what has happened in the past. For the project type presented here, there is potentially a greater challenge because of the very nature of fires—they are unpredictable. The key for developing the protocols is to recognize that the baseline will never be perfect, but that an agreed on methodology can be reached using the best science available.

Like some other types of forestry projects implemented for carbon credits, the development of a fuels management protocol will likely require the collection of project-specific data. Assumptions and default factors will be warranted in cases where collecting data is cost-prohibitive and/or the project is overly complex (such as for the development of the baseline methodology, outlined below). The use of default values is common practice under both national and international accounting guidelines, but it is essential that these assumptions remain both conservative and transparent.

Improved fuels management can reduce losses of carbon stocks from forest ecosystems; reduce the areal extent of burning; reduce fire severity; increase carbon sequestration in residual forest stands; and increase substitution of forest fuels for more carbon-intensive fossil fuels – all which lead to potential **greenhouse gas benefits**. These benefits are estimated as the difference in selected carbon pools between a "baseline" case and a "with project" case, with various fuel reduction treatments as project scenarios. Other greenhouse gases to consider in addition to carbon dioxide might include methane (CH_4) and nitrous oxide (N_2O).

For example, **Figure 1** illustrates how the carbon that would burn in a "business as usual" case (hatched box) might be diverted into a fuel reduction treatment plan (gray box) to reduce the severity of catastrophic wildfires and their associated carbon emissions. Removing hazardous fuel loads before they burn would lead to less intense fires and would thereby cause a larger unaffected vegetation pool. This pool would need to be managed continuously to prevent the excessive buildup of new fuels, but resources allocated towards suppressing fires could be re-directed towards preventing them through better forest management. Because fuels removed from forests could be transported to biomass energy plants and burned as alternative energy sources to fossil fuels, landowners could potentially generate two streams of revenue: dollars from selling carbon credits and dollars from selling biomass.

The focus of this protocol will be on elucidating the carbon benefits that arise from decreasing the extent of fires and the emissions from fires within project boundaries. Project emissions will include the emissions associated with fuel treatment including cutting, transporting and burning of fuels.

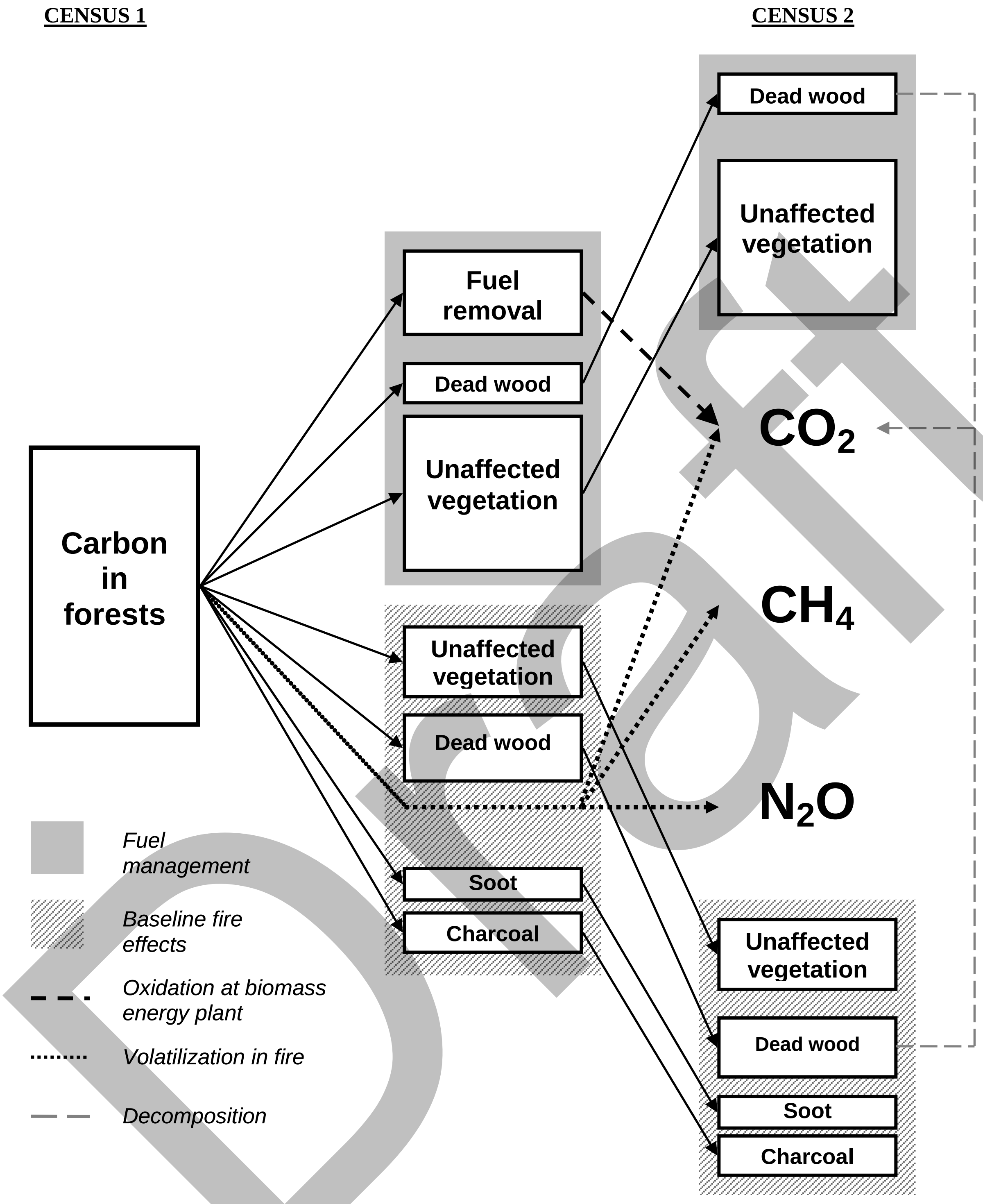

Figure 1. The fate of carbon in forests under baseline (no fuel management) and with-project (with fuel management) scenarios. The goal of a fuel management program would be to divert carbon that would ordinarily burn in a fire (hatched box) towards a program involving fuel removal (gray box). The fate of the fuels removed would depend on the specific treatment; this figure shows fuel removed and transported to a biomass energy plant. Such a management program would result in less intense, less severe fires and a larger pool of unaffected carbon.

1.2 Approach to calculations

Baselines are used as a reference case to estimate the emissions and removals of greenhouse gases attributed to changes in the use and management of land. Baseline scenarios are defined by projecting and quantifying the carbon emissions of a "business as usual" approach to forest management, i.e., the emissions that would occur if current management practices were to continue into the future. In this case, the baseline is related to the likelihood that a fire event would occur at any given location as well as the net carbon, as CO_2 (and potentially other non-CO_2 greenhouse gases such as methane and nitrous oxide), that would be emitted during a typical fire event. A carbon baseline has three components: (1) **a projection of the area** of the forest that burns over a given time frame**,** (2) the change in forest **carbon stocks and associated GHG emissions** resulting from the fire (e.g., Census 1 and Census 2 in Figure 1), and (3) the **pre-fire and post-fire rates of carbon accumulation** in the forest. Each of these can be addressed separately.

The **with-project case** is the net emissions of carbon resulting from project implementation. In the case of fuels management, projects would involve treatments that would reduce the quantity of hazardous fuels. The difference between this "with-project" value and the baseline value would then be calculated as the **carbon benefit** (Figure 2). Initially, net carbon emissions may increase temporarily as a result of project implementation, but these emissions would be offset by the treatment effect.

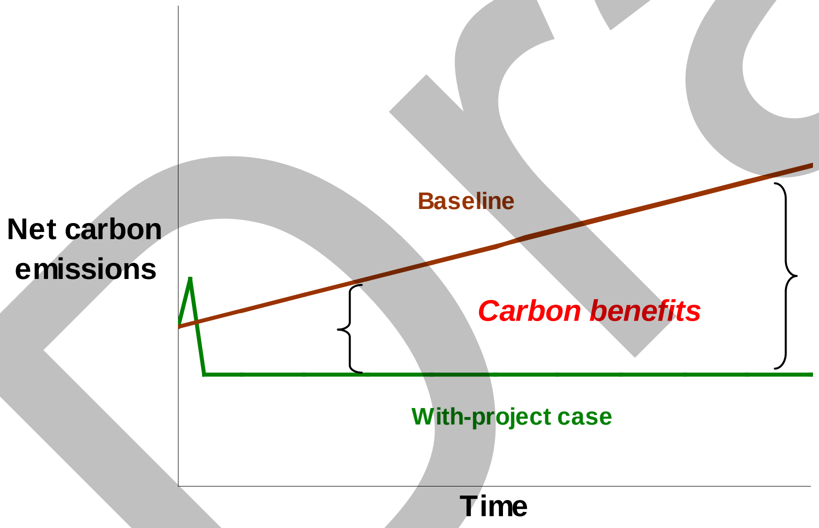

Figure 2. Hypothetical baseline emissions, with-project emissions, and the resulting carbon benefits from changes in management of the land.

1.2.1 Potential calculations

The carbon benefits of fuel reduction activities *could* be estimated as follows:

A. Baseline Emissions

1. Determine the project area (areas of treatment)
2. Stratify lands by age class and fuel load
3. Measure the fuel loads on project lands for each age class stratum

4. Estimate the mean forest carbon stock based on standard protocols procedures (existing within the CA Climate Action Registry [CCAR])
5. Obtain an estimate of the baseline area burned per year from "registry" tables (to be established specific to this methodology) for most recent past 10-yr period and assume fixed for future 10-yr period
6. For each stratum, solve the following equations, then add together for total baseline emissions:

$$BE = BE_{CO_2} + BE_{CH_4} + BE_{N_20} \pm BE_R$$

$$BE_{CO_2} = \sum_{1}^{n} A_n \times \left(C_n \times F_n\right) \times 3.67$$

where:

BE = Baseline emissions (t CO_2-e/ 10 yr)
BE_{CO2} = Baseline carbon dioxide emissions (t CO_2-e/ 10 yr)
BE_{CH4} = Baseline methane emissions (t CO_2-e/ 10 yr)
BE_{N2O} = Baseline nitrous oxide emissions (t CO_2-e/ 10 yr)
BR_R = Emissions/removals of carbon dioxide due to the differential pre- and post-fire effects on rates of carbon accumulation (t CO_2-e/ 10 yr)
A = Area burned =percent per year (ha/yr) x area of treated strata n x 10 years
C = Carbon stock in age class n (t C/ha)
F = fraction of initial carbon stocks lost to fire in age class n and fuel load n (from Table 3)

7. Repeat analysis every 10 years for duration of "project" (could extend for several decades) to reassess the rate of emissions as a result of new treatments, regulations, climate change scenarios, etc. – or just develop updated baselines if management conditions have remained unchanged.

B. Project Emissions

1. Track biomass of fuels removed from forest
2. Track any fires that occur during the project period on the project lands. Measure carbon stock in all pools immediately after any fire.
3. For each stratum, solve the following equation then add together for total project emissions.

$$PE = FE + FTE + EE \pm RE$$

where:

PE = Project carbon emissions (tCO_2-e)
FE = Emissions from any fires that occur on project lands (tCO_2-e)
FTE = Emissions that occur due to fuels treatment (tCO_2-e)
EE = Emissions that occur due to transport and/or combustion of fuels (tCO_2-e)
RE = Emissions/removals due to the differential pre- and post-treatment effects on rates of carbon accumulation (tCO_2-e)

C. Project Benefits

In any given year, project benefit is equal to average annual baseline emissions minus project emissions.

$$PB = BE - PE$$

where:
BE = Baseline carbon emissions (t CO_2-e)
PE = Project carbon emissions (tCO_2-e)

SECTION 2: Baseline

2.1 Background

The WESTCARB II project focuses on terrestrial sequestration pilot activities in two counties: Shasta County, CA, and Lake County, OR (to facilitate early protocol development Shasta County will initially be the sole focus). Although there are several different forest types in these counties, for initial protocol development we focus on the **mixed conifer forest type** (including ponderosa pine, mixed conifer, etc.[1]) found typically in large parts of southern Oregon and northern California. We selected this general forest type based on Schoennagel et al. (2004), who proposed that western forests at **low and mid-elevations** that historically had low to mixed severity fires are good candidates for fuel treatments to restore their historical stand structure and fire regimes.

Historically, the surface fuel layer of low-elevation, ponderosa pine forest were dry during the summer fire season that resulted in frequent and low-intensity surface fires. More recently, fire suppression activities have disturbed this historical fire regime and have resulted in a build-up of ladder fuels at intermediate heights that carry surface fires into the crown, where they can lead to large, catastrophic fires. Mixed-intensity fire regimes occur mostly at mid-elevations, in mixed conifer forest stands defined by a mixture of tree species and densities. The frequency, severity and size of fires in these forests are affected by fuel accumulation and climate, and the impact of suppression practices on fuel loads in these forests varies depending on the tree composition of the forest stand.

2.2 Estimation of area that would burn

The area component of the baseline is a projection into the future of the likely area that would burn in a fire. This raises two key issues:

What should be the spatial scale?
And what should be the temporal scale?

The **spatial scale** needs to be large enough to capture the trend, but not so large that it masks more localized trends caused by differences in state and county-level regulations that govern forest management practices, human demographics and infrastructure, boundaries related to policies, variation in climate and precise species composition. After looking at various scales, we decided to use the two California Department of Forestry **CA-FRAP** (California Fire and Resource Assessment Program) northern California analysis units: **Cascades Northeast** and

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[1] The mixed conifer forest type contains the following WHR types: Sierran mixed conifer, Klamath mixed conifer, ponderosa pine, eastside pine and jeffrey pine.

North Coast. (Figure 3) We also stratified the forests by land ownership class (publicly and privately owned) to reflect differences in management practices, and suggest developing separate carbon baselines for public and private lands to account for these differences. We expect a similar approach could be used, with some modifications, for forests in the remainder of the WESTCARB region.

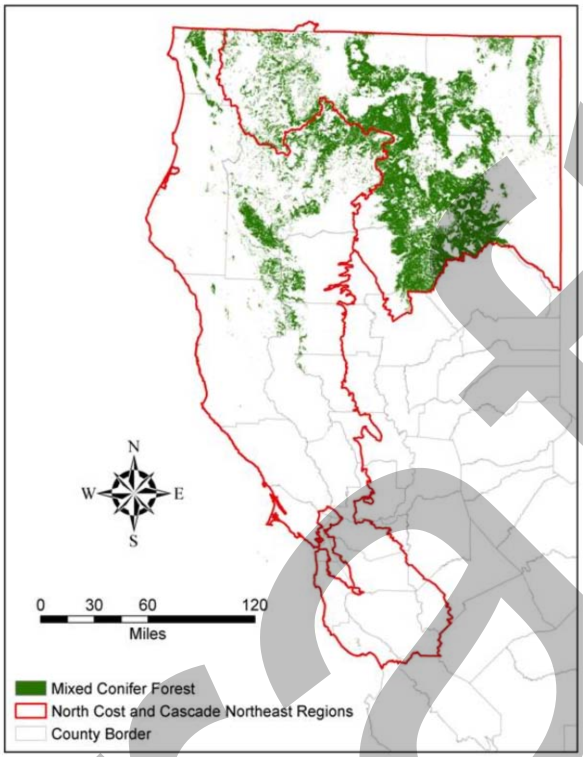

Figure 3. Distribution of mixed conifer forest across the North Coast and Cascades Northeast regions based on the California Land Cover Mapping & Monitoring Program

For the **temporal scale**, the question is: how far back in the historical record does one go to develop a trend for projecting into the future? How far into the future? In many respects, developing an estimate for the area component of the baseline is akin to developing baseline estimates of avoided tropical deforestation. After extensive investigation and model-testing, Brown et al. (2006) concluded that a reasonable and reliable estimate of the rate of deforestation could be obtained from change detection of remote sensing imagery over a recent **past period of about 10 years**. This 10-year rate is then expressed as an average percent of the forest remaining (area deforested over the about 10-year period divided by total area at the beginning of the period, expressed in percentage terms).

Future rates of deforestation, like fire, can be hard to project because they are subject to many factors. However, in the case of deforestation, a general consensus is developing that the rate of deforestation can be reliably projected about **10 years into the future**, with reassessments occurring every 10 years thereafter to adjust the baseline area component. We propose that these time periods could also be appropriate for fire baselines as this time frame is long enough to incorporate natural variations in forest dynamics among years, but also reflects the more recent forest management situation upon which other scenarios will be based.

Using the forest class map and fire data from CA-FRAP (California Fire and Resource Assessment Program), the area of mixed conifer class in the Cascades Northeast and North Coast counties is about 4.6 million acres, with the majority of this area as public land (2.7 million acres, or 58%) and 1.9 million acres (42%) as private land. The total area of forests that have burned in the last 10 and 20 years is 110,776 ac and 283,801 ac, respectively (Table 1, Fig. 4), with approximately 80% of this area burned on public lands in the last 10 years. It is clear from Fig. 4 that many large fires that occurred in this region were <u>not</u> located in the mixed conifer forest type.

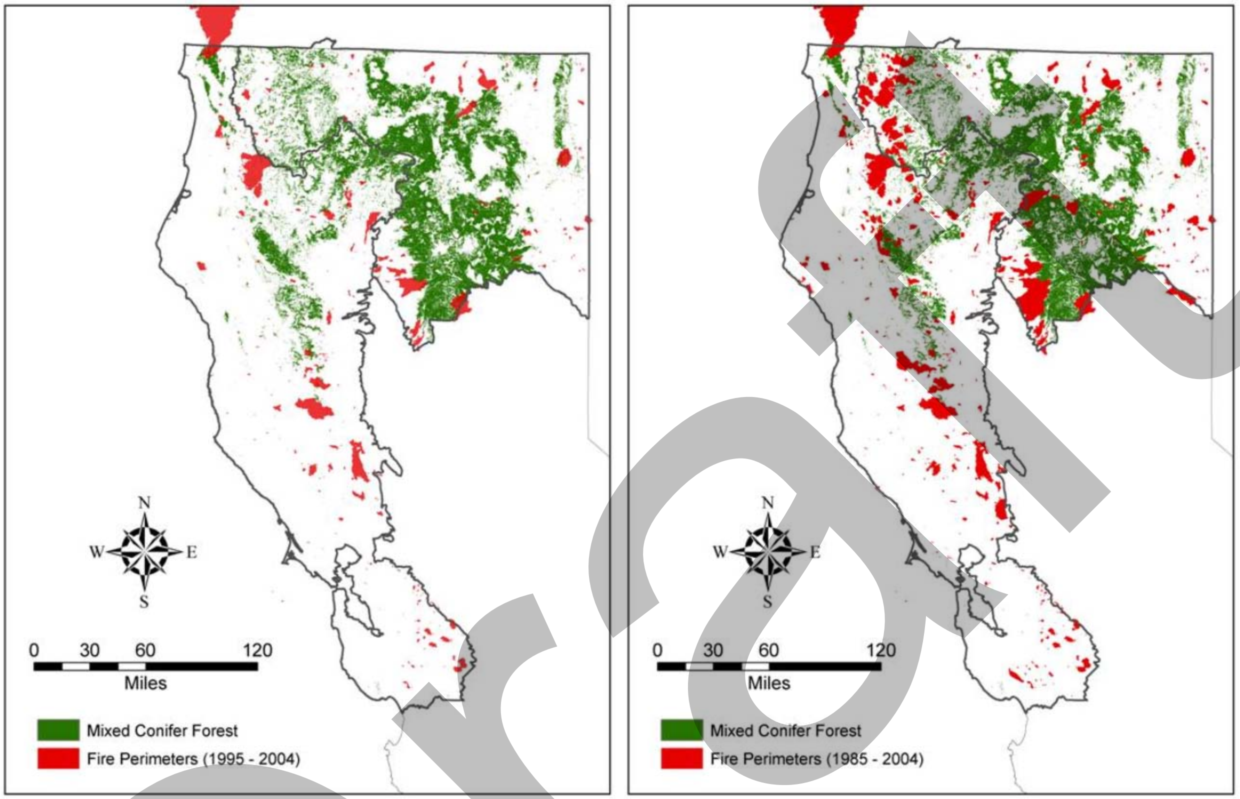

Figure 4. Distribution of mixed conifer forest and fire perimeters for 10-yr period (left) and for 20-yr period (right) across the North Coast and Cascades Northeast regions of the California Land Cover Mapping & Monitoring Program

Table 1. Area of mixed conifer forests that burned in the Cascades Northeast and North Coast analysis regions of CA between 1985 and 2004 (data from CA-FRAP)

Year	1 **Area (ac)** Public	2 **Area (ac)** Private	1 **Percent** Public	2 **Percent** Private
1985	1,863	367	0.070	0.019
1986	129	393	0.005	0.021
1987	83,344	4,272	3.116	0.224
1988	1,976	4,881	0.074	0.256
1989	400	379	0.015	0.020
1990	4,505	15,175	0.168	0.795
1991	314	818	0.012	0.043
1992	5,132	41,741	0.192	2.188
1993	81	1,013	0.003	0.053
1994	5,241	1,001	0.196	0.052
1995	103	0	0.004	0.000
1996	7,342	392	0.275	0.021
1997	79	39	0.003	0.002
1998	3,836	1,020	0.143	0.053
1999	13,670	5,547	0.511	0.291
2000	20,959	4,757	0.784	0.249
2001	16,906	4,345	0.632	0.228
2002	19,895	2,272	0.744	0.119
2003	1,988	3,016	0.074	0.158
2004	2,809	1,799	0.105	0.094
Total 20 years	190,573	93,228		
Total 10 years	87,588	23,188		

Table 2. Ten year average annual percentage of the total mixed conifer forest area burned in the Cascades Northeast and North Coast analysis regions of CA (data from CA-FRAP)

	Annual percentage	
	Public	**Private**
1985-1994	0.385	0.367
1986-1995	0.378	0.365
1987-1996	0.405	0.365
1988-1997	0.094	0.343
1989-1998	0.101	0.323
1990-1999	0.151	0.350
1991-2000	0.212	0.295
1992-2001	0.274	0.314
1993-2002	0.329	0.107
1994-2003	0.337	0.117
1995-2004	0.328	0.122

Based on the data in Table 2, the average baseline area burned in the 10-yr period 1995-2004 in the region is 0.12%/yr for private lands and 0.33%/yr for public lands. Both Tables 1 and 2 illustrate the annual variation in area burned and the impact of catastrophic fires on the annual percentage. The integration of ten years worth of data, however, moderates the impact of catastrophic fires and captures trends in fire incidence (Table 2).

We propose that the area component of the baseline be developed collaboratively between the state Department of Forestry and the relevant US Forest Service units within the state. We envision that the **baseline for area burned will be expressed as an annual percentage for the most recent past 10-year period, and projected forward for the next 10 years**. Lookup tables could provide these projections as values (rates) for each agreed-upon subregion/forest type within the state for a given 10 year period, and could be modified annually to produce updated values. One could imagine that, if indeed landowners became engaged in this type of project for carbon benefits, a project registry could provide the baseline rate of area burned by a "vintage year", which would then be applicable for the next 10 years of the project.

TOPIC 1: Questions, issues and uncertainties for the area baseline:

1. How many years to include in project baseline calculations?
2. Should we separate by forest type and regions within a State?
3. Or should it be by all forests within a region of a State?
4. Are the LCMMP regions a reasonable way to aggregate forests to reflect the factors that affect fire (climate, humans, etc.)?
5. Or should it just be by forest type and State?
6. Is the grouping of 5 WHR types into a mixed conifer forest type reasonable? (Klamath mixed conifer, Sierran mixed conifer, ponderosa pine, eastside pine, Jeffrey pine)
7. Is it reasonable to separate public from private lands? Would it make more sense to separate industrial forest lands which will have different fire relations and then lump the remaining private lands with the public lands?
8. Is the method for calculating baseline area sufficient? Or is it necessary to require modeling for every project?
9. Is an index of climate needed as a modifier for the projected area likely to be burned, and if so what index and how used?
10. Should we try to account for the expected reduction in area burned outside of the treated area that results from treatments inside a project areas?

2.3 Estimation of carbon emissions

The **baseline** emissions are basically equal to the **area** that would burn in the absence of the project **multiplied by the carbon emissions** estimated to result from the burned area. **Pre-fire carbon stocks** exist in live and dead standing trees, understory vegetation, litter and downed dead wood; all of these carbon stocks are potential fuel for fire. Historically, in the mixed conifer forest type, fires would pass through the understory relatively quickly and consume downed dead wood, understory vegetation, and litter. One hundred years of fire suppression has led to a growth in the stocks of all potential fuels. In particular, **tree density has increased** so that young trees can carry fires directly into the canopy of the forest (ladder fuels), and understory vegetation and dead wood stocks have grown so that flame lengths can threaten the canopy.

Pre-fire carbon stocks have five potential endpoints during and after a fire (Figure 1). The first proportion survives the fire to continue as live vegetation, a second proportion is volatilized during the fire and immediately released to the atmosphere, and the remainder is divided between pools of dead wood, soot and charcoal. Soot and charcoal are stable forms of carbon and can remain virtually unchanged for long time periods, while dead wood releases the stored carbon gradually into the atmosphere as it decomposes. The amount of carbon that transfers to these various forms during a fire depends upon a variety of factors, including the quantity of fuel (relative to the carbon stocks in non-fuel tree vegetation), its moisture content, and prevailing weather conditions.

The question becomes: what data are needed to develop the carbon stock component of the baseline that is specific to a particular parcel of land? It is assumed that the resulting **changes** in the forest carbon stocks and thus C emissions due to a fire are related to the **quantity of fuel** on the land and the **initial carbon stock**. For a similar relative amount of fuel (and all else equal), it is assumed that a young forest with low carbon stocks will suffer a greater proportion of loss in carbon stocks after a fire than an older forest with higher carbon stocks.

To quantify the impact of fire on changes in carbon stocks and the resulting C emissions, we propose using tables for both land ownership types (public vs. private) that contain values for the fraction of initial carbon stocks burned and emitted as CO_2. These values would vary as a function of **fuel load** (3-5 classes, assuming, initially, all exist under dry climatic conditions) and **forest age class** (**Table 3**).

A significant proportion of the live pre-fire carbon stocks will remain as dead wood post-fire. Under normal, non-fire conditions, carbon in dead wood is released gradually into the atmosphere through the process of decomposition. During a fire, however, it is likely that all stocks of dead wood will be consumed by the fire and all dead wood that remains after the fire is the result of recently-killed vegetation. To simplify the accounting, we could assume that the carbon in any dead wood that remains after the fire would also be emitted at this time. **(**This is similar to the assumption used in the IPCC national greenhouse gas inventory methods for carbon accounting of harvested forests.)

The values (as fractions) in Table 3 represent the fraction of the initial carbon stock emitted as CO_2 and is calculated as the sum of all aboveground biomass components (live and dead) that are oxidized during the fire *and* the biomass of the fire-killed dead wood that remains after the fire, divided by the pre-fire total aboveground carbon stocks. Filling in the values in Table 3 would rely on the literature, other studies from WESTCARB partners, output from stand/fire models, and new field data. The goal of a fire management program would be to move up Table 3 by reducing fuel loads from high (or medium) to low so that a lower proportion of existing forest carbon stocks are burned by fire.

Table 3. Sample table for calculating the fraction of initial carbon stocks emitted as CO_2 resulting from a fire, as a function of fuel load (low moisture conditions) and forest age. Two such tables would be developed, one each for public and private lands.

Fuel load	**Age Class (yr)**					
	0-20	21-40	41-60	61-80	81-120	121+
1 – Low						
2						
3 - Medium						
4						
5 – High						

The impact of fire on the changes in carbon stocks is not only a function of fuel load and age class—the **moisture condition** of the fuel (related to precipitation and temperature conditions) is also a key determinant of how much of the biomass will burn on site during a fire. For example, a high fuel load with low moisture content will lead to a more severe fire than the same fuel load that is moist. The moisture condition of the fuel will also affect how the fire burns (flaming vs. smoldering) and consequently the relative emissions of methane and nitrous oxide (each with higher global warming potential than CO_2).

How non-CO_2 greenhouse gases will be included and whether airborne soot should be included as a carbon dioxide equivalent will rely on the output of the workshop, on the literature, other studies from WESTCARB partners, and on output from stand/fire models.

An additional baseline consideration is **rate of carbon accumulation in the forest pre-and post-fire**. Pre-fire rates are related to several factors such as species mix, age, management, etc. Post-fire carbon accumulation rates are strongly influenced by factors such as fire intensity (heat of burning), fire severity (extent of burning), soil moisture conditions, nutrient availability, availability of seed sources, etc.

Carbon accumulates during regrowth after a fire, and the rate depends, in large part, on the fire's severity (Figure 5). A severe fire that burns through the entire canopy would likely have a slower rate of post-fire carbon accumulation than a less severe surface fire that leaves a majority of the vegetation intact. On the other hand severe fires increase light and soil nutrients for regeneration, reduce competition for water resources (but reduce the organic carbon base in the soil for regenerating seedlings). Severe fires may lead to an arrested succession whereby a dominant understory species such as manzanita prevents tree reestablishment or where soil conditions are altered to the point where the site is not immediately suitable for seedling establishment at all.

How to incorporate the differences in rates of carbon accumulation resulting from different intensities of fire? Three possible conditions exist: (1) pre- and post-fire rates of accumulation are the same, (2) pre-fire rates are greater than post-fire rates (severe fire), and (3) pre-fire rates are less than post-fire rates. If the pre- and post-fire rates of C accumulation are the same (condition 1), then there is no impact on the baseline as the removals of CO_2 from the atmosphere are the same. For condition (2), the pre-fire forest was removing more CO_2 from the atmosphere than the post-fire forest, thus the baseline net emissions of CO_2 due to the fire need to be increased by the difference in the rates. For condition (3), the post-fire forest is now removing more CO_2 from the atmosphere than the pre-fire forest, thus the baseline net emissions of CO_2 due to the fire need to be decreased by the difference in the rates. Thus in essence is it only the differential rate of carbon accumulation during the post fire situations that needs to be known.

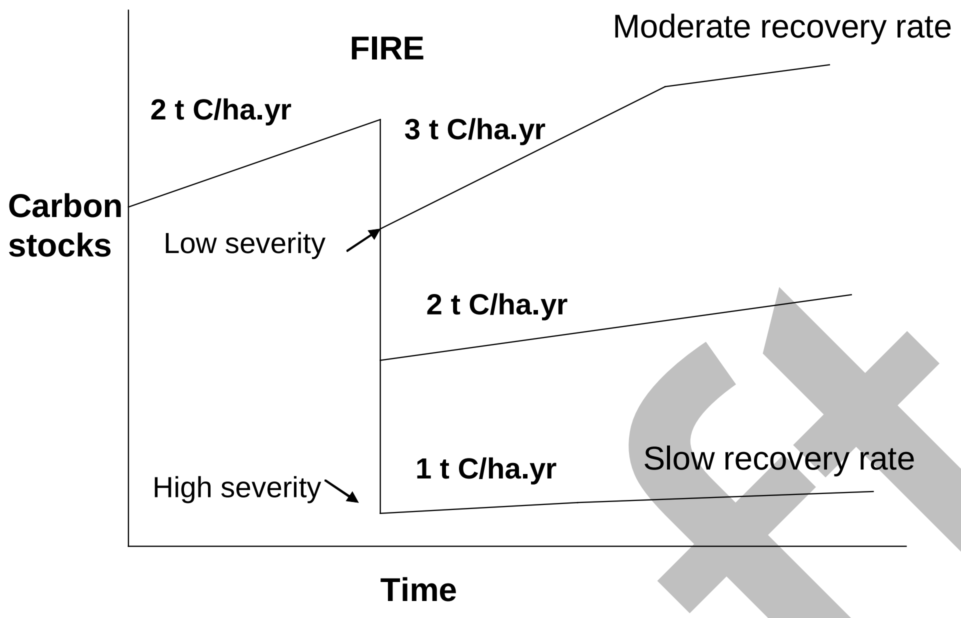

Figure 5. Illustration of hypothetical time course of carbon stocks in a forest stand pre-fire and after fires of various severities. Values on the lines are hypothetical rates of carbon accumulation pre- and post-fire

To illustrate the effects of the pre-and post fire rates of C accumulation discussed above, we use the hypothetical graphs in Fig. 5. For condition (1), the pre- and post-fire rates are the same at 2 t C/ha.yr; there is no difference in the rates of CO_2 uptake from the atmosphere and thus this component of the baseline can be ignored. For condition (2), pre-fire rate is 2 t C/ha.yr and the post-fire rate is 1 t C/ha.yr, and the difference is 1 t C/ha.yr (pre minus post). This means that the pre-fire forest was removing 1 t C/ha.yr more from the atmosphere than the post-fire forest. Thus the baseline net emissions caused by the fire is the gross emissions **plus** an amount equal to the product of the projected area that would have burned and the 1 t C/ha.yr difference in regrowth rate over the 10-yr time interval (assumed duration for the area-burned baseline component). For condition (3), the pre-fire rate is 2 t C/ha.yr and the post-fire rate is 3 t C/ha.yr, and the difference is -1 t C/ha.yr (pre minus post). In this case the post-fire forest is removing more CO_2 from the atmosphere than the pre-fire forest. The baseline net emissions are now the gross emissions from the fire **minus** the product of area projected to be burned and the 1 t C/ha.yr difference in regrowth rate over the 10-yr time interval.

TOPIC 2: Questions, issues and uncertainties for the carbon stock baseline:

1. How should ‘hazardous fuel’ be defined?
2. Where should boundaries be set in terms of fuel loads?
3. Is age class an appropriate method to classify the forest, and if so, where should boundaries be set in terms of age classes?
4. Should the age class categories in Table 3 be replaced by carbon stock categories?
5. How could fuel moisture condition be incorporated into the baseline calculations in a credible manner without producing an overly complex set of calculations?
6. How can we calculate CH_4 and N_2O emissions? Can we and should we do better than IPCC defaults?
7. Should the greenhouse impact of airborne soot be considered? How could this be quantified?
8. How should the differential rates of carbon accumulation between pre- and post-fire conditions be treated? Over what time interval?
9. To what extent are fuel treatments happening on public and private lands currently? And should we consider them as part of the baseline?

SECTION 3: With-Project Carbon Benefits

Once the baseline has been developed and projected, the next steps involve measuring and estimating the change in carbon stocks and resulting C emissions resulting from the treatment. Then the carbon benefit that could be “credited” to the activity is the difference between the baseline projection over an agreed-upon time frame (e.g. 10 years) and the actual C emissions monitored and estimated from applying fuel treatments on specific areas of land. In the baseline case, the C emissions are estimated from a projected percentage of the project area burned. However, in the with-project case, it is expected that the whole project area will need to be treated to claim that the occurrence of severe fires has been reduced. A first step then is to assess what types of fuel treatments make sense for such projects.

3.1 Treatment considerations

Several potential hazardous fuel reduction (HFR) treatments are available to reduce fuel loads in forests and to decrease severity of potential fire. Each of these treatments have different applications, constraints, costs, yields of merchantable and submerchantable material, revenues, air quality impacts, ground impacts and greenhouse gas emission impacts (**Table 4)**.

The important question will be to define what minimum level of treatment will be required in order to qualify the HFR treatment as producing a benefit relative to the baseline and thus eligible for crediting.

Table 4. Benefits, constraints and representative costs for hazardous fuel removal (HFR) treatments.

Fuels reduction treatment	Biomass product yield	Benefits	Constraints	Representative costs ($/acre)
R_x fire	No	Re-introduces fire	Air quality, ground impacts, fire escape, seasonal restrictions, immediate CO_2 emissions	35-300;average 92
Masticate – leave on site	No	Efficient, useful for less accessible sites	Leaves fuel on site, gradual CO_2 emissions	100-1,000
Cut-pile-burn	No	Can be used on less accessible or steep sites	Leaves fuel on site, air quality, immediate CO_2 emissions	100-750
Cut-lop-scatter	No	Can be used on less accessible or steep sites	Leaves fuel on site, gradual CO_2 emissions	105-280
Cable yarding for biomass removal	Yes	Can be used on less accessible or steep sites	Expensive, ground impacts	$80-130/CCF*
Cut-skid-chip-haul (for submerchantable biomass)	Yes	Removes fuel from site; some product value; allows renewable energy generation; greatest CO_2 benefit	More expensive; limited to gentler slopes, areas closer to roads for removal, limited haul distance to biomass plant	$34-48/BDT* + haul cost $0.35/BDT. mile $560-1,634/acre

CCF= 100 cubic feet; BDT = bone dry tons

3.2 With-project carbon emissions and removals

Implementing a hazardous fuel treatment results in carbon emissions to the atmosphere from several sources:

- Emissions resulting from the burning of fossil fuel by harvest equipment used in cutting and removing biomass, and emissions from transporting biomass to a power plant if this type of treatment is implemented.
- Emissions from the decomposing biomass fuel if left on site.
- Emissions from burning the biomass fuel either the piles left on site or in a power plant. If done in a power plant, the biomass fuel burns more efficiently than in an on-site fire, producing less soot, charcoal, and non-CO_2 GHG.

The treatment is also likely to have an effect on the rate of carbon accumulation of the treated forest, and as with fire the effect could cause the rates to increase, decrease, or be no different from the pre-treatment forest (see discussion above in relation to Fig. 5).

Unlike the baseline case, most of the emissions and removal will be monitored and estimated as would be required of any registry. The only variable that could not be readily monitored and estimated is the pre-treatment rate of carbon accumulation (also the pre-fire rate in the baseline).

However, using e.g. tree cores, well parameterized models, and other data, it is possible that acceptable rates of pre-treatment carbon accumulation could be estimated with a desired precision and accuracy (however, as illustrated in Annex 1, it is possible that knowledge of the pre-treatment and pre-fire fire rate of carbon accumulation is not needed).

3.3. Steps for monitoring a carbon project

To participate in a fuel management program, we propose the following conservative requirements for project monitoring:

1. Assume benefit for 10 years after treatment
2. Benefit only possible for treated areas
3. Re-treatment possible after 10 years for continued benefit (new baseline must be applied every 10 years
4. A minimum (as yet undefined) level of treatment is required to qualify for benefits relative to the baseline
5. Measurement required of all carbon pools immediately after fuels treatment
6. Measurement required of biomass of all fuels extracted from the forest
7. Tracking required of vehicle usage for fuels transport
8. Measurement required of any fires that occur in the project area and stocks remaining after fire.

TOPIC 3: Questions, issues and uncertainties for calculating project carbon benefits:

1. What is the minimum level of treatment that should be required to qualify for carbon benefits?
2. Is it reasonable to give benefit for 10 years following initial treatment? Is this too generous or too conservative?
3. Is there any way to consider benefits that arise beyond the project boundaries?
4. What treatments should be considered for hazardous fuel management?
5. Which treatments are most commonly used?
6. Which treatments are most profitable, in terms of both dollars and carbon benefits?
7. How long does the impact of fuels treatment last? Is the ten year constraint before re-treatment appropriate?

SECTION 4: General Considerations on Methodology

TOPIC 4: General questions, issues and uncertainties for methodology:

1. Is the approach taken here conservative to the point where it is hard for a project to receive benefit for the genuine good its treatments have caused?
2. What is the balance between being conservative so as not to over-credit and reflecting genuine decreases in fire extent and fire severity?
3. What is the balance between creating a simple methodology that can be applied by someone without great experience, and accurately capturing on the ground impacts?
4. Should we allow the option of using more complex methods (e.g. modeling) to quantify benefits if capacity exists (the concept of using a tier approach for such activities does exist in national accounting methods)?

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Annex 1

Here we illustrate how it may not be necessary to know what the pre-treatment and pre-fire rates of carbon accumulation are (for the baseline and with project cases, they are the same value). In the baseline and with project equations given in section 1.2.1 A and B the following terms are included:

BR_R = Emissions/removals of carbon dioxide due to the differential pre- and post-fire effects on rates of carbon accumulation
RE = Emissions/removals due to the differential pre- and post-treatment effects on rates of carbon accumulation

The term BR_R can be expressed as equal to CB-CP, where CB= background carbon accumulation rate pre fire and CP = carbon accumulation post fire.

The term *RE* can be expressed as equal to CB-CT, where CB is the same background carbon accumulation rate as pre fire or in this case pre treatment (the same forest in both cases) and CT is the carbon accumulation rate post treatment.

The carbon benefits are the difference between the baseline emissions and the project-case emissions. When simplifying the two equations representing the baseline and project emissions, the terms for BR_R and *R*E can be replaced by
(…baseline emissions eq.………+CB-CP) – (…project emissions……+CB-CT)

Simplifying this, the term CB drops out and one only needs to know the difference in the rate of carbon accumulation post fire and post treatment. Post treatment would be measured, but post fire would have to be modeled. However, this discussion does show that at least knowledge of one quantity is not needed for the fire methodology.

APPENDIX B

Developing and Testing a Framework for Estimating Potential Emission Reduction Credits: a pilot study in Shasta County, California, USA

Submitted to
Winrock International

In fulfillment of Contract #: 5619.1FM.-08-01

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March 21, 2010

Executive Summary

To assist Winrock International in establishing a rigorous approach for emissions reduction credits (ERCs), Spatial Informatics Group, in conjunction with the University of California, is developing a methodology that that uses scientifically based models for predicting changes in fire behavior and related emissions, both with and without hazardous fuels reduction treatments. To make these predictions, our report focuses on the development and testing of four elements in this framework: fire probability mapping, delineation of firesheds, choice of a fuel classification standard, and a baseline fire hazard assessment (without fuels treatments). This work was largely performed as a pilot study using data from Shasta County, California, USA. Long-term fire probability maps were developed for Shasta County using Maxent, a recently developed probabilistic distribution modeling tool. These maps can be used to calibrate ERC analysis, and they also serve as inputs into other elements of the framework. A total of 45 firesheds were delineated for Shasta County using an analysis of spatial distribution of fuels, weather, topography, potential fire behavior, and fire risk in a multivariate clustering model. Various fuel classification systems were considered for use in the ERC framework, with the fire behavior and FCCS formats standing out as the most appropriate. Emissions estimates were made for Shasta County using mapped FCCS fuel models and for four areas in the Sierra Nevada using fire behavior fuel models, demonstrating the feasibility of using these models in an integrated manner for the framework. A baseline fire hazard analysis was also performed, after generating mapped fire behavior characteristics for the current landscape in Shasta County under a historically severe fire weather scenario.

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1. Introduction

The western U.S. has millions of acres of forestlands in overstocked condition and at risk of catastrophic wildfire. Reduction of unnaturally high fuel loads is a primary component of the National Fire Plan, the Healthy Forests Restoration Act, and other planning efforts such as the Sierra Nevada Forest Plan Amendment. Central to the economics of fuels reduction is the ability to remove and use forest biomass for higher value purposes. One strategy for changing the economics of fuels treatments is to sell emission reduction credits (ERCs), some of which may be derived from reducing wildfire emissions through forest fuels treatments (e.g. thinning of merchantable and non-merchantable trees, mastication, prescribed fire, etc), and using the resulting biomass waste stream to generate renewable electricity. EPA and those implementing AB32 in California require that ERCs be quantifiable, real, permanent, enforceable, verifiable, and surplus. An integrated approach is therefore needed to objectively quantify emissions generated from wildfires and to ultimately assess the effects of fuel treatments.

To assist Winrock International in establishing a rigorous approach for ERCs, Spatial Informatics Group, in conjunction with the University of California, is developing a methodology that includes scientifically based models for predicting changes in fire behavior and related emissions, both with and without hazardous fuels reduction treatments. The goal is to produce an integrated framework of process-based models to provide localized estimates of relative emissions reductions (i.e. conditional probabilities and emission amounts, contingent on a fire happening in a specific treated area). To perform such an assessment, fuels must be characterized as inputs to fire behavior and emissions models, and the size and shape of the area for fire hazard assessment (i.e. the fireshed) must be identified. The potential for emissions reductions to actually be realized in different locations and vegetation types must also be quantified (i.e. baseline absolute probabilities, from long-term observed relationships between fire and environmental variables that influence regional fire occurrence rates).

The ERC framework being developed consists of several components. Firesheds are delineated as units of analysis. Within a fireshed, baseline (untreated) fire hazard and emissions are estimated. Once potential treatments are defined for a fireshed, fire hazard and emissions are estimated for the treated landscape, accounting for not only changes within a treatment area, but changes due to fire shadow effects. Fire shadow effects are changes in fire behavior and emissions that occur due to treatments, but are outside of treatment areas. Potential ERCs would be based on estimates of pre- and post- treatment fire hazard and emissions. These estimates are modified by the long-term probability of occurrence across the fireshed. Fig. 1 summarizes components of this conceptual framework. This report focuses on the development of four elements of this framework: assessment of long-term fire occurrence probabilities, delineation of firesheds, choice of a fuel classification standard, and a baseline fire hazard assessment. This work was performed as a pilot study using data primarily from Shasta County, California, USA.

Shasta County, in north-central California, spreads across the northern Sacramento River Valley, from the eastern Klamath Mountains on the west to the Modoc Plateau and Mt. Lassen on the east. Elevations range from 107 m (350’) along the Sacramento River to 3188 m (10,457’) at the summit of Mt. Lassen, with precipitation ranging from ~50 cm on the Modoc Plateau to ~300 cm on Mt. Lassen. Mixed conifer forests are the most common vegetation type within the county (with more pine at the lower range, and more fir at the upper elevations). The county also includes large tracts of oak and oak/pine woodland, oak savanna, non-native annual grasslands, and mixed and montane chaparral.

2. Long-term Fire Probability Mapping

2.1 Background

Carbon accounting is a conceptually straightforward method of tallying the sources and sinks of carbon. However, quantifying carbon stocks and flows (whether historical, current, or future) for ecological systems is complex because of the spatial and temporal trends, interactions, and feedbacks of ecosystem processes. Wildfires, which are crucial disturbance processes in many of the world's ecosystems, are a prime example of that complexity. Wildfires combust biomass and are a source of carbon emissions, at least in the near term (Randerson et al., 2006), although they may act as a long-term carbon sequestration mechanism in some systems.

Fires occur as a function of a "fire regime triangle" of factors that regulate long-term fire activity: ignition sources, vegetation type, and climatic conditions during the fire season (Moritz et al., 2005; Fig 2). Spatial and temporal variation in these three factors interact, and the outcomes – the area burned, burn severity, seasonality, fire size, and fire intensity – are well described as stochastic events regulated to varying degrees by different factors in the fire regime triangle. Patterns of fire events in a specific location over time are used to describe its fire regime. For example, weather conditions and patterns vary from year to year, often in multi-year cycles (Kitzberger et al., 2007), such that long-term data are required to estimate the boundaries of historical variation in fire activity.

Applying fuel treatments to forested stands has been proposed as one method to reduce the risk of both catastrophic wildfires and the area burned during a wildfire, as well as carbon emissions from forests in California. The costs associated with treating millions of acres of forested lands are a central issue in this process, and sale of emission reduction credits may be one way of improving the economics of fuel treatments. If emission reduction credits are to be given for these treatments, it is necessary to establish a robust estimate of the baseline fire return intervals (i.e. from long-term mapped fire occurrence probabilities) for gauging the effectiveness of treatments at reducing carbon emissions. This is because some portions of the landscape are in more fire-prone environments than others, which means that some fuels treatments are more likely to achieve their emissions reduction benefits than others. Long-term expected fire occurrence probabilities are also necessary for assessing the relative merits of forest carbon sequestration projects (i.e. through quantifying environmental uncertainty and potential losses over 100 years), although establishing these baseline metrics is not carried out routinely (e.g. Richards and Stokes, 2004).

Winrock International developed a pilot study (Brown et al., 2006) to estimate historical rates of carbon emission from the area burned by wildfires within the mixed conifer forests of two ecoregions in northern California: the Cascades Northeast and North Coast, as defined by the

California Department of Forestry and Fire Protection's (CalFire) Fire and Resource Assessment Program (FRAP). Historical burn rates were proposed as a baseline for comparing the effectiveness of stand treatments in the future. A temporal moving window approach was suggested to determine baseline burning rates for the mixed conifer forest area. For example, the observed area burned over a ten year period might be used to forecast burn rates in the subsequent decade. However, there is no way to assess how many decades of data are needed to quantify variability in burn rates and if any decade sampled is representative of ongoing patterns, particularly for vegetation types that may only burn once over multiple centuries. Long-term fire occurrence probabilities can also be sensitive to the spatial window used in their determination. These shortcomings were assessed in an earlier report (Waller et al. 2007), in which a more rigorous fire probability mapping method was proposed.

A variety of statistical approaches has been developed at different spatial scales to relate fire occurrence probability at a location to variability in environmental characteristics (e.g. McKenzie et al., 2000; Cardille et al., 2001; Parisien and Moritz, 2009; Krawchuk et al., 2009). Such models can consider a wide range of predictor variables, including vegetation characteristics (e.g. cover type, productivity), topographic factors (e.g. slope, aspect, and landscape position), climate (e.g. averages and seasonality), ignition potential, and anthropogenic factors (e.g. human population pressure and land-use) as candidates to describe spatial variation in long-term fire occurrence probabilities. Many open questions remain, however, about the best variables to use, inherent sensitivities to modeling decisions, and techniques for training and testing such models. Here we describe a scientifically rigorous method of quantifying baseline fire occurrence rates, based on long-term fire patterns (i.e. multiple decades) and spatially explicit environmental variables. This approach has successfully been applied to regions of California and can be extended to the entire western U.S. (Parisien and Moritz, 2009).

2.2 Methods

We used the Maxent statistical framework, a recently developed probabilistic distribution modeling tool (Elith et al., 2006; Phillips et al., 2006), to generate spatially explicit fire probability maps for Shasta County, California. Maxent estimates the target distribution by finding the distribution of maximum information entropy (i.e. closest to uniform) subject to the constraint that the expected value of each feature under this estimated distribution matches its empirical average. This approach requires fire history records (locations) for an area as training data and spatial environmental layers as independent predictor variables of fire presence, establishing complex statistical relationships between fire occurrence and the environmental variables that characterize the most suitable locations for its occurrence. No fire absence data are required, as would be necessary for many distribution mapping tools (Philips, 2008). Special features of Maxent, including regularization and cross-validation of data, help to prevent overfitting of training data and allow the generation of robust fire-probability maps. The methodology employed here could thus be extended to any other region with appropriate fire history and environmental data (e.g. Parisien and Moritz, 2009; Krawchuk and Moritz, 2009; Krawchuk et al., 2009).

Training data for Maxent were obtained from fire history maps (1900-2007)(CalFire FRAP, 2010) and climate data (PRISM at ~800 meter resolution and Daymet at 1-km resolution) covering Shasta County. Monthly and annual means of environmental variables were sampled within the area burned by each fire for the period under consideration. Initial modeling used 32 environmental variables (Tab. 1) as predictors (independent variables), constituting the full model. Subsequent correlation analyses among these 32 variables led to the development of a reduced, 15-variable model. The reduced set included the minimum and maximum monthly values of temperature, precipitation, precipitation frequency, relative humidity, solar radiation, potential evapotranspiration, water balance, and cumulative annual deficit of soil moisture. Northern California was determined to be an appropriate geographic region from which to develop models. Final Maxent models were based on an average of a suite of four models: two different variable sets (32-variable ensemble and 15-variable ensemble) and two different fire size thresholds in each region (1000 acre and 5000 acre).

Maxent's logistic output is a relative fire occurrence probability, arbitrarily scaled between zero and one; therefore, it is not a true annual burn probability, nor necessarily a probability of burning over the time period from which the training data were collected. The results must be rescaled using fire history data to be converted to meaningful fire occurrence probabilities. The approach used here involved determining the mean annual burn rate from fire history data for the training area, and then dividing this by Maxent's mean fire probability value for the same area, to determine a conversion factor between the two products. Applying the derived ratio to the Maxent relative probability occurrence map results in the appropriate fire occurrence probability map. This result can also be inverted to give an expected fire return interval.

California's fire history data are considered fairly reliable back to 1950, but using a time window of 1950-2007 to determine an annual burn rate provides a relatively low estimate of annual burning compared to a window that includes only more recent years. Fire reporting has become more accurate (e.g. older data may be missing fires), and recently, fire activity has increased perhaps due to changes in the climate. Using 2001-2007 thus provides a more recent higher burn rate that can be thought of as an upper estimate of annual burning. Fire history data from two time windows (1950-2007 and 2001-2007) were used to generate two conversion factors that could be applied to the Maxent relative probability outputs to get upper and lower estimates of annual burn probabilities. These results were then inverted to give expected fire return interval products. In addition to considering the average output of these four models, we generated approximate 95% confidence interval products for each model based on the standard deviation (SD) output from Maxent (mean +/- (1.96*SD/root n)) where n refers to the number of bootstrapped replicates in a Maxent model run. These upper and lower confidence interval products from each model were then separately averaged to generate multi-model upper and lower confidence interval products. Further details on model fitting methods can be found in Parisien and Moritz (2009).

2.3 Results

Relative fire occurrence probabilities were mapped for Shasta County and fire return intervals were summarized with histograms according to vegetation type. For vegetation type classes, we computed probabilities according to WHR (wildlife habitat relationships) type in the FRAP-LCMMP (Land Cover Mapping and Monitoring Program) land cover map.

Among the many model input scenarios and model averaging techniques investigated, we found considerable spatial variation in long-term fire occurrence probability patterns. Consistent with our previous work, this heterogeneity (e.g. Fig. 3a) reflects important differences in environmental variables that determine how fire-prone an area tends to be. However, there was also variation among the individual model runs that were eventually averaged to produce each fire occurrence probability surface, which is reflected in mapped SD products (e.g. Fig. 3b). While it is encouraging that some regions of the study area may show relatively little variation among modeling runs (e.g. much of coastal and far northern area in Fig. 3b), other areas are much more sensitive to choices made for individual models. Furthermore, due to inherent variation in independent variables, we found that expected fire return intervals are not uniform within the climates of any given vegetation type (e.g. Fig. 4). This is not surprising, given that some locations can tend to be more fire-prone than others, even within a particular vegetation type.

The Blue oak woodland, mixed chaparral, and Sierra mixed conifer types with shorter fire return intervals, tend to be normally distributed around a most common burn rate near the mean; only Sierra mixed conifer vegetation exhibited "heavy tailed" distributions with small amounts showing very long expected fire return intervals (Fig. 4). Despite this variation, there are some clear trends among the climates of the different vegetation types. In this example, Blue oak woodlands and mixed chaparral tend to burn most frequently (~100-160 year range of fire return intervals). Fire return intervals begin to lengthen with increasing elevation to the Sierran mixed conifer forests (~120-350+ year range of fire return intervals), and even further in higher elevation fir forests (averages of ~200 years for White fir and ~300 years for Red fir forests; data not shown).

Another sensitivity examined was that of the conversion factor used to transform relative fire occurrence probabilities to expected fire return intervals. For example, recalculating the fire return interval distributions for Sierra mixed conifer with a 1950-2007 historical annual burn rate instead of one based on 2001-2007, we see that mean fire return intervals are lengthened by well over a century (Fig. 5).

2.4 Discussion

Long-term fire probability maps were developed for Shasta County using Maxent, a recently developed probabilistic distribution modeling tool. These maps are crucial for calibrating ERC analysis, and they are also useful inputs to the delineation of firesheds.

Because modeled fire probabilities can be sensitive to model training samples, the estimates given here should be interpreted with caution. For example, we find substantial differences between models, depending on whether training points are gathered from northern California or all of California. Extensive exploratory analysis and sensitivity analyses led to the conclusion that regional models were more accurate and realistic than spatially transferred models (i.e. models applied away from their source training data). While this has negative implications for spatial transferability and robustness of any particular model, it also suggests that regional datasets have enough data to develop a good local model of controls on long-term fire occurrence probabilities.

It is clear that various measures of model performance have limitations. For example, some common metrics (e.g. AUC – area under the curve) are sensitive to sample prevalence and the geographic extent over which it is applied (Lobo et al., 2008). Furthermore, it is difficult to treat any fire data as "truth" against which a product can be perfectly judged, due to the somewhat stochastic nature of fire. Various measures may be adequate for rough model comparison, but there is no one perfect measure for fire probability evaluation. At the very least, refitting models on some periodic basis is required, so that new fire occurrence data and associated environmental characteristics are integrated into long-term mapped estimates of fire occurrence probabilities. Regardless of the application, it is most appropriate to examine a suite of fire return interval estimates (e.g. low, medium, and high) for a specific area, to incorporate the potential range of natural variability inherent in fire regimes there.

3. Fireshed Delineation

3.1 Background

The term "fireshed" is increasingly being used to denote management units for fire planning. This is similar to the notion of natural resources being managed on a "watershed" basis, with actions in different portions of the watershed having effects on other parts within the watershed, or on the ultimate output (water resources) of the unit. Events or actions such as wildfire or fuels management activities in a fireshed can also have effects on areas greater than just the local area immediately affected. For example, forest thinning in one area may have a "shadow effect", not only altering fire behavior and emissions in the treatment unit, but in adjacent areas as well. The cumulative effects of multiple treatments in an area may therefore result in greater effects across the entire area than just the sum of the individual treatments. Firesheds may also capture areas where similar fire response strategies may be used to influence wildfire outcomes (Bahro et al., 2007). These examples demonstrate the need for a planning unit greater in size than that of wildfires, treatments, or other management activities.

Firesheds are generally delineated based on topography, fuels and vegetation patterns, assessment of fuel treatment effectiveness, barriers to fire spread, and fire behavior expected under relatively extreme fire weather conditions. Currently the USDA Forest Service is implementing and refining its Stewardship and Fireshed Assessment Process (SFA) across many of its forests in California (Bahro et al., 2007). An early part of this broad planning process is to delineate firesheds, within which fire management activities can be effectively planned and fuel treatment effectiveness evaluated. Fireshed delineation within the SFA process is a collaborative process, based on elements such as stakeholder input, expert opinion, and simulation of the "problem fire" for the planning area. The problem fire is a simulated fire that is of primary concern to stakeholders for its potential impact to lives, property, forests, and watersheds (Bahro et al., 2007). It is based on exploration and examination of fire history and historical weather for an area.

For the process being undertaken by Winrock International of assessing potential emission reductions from fuel treatments, an effective planning and assessment unit is also required. The fireshed concept meets the needs of this process. Here, we seek to improve on current, somewhat subjective methods of fireshed delineation by adding a new ecologically and statistically based approach. We integrate data for Shasta County on land cover, weather, topography, and fire probability into a semi-automated statistical process that divides or regionalizes the study area into firesheds.

3.2 Methods

Our methodology for delineating firesheds generally considers five main factors: the "fire behavior triangle" (fuels, weather and topography) (Pyne et al., 1996), barriers to fire spread (both natural and anthropogenic), potential fire behavior (under a "near-worst case" weather scenario), fire occurrence probability patterns (as discussed in section 2), and fire history (CalFire FRAP Database, 1900-2007). The analysis was performed in a Geographic Information System (ArcGIS 9.3 software). We began the process by performing an analysis of barriers to fire spread in Shasta County. These barriers included major roads, major water courses, urban areas, areas with no burnable vegetation, and agricultural areas. The outlines of these barriers were combined into one polygon layer. Shasta County was then divided up by this barrier layer to form "barrier units". These barrier units served as our broadest unit of analysis, as fire would likely be contained within these large units. Each barrier unit was analyzed separately. Barrier units were subsequently divided into smaller units, termed "fire basins", based on the California Watershed Boundary Dataset (WBD) subwatershed delineations (6th level, 12-digit)(CalWater, 2010). These topography-based polygons are hydrologic units that define the aerial extent of surface water drainage to a point. They served well as our smallest, most basic units of analysis, as they are generally smaller than our anticipated firesheds (~3000 to ~40,000 acres), and are to some degree also naturally bounding units for fire.

Each fire basin was then attributed with a value for each of several environmental variables of interest. Fire basins were given values for majority vegetation type (from the National Land Cover Database 2001), wind speed expected under a near-worst case scenario (overall 25mph from the southwest) averaged over the entire fire basin (as modeled in WindNinja 2.0 software) (Forthofer, 2009), and topographic roughness index (TRI). The topographic roughness index is a measure of how quickly the terrain (elevation, slope aspect) changes over a given distance (Stambaugh and Guyette, 2008). Each fire basin was also assigned values for potential fire behavior (mean flame length, mean fire line intensity, and majority crown fire activity level) as modeled in FlamMap 3.0 (Finney, 2006) under near-worst case weather conditions (97.5th percentile). Finally each fire basin was assigned a value for mean annual burn probability, averaged over the entire fire basin. The result of these assignments was a multivariate dataset for each barrier unit, with each fire basin as an observation, attributed with the multiple variables mentioned above.

Within each barrier unit, our goal was to aggregate the smaller fire basins into larger units (firesheds) based on multivariate analyses of the fuels, weather, topography, fire behavior, and fire probability data assigned to each fire basin. Units which were the most similar and adjacent to one another would get aggregated into larger firesheds. The minimum size of the fireshed in

Shasta County was based on the idea that that each fireshed should be larger than the "problem fire" or a near-worst case scenario fire. Our minimum fireshed size was three times the 80th percentile historical fire size, or approximately 10,000 acres. We aggregated the fire basins using several methods. The first analysis is called spatially constrained agglomerative clustering (performed in BoundarySeer 1.3 software). In this multivariate statistical method, clusters of polygons are formed by agglomerating individual polygons based on similarity of variables and adjacency (Jacquez and Maruca, 2003). Formation of clusters (in order to form firesheds) is constrained so that clusters form contiguous areas. Agglomeration of fire basins stops when the process reaches the user-defined number of clusters within a barrier unit. This number was determined for each boundary unit by performing a goodness-of-fit analysis for varying numbers of clusters. This analysis only used the numerical data available. We further refined clusters by using Wombling techniques (also in BoundarySeer 1.3) on our categorical data (land cover type and crown fire activity). In cases where clusters did not meet the minimum fireshed size requirement, they were manually combined with other clusters based on adjacency, topography, and land cover type. In some instances, it was not possible to meet the minimum size requirement due to fire barriers and county lines.

3.3 Results

Shasta County was initially divided into 16 barrier units. These barriers split the initial 141 subwatersheds into 193 fire basins. Cluster analysis grouped these fire basins into 45 unique firesheds (Fig. 6). Majority NLCD cover types represented in the firesheds were 42 (Evergreen Forest), 43 (Mixed Forest), 52 (Shrub/Scrub), and 71 (Grassland/Herbaceous). Fireshed size ranged from 6335 acres to 163,176 acres. Among firesheds, fire probability ranged from 0.26 to 0.59. Mean wind speed ranged from 21.9 to 25.1 mph. Mean TRI ranged from 1 to 1.123. Mean surface flame length varied from 2.1m to 39.6m. Mean fireline intensity ranged from 1,334 kW/m to 65,216 kW/m. 26 of 45 firesheds burned with the majority of their area in crown fire class 1 (no crown fire), while 5 firesheds burned with the majority of their area in crown fire class 2 (passive/torching) , and the remaining 14 firesheds burned with the majority of their firesheds in class 3 (active crown fire). Full details of all fireshed characteristics are summarized in Tab. 2.

3.4 Discussion

In the absence of any repeatable and objective available process for currently delineating firesheds, we have demonstrated the feasibility of a new statistically based approach. This process theoretically divides our study area into relatively homogenous units that can be used for analysis and planning at the scale of the "problem fire", which in this case was represented by approximately three times the 80th percentile fire size, or 10,000 acres. It is important to note that our delineation process is primarily statistical in nature, taking into account fuels, weather, topography, fire probability, and potential fire behavior. As such, some of the firesheds as delineated here may not be reasonable units for management or planning, which may take into account such things as political boundaries, access, other management activities, etc.

Similar to the Stewardship and Fireshed Assessment Process, our fireshed delineation process continues to be refined. Areas for further investigation include using different initial area units other than subwatersheds. For example in areas where homogenous units of vegetation have been defined (e.g. forest “stands”), these might provide a better initial units for clustering. Smaller initial units or fire basins might, however add significantly to the complexity of the analysis. The barrier analysis might also be improved by closer examination of whether certain roads, waterways, or urban areas will actually act as barriers to fire spread. In terms of clustering of fire basins, a better way to mix analysis of numeric and categorical data needs to be investigated, rather than manual adjustment of fireshed boundaries. Additionally, as mentioned above, the analysis did result in some irregularly shaped firesheds, which may prove difficult for planning and management. Integrating our statistical approach with more “expert opinion” based approaches is an avenue for further consideration.

4. Fuel Classification Standard

4.1 Background

Fuelbed characterization and classification is one of the most critical element of emissions estimation. A fuelbed is composed of the live and dead vegetative materials that can combust in a fire. It can include various vertical strata, including duff and litter on the forest floor, dead and downed woody material, live and dead herbs and shrubs, small trees in the under- and mid-story canopy, and live and dead trees of the upper canopy. Fuelbeds also vary horizontally (aerially) across the landscape. To account for horizontal variation, a particular study area can be spatially classified into one or more fuelbed types, each considered homogenous within itself. Fuel models are numerical descriptions for particular fuelbed types, which can be used to estimate fire behavior or smoke emissions. Fuel models were originally devised as a way to organize fuel data for input into Rothermel’s (1972) mathematical fire spread model (Deeming et al., 1977). Various fuel model systems exist and are in use today, which have developed along different lines for different purposes. Choosing appropriate fuel models for the emissions reduction framework will depend largely on data availability, appropriateness of available models for fire behavior and emissions estimation, and the desired level of accuracy for these estimates.

4.1.1 Fire Behavior Fuel Models

The most widely used fuel model systems have developed out of fire behavior modeling, based on the Rothermel fire spread equations (Rothermel, 1972). The most current and widely used implementations of the Rothermel equations are the computer programs BehavePlus (Andrews et al., 2008), FlamMap (Finney, 2006) and Farsite (Finney, 1998). BehavePlus is a non-spatial fire behavior prediction program, estimating fire characteristics for a single homogenous fuel bed. FlamMap and Farsite are spatial implementations, predicting fire characteristics and fire spread across a digitally mapped landscape. These programs depend on inputs of weather, topography, and a standard or custom set of fuel models to predict such fire characteristics as flame length, fireline intensity, and crown fire activity.

The original 13 fire behavior fuel models (described by Anderson, 1982), and their updated versions (described by Scott and Burgan, 2005) are widely used by fire agencies for wildfire and fuel treatment planning. In addition to weights per unit-area of different fuels particles in each stratum, these fuel models specify various other characteristics such as heat content, surface area-to-volume ratio, and moisture of extinction. The national LANDFIRE project mapped these fuel models across the country for regional scale planning (USDA, 2010). Many smaller scale mapping efforts have been done for specific areas. These fuel maps can be created by field sampling in an area with fuel model classification in mind, or by interpreting remotely sensed imagery, but more often are “crosswalked” between vegetation type classifications and fuel models. “Crosswalking” involves translating mapped vegetation types into fuel models, based on expert opinion of how a particular vegetation type might relate to a particular fuel model. Sometimes specific vegetation types can be reliably equated to particular fuel models, but other times vegetation type descriptions may not lend themselves to direct correlation.

4.1.2 Fire Danger Fuel Models

The National Fire Danger Rating System is a set of computer algorithms, programs, and models aimed at estimating fire danger. Fire danger in the NFDRS is a characterization of the potential for initiation, rate of spread and difficulty of control of a wildland fire (NWCG, 2002). It is used primarily by land management agencies for fire planning, staffing, and suppression purposes. Inputs into the NFDRS include antecedent weather, topography, live and dead fuel moisture, and fuel types. The outputs of the NFDRS are three relative ratings: Occurrence Index, Fire Load Index, and Burning Index. Fire danger estimations are designed to be representative of general conditions over broad areas, as opposed to fire behavior prediction (e.g. the FlamMap model) which is site specific.

A major input into NFDRS is the fuel model. The NFDRS contains a set of 20 fuel models developed specifically for this system, which is why NFDRS is being considered here. These twenty models are designed for making general fire danger predictions over large areas – often tens of thousands of acres in size. They are not necessarily designed to predict site-specific fire behavior, which is influenced highly by such factors as specific slope, wind speed, and fuel moisture. Additionally, while the fuel models do incorporate characteristics for dead and live woody material, they are not descriptive enough to simulate such complex processes as crown fire or post-frontal combustion. As such, the NFDRS fuel models are likely not appropriate for either the fire behavior prediction or the emissions estimation to be performed in our framework.

4.1.3 Fire Effects and Emissions Fuel Models

Fire emissions models such as Consume (Prichard et al., 2010a), the Fire Emissions Production Simulator (FEPS) (Anderson et al., 2004), and the First Order Fire Effects Model (FOFEM) (Reinhardt et al., 1997) have developed in parallel with fire behavior modeling, but have different data requirements. This is primarily due to the fact that accurate emissions estimations often require different descriptions of fuelbeds, than do fire behavior prediction models. They also require coupling of frontal surface fire, post-frontal surface fire, and crown fire in making estimates. Fire behavior fuel models are primarily designed for modeling either surface or crown fire behavior (e.g. fire at the flaming front). Pollutant emissions, however, are not only the result of fire at the flaming front, but are also greatly affected by post frontal combustion (e.g. smoldering), burning of jackpot accumulations, and other combustion processes.

Consume is a Windows-based computer application that can predict fuel consumption, pollutant emissions, and heat release based on a number of factors including fuel characteristics and environmental conditions (Prichard et al., 2010a). Among the primary benefits of this model is that it allows for very detailed specification of the fuelbed. Consume uses the Fuel Characteristic Classification System (FCCS) model for fuel classification. It accounts for virtually the entire range of vertical fuel strata, including duff, basal accumulations, squirrel middens, litter, ground lichen and moss, sound and rotten dead wood, stumps woody fuel accumulations, grasses and herbs, shrubs, trees, snags, and ladder fuels, with different algorithms for computing emissions from each of these strata. Consume also has a useful hierarchical project structure which allows the user to specify different fuelbeds within project units, and different units within a project. Users can customize fuelbeds to account for local variation.

The FCCS fuel models are a very detailed approach to fuelbed classification, describing fuelbeds in terms of various vertical strata including duff, basal accumulations, squirrel middens, litter, ground lichen and moss, sound and rotten dead wood, stumps, woody fuel accumulations, grasses and herbs, shrubs, trees, snags, and ladder fuels (Prichard et al., 2010b). The FCCS fuel models feed directly into the Consume emissions model. More than 300 fuel models have been described to date in the FCCS. The latest version of FCCS will make suggestions for crosswalks from FCCS to fire behavior fuel models, but not the other way around.

Similar to Consume, FEPS is a Windows-based computer application that can predict fuel consumption, pollutant emissions, and heat release of prescribed or wildland fires. Users describe an “event”, specifying up to five fuel beds, fuel moisture, fuel consumption, and hourly values for area burning and wind. Total burn consumption values are distributed over the life of the burn to generate hourly emission and release information (Anderson et al., 2004). Users can input their own fuel characteristics or use and/or modify fuel models built into FEPS. Fuel inputs are specified as tons per acre of canopy, shrub, grass, woody vegetation, litter and duff, and users can specify whether fuels are activity (e.g. slash) or natural. Users can load values from the NFDRS fuel models, as well as the FCCS fuel models.

FOFEM is a computer program and set of algorithms used to predict first order (direct or immediate) consequences of fire. This includes predicting tree mortality, dead fuel consumption by size class and resultant fire intensity over time, pollutant emissions by flaming and smoldering combustion, and soil heating at a range of soil depths over time since ignition (Reinhardt, 2008). FOFEM uses fuel models based on vegetation type (SAF/SRM cover type or NVCS cover type). The user is allowed to choose the vegetation type in question, and each vegetation type in FOFEM has default fuel characteristics associated with it. These defaults were developed through an exhaustive search of fuels literature (Reinhardt, 2008). Input characteristics include tons/acre of litter, duff, dead woody fuels, herbaceous, shrub, and canopy fuels. The user can change these inputs for their specific study site. Additionally, the latest version of FOFEM allows for use of FCCS fuel models.

4.1.4 Choice of fuel models for ERC Framework

Tab. 3 describes the different fuel models available and the pros and cons of each. For the ERC framework being developed here, we must estimate changes in both fire behavior characteristics as well as emissions. Regarding fire behavior prediction, the fire danger fuel models are designed for the NFDRS system, which estimates broad scale surface fire danger, outputting such indices as burning index. We are more interested in specific potential fire behavior for a study site, including crown fire activity. Though they use some of the same basic equations (e.g. Rothermel, 1972), current models for predicting fire behavior and spread (BehavePlus, FlamMap, Farsite) utilize the fire behavior fuel model format (e.g. Anderson, 1982 and Scott and Burgan, 2005) in combination with vegetation canopy characteristics. Scott and Burgan (2005) is the most recent and comprehensive description of fire behavior fuel models available, and will suit the needs of the fire behavior portion of this project. These fuel models, designed primarily for modeling surface and crown fire at the flaming front (vs. post frontal combustion) do not translate easily into inputs for emissions estimates, however. We did attempt a translation of fire behavior fuel models for use in emissions models, with limited success (described below).

For the most accurate emissions estimates, we would ideally have all the data inputs for all fuel strata characteristics (such as duff and litter loading, shrub cover, dead fuels, etc) available to us for an entire study area at some small resolution (e.g. 10m). Among the fuel models used in the three primary emissions estimate programs (FCCS, SAF/SRM/NVCS vegetation cover types, NFDRS) the FCCS fuel models are included for use in all three. Additionally, the FCCS system allows for the most detailed description of fuel profiles. FCCS fuel models have been mapped from LANDFIRE vegetation characteristics for the western United States. The availability, flexibility and detail of the FCCS fuel models warrant their use in the ERC framework. The Consume model makes the best use of the detailed FCCS fuel bed descriptions.

4.2 Methods

We estimated baseline emissions for forested areas in Shasta County using mapped FCCS fuel models obtained from the LANDFIRE database (shown in Fig. 7). This process required first using fire behavior fuel models (Scott and Burgan, 2005) and canopy data from LANDFIRE to estimate baseline fire behavior for Shasta County (see section 5 for further details) in FlamMap. This allowed us to estimate the proportion of the forest canopy consumed in each FCCS fuel type, an input required in Consume. We then calculated acreage for each FCCS forest fuel type in Shasta County. For the emissions modeling, we input each FCCS fuel model, its fuel characteristics, and its acreage into Consume. We used the default (unmodified) FCCS fuel model characteristics for each fuel model. Tab. 4 summarizes the “preburn” fuel loading for forested areas in Shasta County after we input all fuel models. We were then able to simulate fire under a “very dry” weather scenario, where 10 hour fuel moisture was 6%, 1000 hour fuel moisture was 10%, and duff fuel moisture was 25%. Tab. 5 summarizes our estimates of emissions for forested areas of Shasta County modeled under this scenario.

In a separate project (described in Saah et al., 2010), we estimated emissions for four study areas in the Sierra Nevada Mountains of California, again using FlamMap and Consume. However for this project we used fuel models and canopy data from the LANDFIRE database, as well as fuel model and canopy data gathered from local field studies, in order to compare the emissions results. We also attempted to use fire behavior fuel models (Scott and Burgan, 2005) instead of FCCS fuel models in Consume, in order to assess the feasibility of this method. Similar to our simulations in Shasta County, we first modeled fire behavior in FlamMap, in order to estimate percent of the forest canopy consumed by fuel model. Next, we created our own custom fuel models by manually entering dead/downed and live surface fuel loading information published for each of the standard fire behavior fuel models, in order to use these models (instead of FCCS models) in Consume. We repeated this process for each fuel model mapped in each study area, and then simulated fire under a “very dry” weather scenario (described above), and determined the total emissions by acreage.

4.3 Results

In the emissions estimation for Shasta County, 29 FCCS fuel models were represented in the forested areas analyzed (Fig. 7). Total preburn fuel loading averaged over all fuel models was 60.08 tons/acre, with 22.5 tons/acre in the forest canopy, 2.7 tons per acre in the shrub layer, 0.2 tons/acre in the herbaceous layer, 16.7 tons/acre in the dead and down woody fuels layer, 1.9 tons/acre in litter, lichen, and moss, and 16.2 tons/acre in ground fuels (duff, basal accumulations, and squirrel middens). Canopy consumption in the various fuel models ranged from 13 to 94%. Fire simulation for the study area resulted in 55.42 tons/acre of total pollutants, with 53% of emissions resulting from smoldering or residual combustion (as opposed to flaming combustion).

For the four study sites in the Sierra Nevada, we were able to make emissions estimates using fire behavior fuel models, but the only publicly available data for these models was for surface fuels <3” in diameter and canopy fuels. This allowed for modeling fire at the flaming front and in the canopy only, not post-frontal or residual combustion (e.g. smoldering, burning of large woody debris, etc.). Using locally gathered data, total pollutant emissions were estimated to be 28.2, 28.7, 14.8, and 10.6 tons/acre for the Kings River, Last Chance, Plumas-Lassen, and Sagehen study sites respectively. Using national LANDFIRE data, total pollutant emissions were estimated to be 31.4, 42.0, 38.9, and 29.9 tons per acre for Kings River, Last Chance, Plumas-Lassen, and Sagehen respectively. LANDFIRE-based estimates were 11%, 47%, 163%, and 181% greater than local data-based estimates.

4.4 Discussion

The Sierra Nevada study described above highlights the limitations of using fire behavior fuel models for estimating emissions. Because the fire behavior fuel models characterize only those fuel elements needed for predicting surface fire behavior (and crown fire behavior if canopy data is available), this method limits emissions predictions to only those produced from the flaming front. It is clear that in order to estimate both fire behavior/hazard and emissions we will need two separate classification systems. The most descriptive and site specific fuel models are those described by Scott and Burgan (2005), which feed directly into the most commonly used fire behavior prediction models and programs (e.g. BehavePlus, FlamMap, and Farsite). These programs also allow you to create use custom fire behavior fuel models or adjust standard models to allow for fuel profiles that don’t fit the standard models.

The emissions estimates made for Shasta county demonstrate the feasibility of using the FCCS fuel model format for our ERC framework. The FCCS format allows for much more complex descriptions of fuel beds than do other fuel classification systems. The >300 standard fuel models in the FCCS are built into all three of the major emissions models considered here –

Consume, FEPS, and FOFEM. Of these, Consume appears to make the best use of the different fuel strata described in the FCCS format. It also allows the user to create new fuelbeds in the FCCS format or customize standard models, when standard models don't fit the study area. If field data is collected to classify a study are in the FCCS format, some additional information would be needed to translate data into the fire behavior fuel model format, including surface area to volume information, moisture of extinction, and heat content. The FCCS program will, however, make suggestions for crosswalking an FCCS fuel model into a fire behavior fuel model. Overall, the FCCS format, with the addition of the fire behavior fuel characteristics mentioned above, would be enough information to make both fire behavior estimates as well as emissions estimates.

If using separately derived datasets for fire behavior fuel models and emissions fuel models, caution should be exercised to make sure models are consistent between datasets, especially when making fire behavior and emissions estimates on small scale projects. In addition, it is important to remember that FCCS mapping in the LANDFIRE database are derived from vegetation maps, also in the database. LANDFIRE data is intended for regional or broad scale analysis or planning efforts, and as such is generally appropriate for studies such as those considered here (e.g. Shasta County). For smaller scale, local studies, other data sources may be more appropriate.

5. Baseline Fire Hazard Assessment

5.1 Background

To measure potential change in fire behavior, we must first establish a baseline, which in this case is an estimation of potential fire behavior for a study area prior to any treatment scenarios proposed. We can then simulate modifications to the landscape, estimate fire behavior again, and measure potential changes. Changes in fire behavior can also be used as inputs into emissions models, to examine changes in potential emissions. As noted earlier, these changes are conditional on a fire occurring in a given area, which can vary considerably. We performed a baseline fire behavior assessment of Shasta County for this purpose.

5.2 Methods

Mapped data for fire behavior assessment were downloaded from the national LANDFIRE database for Shasta County, representing the most current, best coverage, and readily available data. These data layers comprised the typical landscape "data stack" used in current spatial fire behavior models, including 30m resolution maps of fire behavior fuel models, elevation, slope, aspect, canopy height, canopy cover, canopy base height, and canopy bulk density. LANDFIRE data is already co-registered for use in fire behavior programs and geographic information systems. We projected the LANDFIRE data into a UTM coordinate system in preparation for analysis. Weather inputs (temperature, humidity, and fuel moisture) for fire behavior simulations were created for three weather severity scenarios: 90th, 95th and 97.5th percentile. The weather conditions for each scenario were determined by examining historical weather data in the program Fire Family Plus (USDA Forest Service, 2002). Spatially explicit wind conditions under each of these weather scenarios were derived at 100m resolution in WindNinja software using a typical general direction and wind speed estimated from historical analysis. Potential fire behavior was modeled using landscape, weather, and wind inputs in the fire behavior simulation program FlamMap (Finney, 2006). FlamMap does not simulate fire spread, but rather burns the entire landscape "instantaneously" to give a snapshot of potential fire behavior for the given landscape and conditions. Though a variety of outputs and measures are available, we chose to estimate flame length, fire line intensity, and crown fire activity. Flame length can be used as a measure of suppression difficulty, and fire line intensity as a measure of potential fire severity. Crown fire activity is of primary concern as well, as fuel treatments are aimed at preventing large "catastrophic" wildfires, or those that consume most or all of the forest canopy.

5.3 Results

Flame lengths in wildlands (areas with burnable vegetation) across Shasta County averaged 9.4 m, ranging from 0.1 to 237.2 m. Areas of highest flame length were generally concentrated in the forested areas of the southeast, and the mountainous areas of the north and west (Fig. 8). Fireline intensities followed a similar pattern, averaging 11,714 kW/m, ranging from 3.19 to >800,000 kW/m. The majority of forested vegetation (57%) experienced high crown fire activity (crown fire activity class 3 – active crown fire; see Tab. 6).

We also classified fire behavior characteristics into three categories: low, medium and high. Flame length classes were determined using fire suppression benchmarks as follows: Low = <1.2 m (4 ft) = fire can generally be attacked at the head or flanks by persons using hand tools, Med = 1.2 m (4 ft) – 2.4 m (8 ft) = fires are too intense for direct attack with hand tools, but equipment such as plows, dozers, pumpers, and retardant aircraft can be effective, and High = >2.4 m (8 ft) = fires present major control problems, i.e. torching, crowning, and spotting (Pyne et al., 1996). Fireline intensity classes, which correspond to flame length classes, were calculated using the following equation (Pyne, 1996):

$$I = 259.833(L)^{2.174}$$

where:

I = Fireline Intensity (kW/m)

L= Flame Length (m)

Crown Fire Activity is automatically predicted by FlamMap in three classes, where 1 = Low = No crown fire activity, 2 = Med = Passive crown fire activity or individual tree torching, and 3 = High = Active crown fire. Independent (running) crown fire activity is not modeled in FlamMap. Fire behavior was summarized by class and general vegetation cover type (Fig 9). In all three vegetation types, the majority of the study area is predicted to burn in the high classes for flame length and fireline intensity. For forested areas, crown fire activity is predicted to be "high" (class 3) for the majority of the study area. This is likely due to the fact that our fire behavior predictions were made under 97.5th percentile weather conditions (i.e. severe fire weather).

5.4 Discussion

These regional (countywide) estimates of potential fire behavior seem consistent with the severe fire weather conditions under which they were modeled, with approximately 50 to 80% of the landscape burning in "high" fire severity classes (Figs. 8 and 9). This suggests that under these extreme conditions (97.5th percentile) a majority of the landscape is at risk of fire that is difficult to control (high flame lengths and fireline intensities) and damaging to the forest canopy (high crown fire activity class). The primary goals of fuels treatments are to reduce the risk of high severity, large scale, highly damaging wildfire, as well as the potential for large smoke emissions into the atmosphere. This assessment can be considered an estimate of current fire hazard within the study area prior to any proposed future treatments. Changing the landscape data inputs to simulate treatments and running simulations again will allow us to detect potential changes from treatments. Additionally, these data serve as vital inputs into several other parts of our framework (Fig. 1), including the delineation of firesheds and estimates of potential emissions.

Our baseline fire hazard assessment used national LANDFIRE data for landscape and vegetation characteristics, as this is the only dataset available for the entire county that will support fire behavior analysis. It is important to note that these data, while high resolution (30 m), are generally intended to support regional scale analysis. While Shasta County may be considered "regional", we did note some discrepancies in the LANDFIRE data that may suggest smaller scale analyses are warranted. Specifically, there appeared to be some linear differences in mapped canopy characteristics in the northern part of the county, which could have been due to consolidation of different mapping efforts, or to lag time in updating data for different parts of the county. It would be worth investigating the source of these linear changes in mapped data to make sure we have the most current and accurate representation of the landscape. Additionally, it will be important to track whether these data are updated in the LANDFIRE database, because in an assessment of fuel treatment effects, we will want to isolate change due to treatments, as opposed to change from other sources. This will necessitate using the same base data in both pre- and post- treatment analyses.

6. Conclusions

The information gained from investigating the four topics in this report (i.e. relative fire probabilities, fireshed delineations, fuel classification standards, and baseline fire hazard) is intended to support our general framework for estimating potential changes to fire hazard and smoke emissions due to fuel treatments on the landscape (Fig. 1). This in turn should provide a scientific basis for estimating potential ERCs that can be tied to on-the-ground fuel treatment activities. While development is still ongoing, this work strengthens the foundation for a scientifically sound, contemporary and rigorous model of change that can support the process of carbon accounting. The framework was developed with many criteria in mind. Among these are the following: (1) the framework must make use of the most current models, technology, and information; (2) it must focus on an appropriate scale of analysis; (3) it must be able to account for appropriate variables that may affect its outcomes; (4) it must be scalable, not only spatially but relative to data availability; and (5) it must be spatially explicit in its outputs. Each of the elements addressed in this report can be evaluated in terms of these criteria.

The fire probability mapping methodology shows promise as a way of estimating long-term expected fire return intervals for an area, which is critical if one is to estimate the true value of fuel treatments in one area over another. It uses not just a singular estimate of fire risk (e.g. historical locations), but instead takes into account our best knowledge of the many factors that affect how fire-prone a particular area may be (e.g. long-term fire patterns and a myriad of environmental variables). It is scalable in that we can add spatially explicit data on any number of factors (e.g. road density or proximity to urban centers) and use training data to determine how significant these factors are. It is spatially explicit, but generally limited to the resolution of our input data, particularly climate data. It is, however, well suited to coarse-scale questions of fire return intervals, as opposed to fine-scale fire behavior at the stand level. To some degree, models may be “location specific” such that separate models might need to be developed for very different fire environments.

Our fireshed delineation methodology is a novel way of focusing our analysis on an appropriate scale. It improves on current methods, based on “problem fire” analysis, management constraints, and expert opinion, by adding an ecologically and statistically based element to the process. Though we focused on fuels, weather, topography, fire risk, fire behavior, fire barriers and fire history to delineate our watersheds, the process is flexible enough to allow use of other environmental variables that may help refine or create fireshed boundaries. A primary challenge lies in defining what constitutes a “homogenous” unit to use as the basis for creating firesheds. We chose to start with subwatersheds (HUC12), but other units may be more appropriate, such as forest “stands”. However, this type of data may not be available or appropriate for the regional type analysis done here.

The FCCS and fire behavior fuel model formats appear to be the most appropriate for use in the ERC framework. The FCCS and fire behavior fuel model formats feed into the most current fire behavior and emissions models. The FCCS format, with a few fire behavior variables added, allows for a very detailed description of fuel profiles. To the extent that we can apply homogenous fuel profile classifications to particular areas, they are spatially explicit and scalable. We can use data from various sources for these two fuel model formats, including the national LANDFIRE database which includes maps of both for the western United States. For smaller scales, we can use locally collected data to create or classify areas into fuel models. The fire pollutant emissions estimates made for Shasta County demonstrate, at least on a regional scale, how these fuel models can be applied in our ERC framework.

The fire behavior assessment for Shasta County performed here demonstrates how we can create a baseline for assessment of fire hazard change. We used the most widely accepted spatial fire behavior models (Rothermel, 1972; Finney, 2006) to predict fire behavior characteristics on the current landscape under a severe fire weather scenario. We used LANDFIRE data at 30m resolution, though our analysis may not have warranted this high level of specificity. The fire behavior models are able to account for different resolutions of data, and are not necessarily affected by the size of the landscape. Because of the LANDFIRE database, data availability was not an issue, but rather data quality was in question (regarding crown fire characteristics). Using more locally gathered data (as opposed to the remotely sensed LANDFIRE) is possible in this process, and it may be warranted in finer scale analyses or smaller study areas. The models are expandable in that one can create custom fuel models for input, as well as adding supplemental data on canopy characteristics and ground fuels.

Further development of the framework is in progress to quantify treatment effects on vegetation and on fire behavior (both within treatment areas and in shadow areas) using the Forest Vegetation Simulator model (Dixon, 2002). We are continuing to refine the fireshed delineation process, looking at additional spatial multivariate clustering techniques. Fire probability mapping is being refined through additional model validation and sensitivity analyses. We are continuing to explore the use of FCCS and fire behavior fuel models in emissions models, including the BlueSky Framework. In summary, our work demonstrates that an integrated set of quantitative models can make many of the most complex issues inherent in wildfire emissions accounting a tractable problem.

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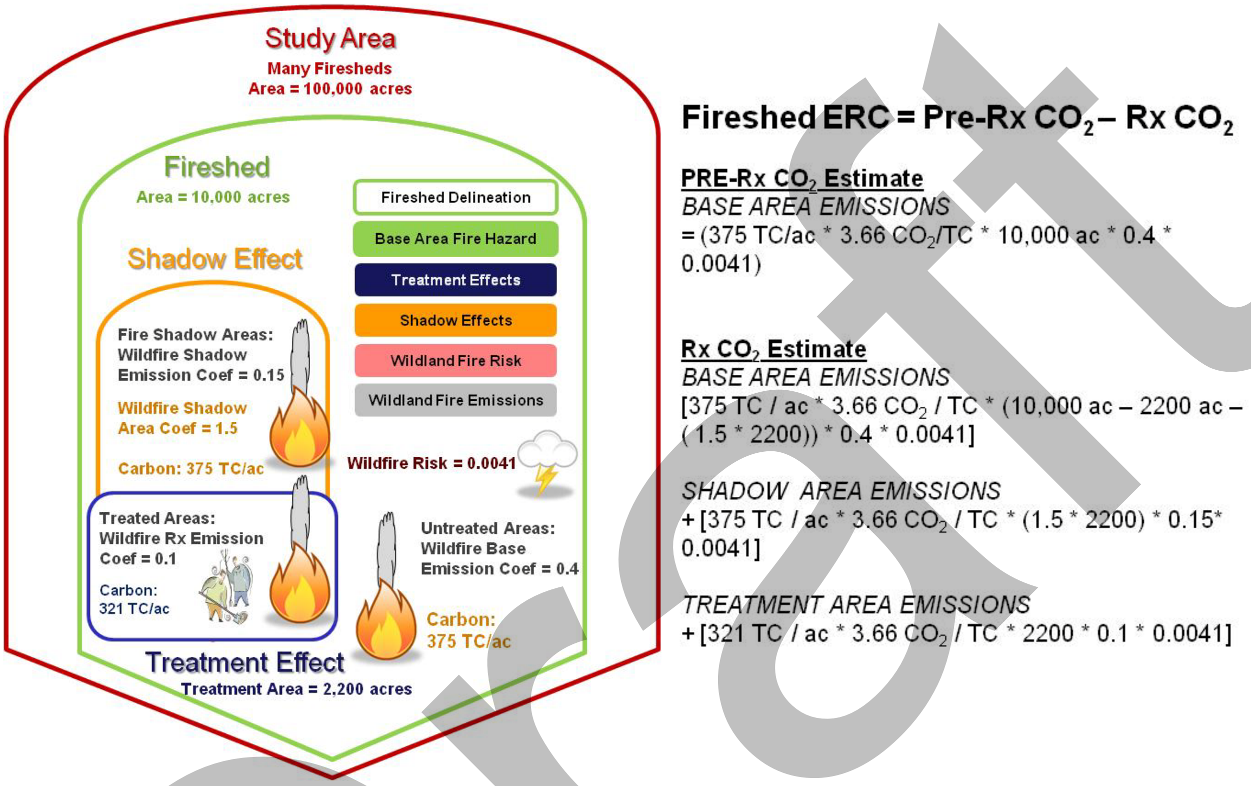
8. Figures and Tables



Fireshed ERC = Pre-Rx CO_2 – Rx CO_2

PRE-Rx CO_2 Estimate

BASE AREA EMISSIONS

= (375 TC/ac * 3.66 CO_2/TC * 10,000 ac * 0.4 * 0.0041)

Rx CO_2 Estimate

BASE AREA EMISSIONS

[375 TC / ac * 3.66 CO_2 / TC * (10,000 ac – 2200 ac – (1.5 * 2200)) * 0.4 * 0.0041]

SHADOW AREA EMISSIONS

+ [375 TC / ac * 3.66 CO_2 / TC * (1.5 * 2200) * 0.15* 0.0041]

TREATMENT AREA EMISSIONS

+ [321 TC / ac * 3.66 CO_2 / TC * 2200 * 0.1 * 0.0041]

Figure 1: Conceptual framework for estimating potential wildland fire emission reduction credits for a particular fireshed. Major elements of the process include fireshed delineation, estimation of base area, treatment area, and shadow area fire hazard and emissions, and estimation of wildfire risk. The fireshed is the major unit of analysis. Treatments are fuels reduction projects such as thinnings or prescribed fire. Fire shadows are areas outside treatments that are affected by treatments in terms of fire hazard or emissions. CO_2 emissions estimates (pre and post treatment) are a function of total stored carbon, CO_2 contained per mass of carbon, size of fireshed, emission coefficient, and wildfire risk.

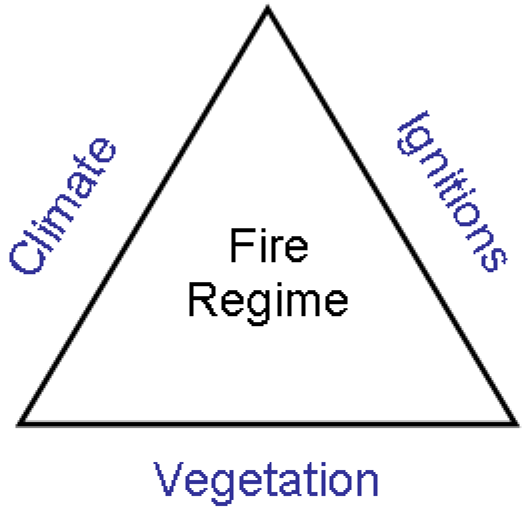


Figure 2: Controls on a fire regime. The vegetation axis incorporates fire-related characteristics of the plant community, such as biomass productivity rates, canopy structure, and chemical flammability characteristics. The climate axis represents atmospheric conditions conducive to combustion, such as how intense and how often hot, dry, windy conditions occur. The ignitions axis captures the spatial and temporal patterns of both human and natural sources of fire. (Modified from Moritz et al. 2005).

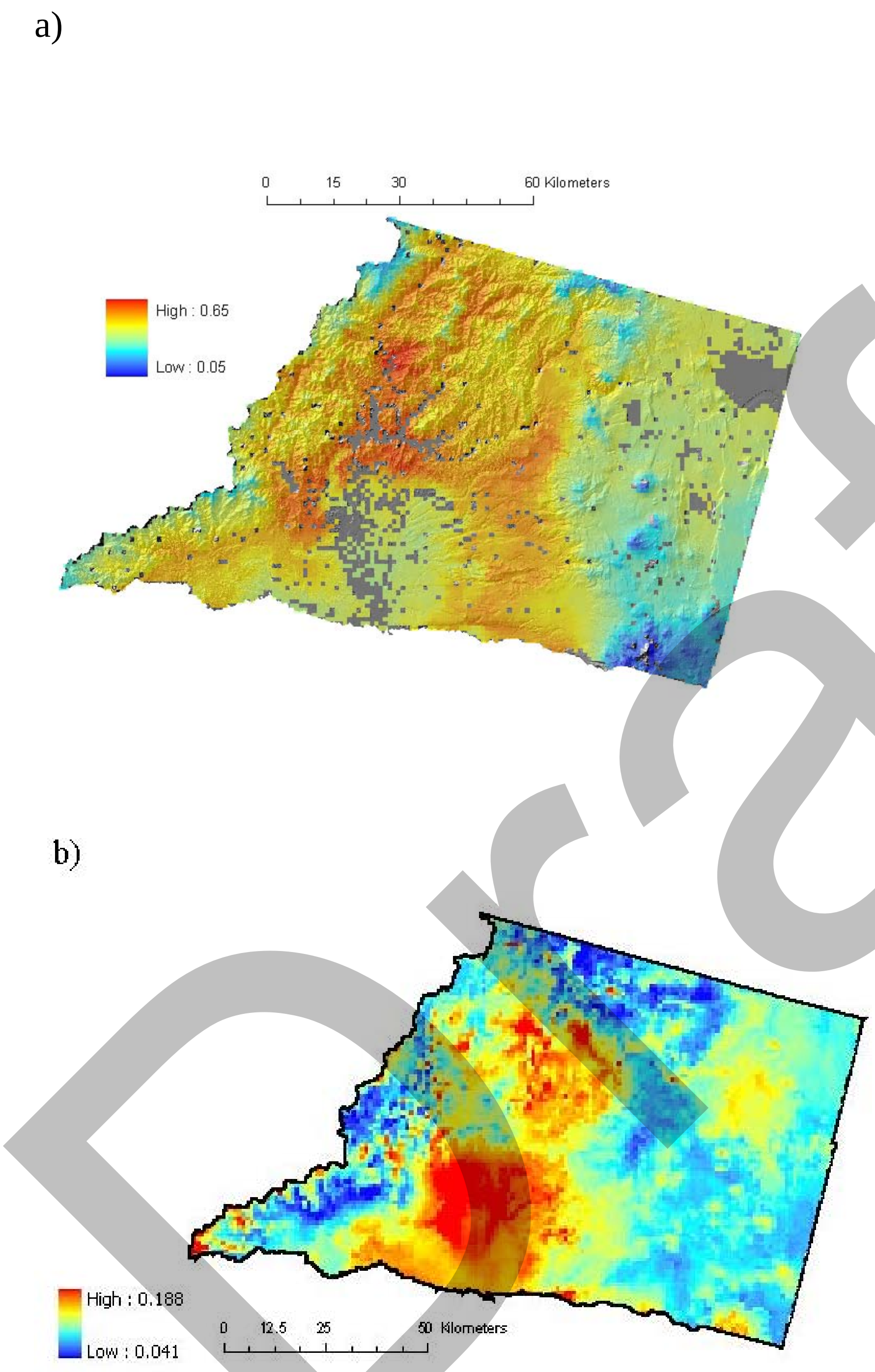
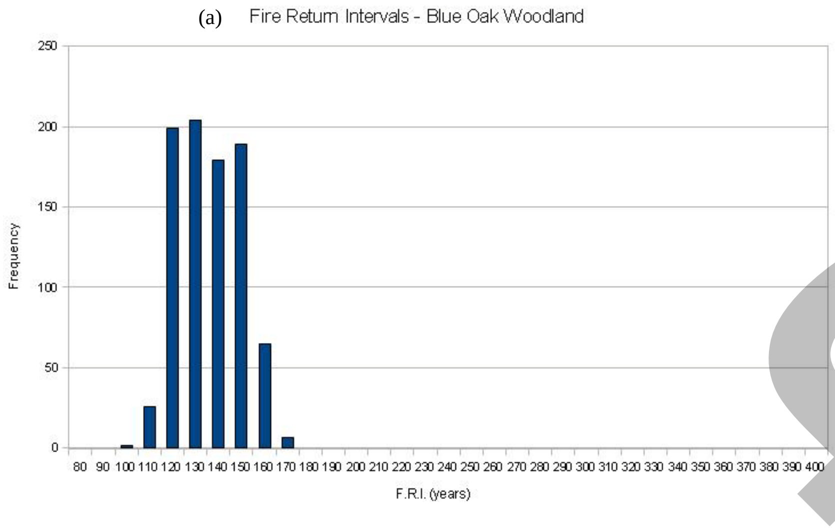
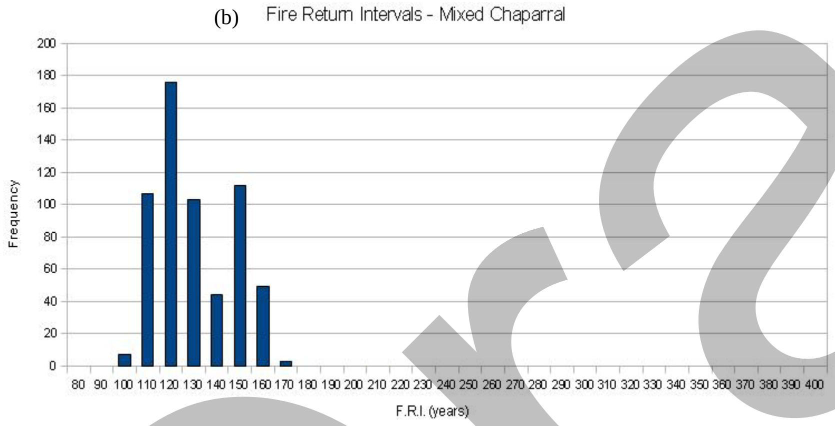


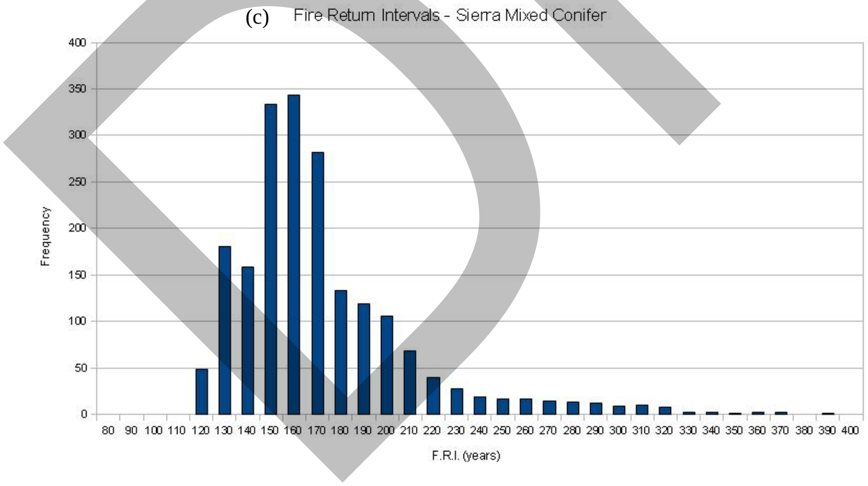
Figure 3: Example of mean (a) and standard deviation (b) of the relative fire occurrence probability of four model scenarios for Shasta County, California. The combination of models included 2 different variable sets (32 variable ensemble and 15 variable ensemble), and 2 different fire size thresholds in each region (1000 acre and 5000 acre). Relative fire occurrence probability values range from 0 to 1.



(a) Fire Return Intervals - Blue Oak Woodland



(b) Fire Return Intervals - Mixed Chaparral



(c) Fire Return Intervals - Sierra Mixed Conifer

Figure 4: Histograms of fire return intervals by vegetation type: (a) Blue oak woodland, (b) mixed chaparral, and (c) Sierra mixed conifer. Fire return intervals are calculated based on transformation of relative fire probabilities and historical burning rates for Shasta County over 2001-2007 (from example models shown in Fig. 3).

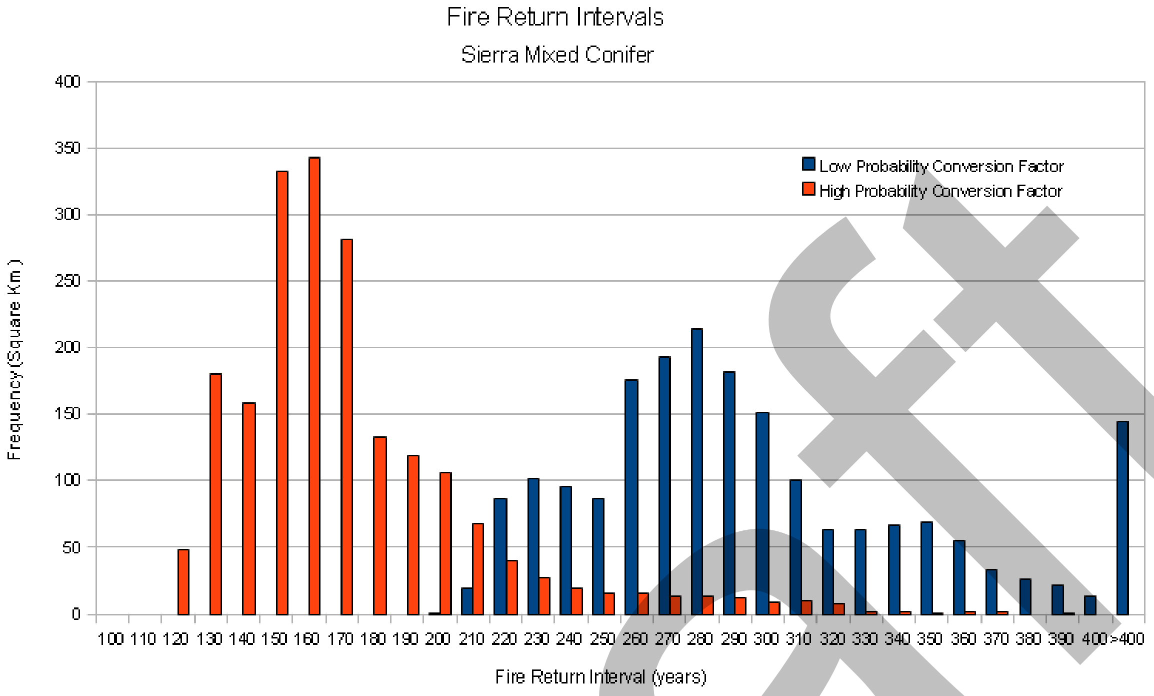


Figure 5. Fire return interval distributions for Sierra Mixed Conifer forest in Shasta County, given different conversion factors for transforming relative mapped fire occurrence probabilities to fire return intervals. The "Low Probability" conversion factor is based on the area burned over the full 1950-2007 period, while the "High Probability" conversion factor is based on area burned during 2001-2007. Here the full 1950-2007 period of record results in much lower fire return intervals (e.g. median = 157 yr, mean = 166 yr) than using the more recent 2001-2007 period (e.g. median = 281 yr, mean = 297 yr).

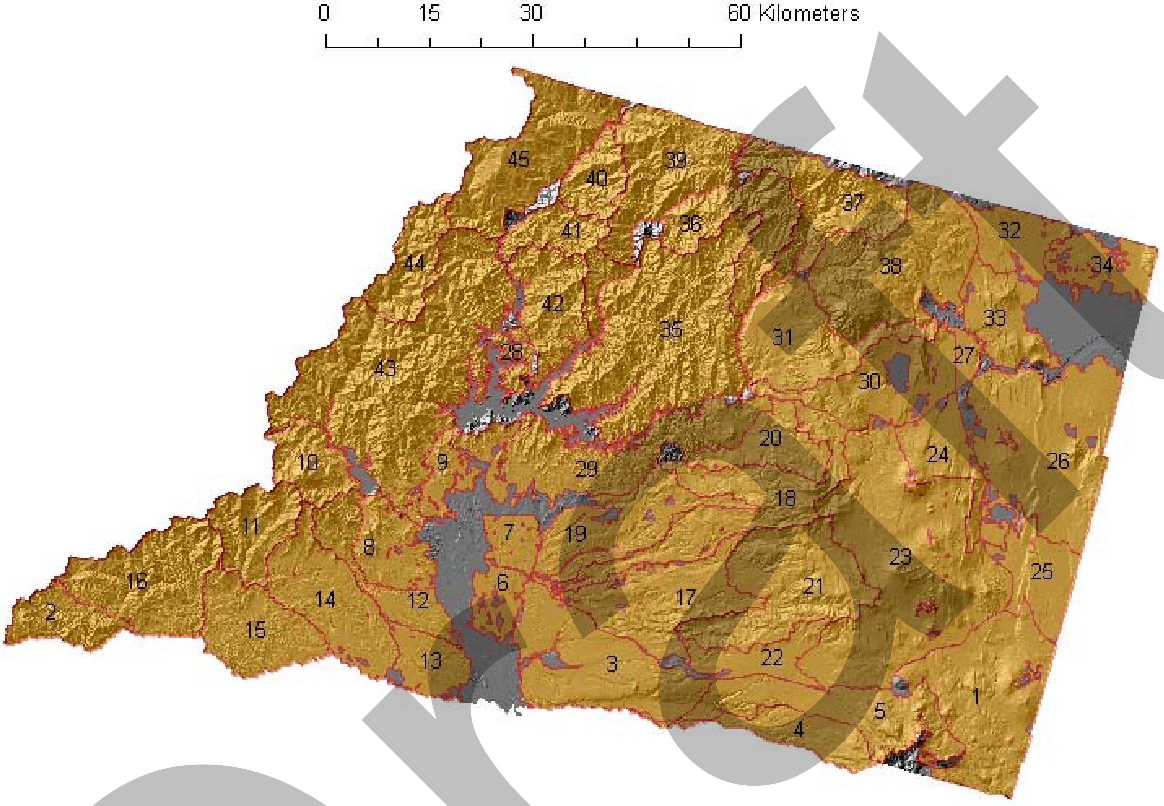


Figure 6: Firesheds delineated for Shasta County, California. Areas not enclosed by a fireshed are non-wildland/non-burnable, i.e. water, urban, agricultural, or barren.

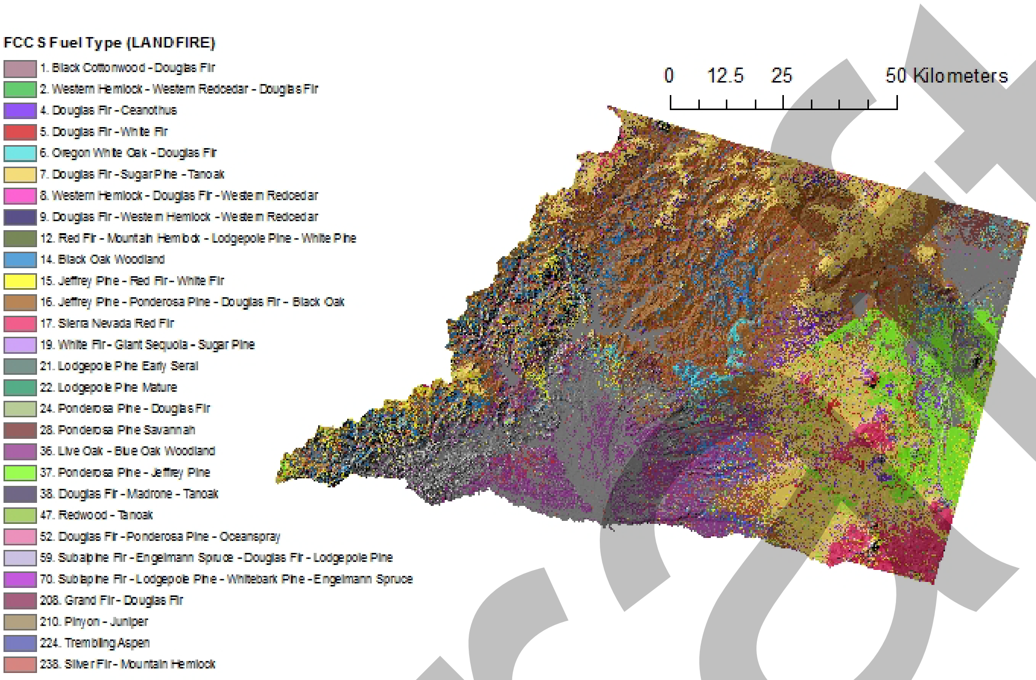


Figure 7: FCCS Fuel Types mapped for forested areas in Shasta County, CA from the National LANDFIRE Database.

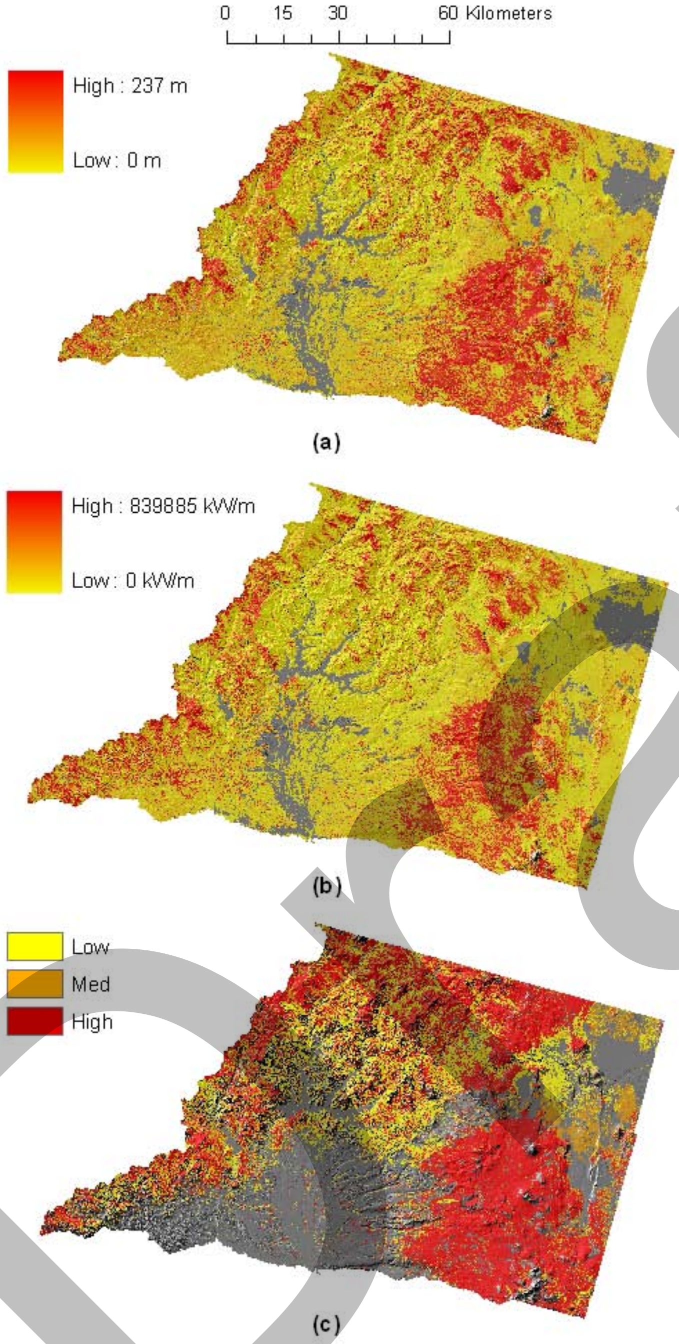


Figure 8: Baseline fire hazard assessment for Shasta County, California. (a) Flame Length (m). (b) Fireline Intensity (kW/m). (c) Crown Fire Activity Class (forested areas only)

Figure 9: Baseline fire behavior characteristics for Shasta County, California, separated by general vegetation type (NLCD). Flame Length: Low = 0 - 1.2m, Med = 1.2 - 2.4m, High = >2.4m. Fireline Intensity: Low = 0 – 346 kW/m, Med = 346 – 1730 kW/m, High = >1730 kW/m. Crown Fire Activity: Low = surface fire, Med = passive or torching crown fire, High = active crown fire.

Predictor Variable	Description	Strongest Correlations (32)	Strongest Correlations (15)
Balance	Annual water balance (PPT-PET), monthly carryover	ppt_ann (0.98); maxm_ba(0.97)	
Defcapz	Annual Deficit: Water Balance, no monthly carryover	ppt_ann (0.88); maxm_ba(0.85)	**maxm_ba(0.85)**
Elev	Elevation	humann (-0.85); tmaxmea (-0.84)	
Humann	Annual average vapor pressure (absolute humidity)	all humidities (>0.94)	
Humhigh	Highest monthly average vapor pressure	all humidities (>0.94)	
Humlow	Lowest monthly average vapor pressure	all humidities (>0.94)	
Maxm_ba	Maximum monthly water balance	pmaxm_l(0.99); ppt_ann(0.99)	**pmaxm_l(0.99)**
Minm_ba	Minimum monthly water balance	minm_de(1.00); petm_mm (-0.93)	**petm_mm(-0.93)**
Minm_de	Minimum monthly deficit	minm_ba(1.00)	
Mnths_a	Number of months at deficit	ppt_ann(-0.93); maxm_ba(-0.93)	
Pcpfrqa	Annual precipitation frequency	pcpfrqw(0.91)	
Pcpfrqd	Lowest monthly precipitation frequency	pminm_l(0.84);vpdm_mi(-0.83)	**pminm_l(0.84)**
Pcpfrqw	Highest monthly precipitation frequency	pcpfrqa(0.91)	**defcapz(0.82)**
Pet_yea	Annual potential evapotranspiration (PET)	petmin(0.80)	
Petm_mm	Maximum monthly potential evapotranspiration	minmde(-0.93);minmba(-0.93)	**minm_ba(-0.93)**
Pet_min	Minimum monthly potential evapotranspiration	radlow(0.85);pet_yea(0.80)	**radlow(0.85)**
Pmaxm_l	Maximum monthly precipitation	maxmba(0.99);ppt_ann(0.98)	**maxm_ba(0.99)**
Pminm_l	Minimum monthly precipitation	pcpfrqd(0.84)	**pcpfrqd(0.84)**
Ppt_ann	Annual precipitation	maxmba(0.99);pmaxm_l(0.98)	
Radann	Annual radiation	radlow(0.87)	
Radhigh	Maximum monthly radiation	humhigh(-0.77)	**petm_mm(0.64)**
Radlow	Minimum monthly radiation	radann(0.87)	**pet_min(0.85)**
Rangem_	Maximum minus minimum monthly water balance	pmaxm(0.98);ppt_ann(0.97)	
Relativ	Maximum monthly relative humidity	rltvmin(0.68)	**rltvmin(0.68)**
Rltvmin	Minimum monthly relative humidity	minm_de(0.69)	**minm_ba(-0.69)**
Tmax_mi	Maximum minus minimum monthly temperature	tminm_l(-0.59)	
Tmaxm_l	Maximum monthly temperature	tmaxmea(0.91)	**pminm_l(-0.51)**
Tmaxmea	Mean maximum monthly temperature	tmaxm_l(0.91)	
Tminm_l	Minimum monthly temperature	tminmea(0.90)	**pcpfrqd(-0.73)**
Tminmea	Mean minimum monthly temperature	tminm_l(0.90)	
Vpdm_ma	Maximum monthly vapor pressure deficit		
Vpdm_mi	Minimum monthly vapor pressure deficit	tmaxmea(0.83);pcpfrqd(-0.83)	

Table 1: Predictor variables used in Maxent fire probability analysis. Bolded variables are members of the reduced 15-variable set.

Fireshed	NLCD Cover Type	Area (Acres)	Fire Probability	St. Dev.	Windspeed (mph)	St. Dev.	Topographic Roughness Index	St. Dev	Surface Flame Length	St. Dev.	Surface Fire Line Intensity	St. Dev	Crown Fire Activity Class
1	42	85157	0.261	0.054	23.53	3.79	1.019	0.017	27.88	22.88	42526.42	45943.67	3
2	42	24859	0.389	0.061	21.90	4.02	1.081	0.030	20.95	25.18	37142.80	50837.22	1
3	71	73845	0.461	0.050	24.25	1.91	1.006	0.008	7.89	12.00	9219.33	20322.60	1
4	42	25997	0.447	0.103	22.80	2.86	1.015	0.015	37.10	20.38	58395.47	41651.88	3
5	42	56444	0.339	0.140	23.65	3.91	1.029	0.034	30.45	23.58	47855.28	46991.94	3
6	71	14817	0.392	0.018	23.86	0.50	0.999	0.001	3.66	5.77	3995.48	8698.73	1
7	71	13811	0.433	0.014	23.85	0.56	1.000	0.002	2.84	4.96	2493.71	6219.85	1
8	52	27656	0.551	0.045	24.02	2.30	1.021	0.020	7.59	11.42	10513.81	18390.39	1
9	43	21696	0.538	0.058	23.76	2.52	1.026	0.025	9.25	12.01	12346.17	17856.13	1
10	42	25386	0.454	0.065	23.36	6.03	1.080	0.029	22.89	28.42	39622.69	62399.55	3
11	42	31825	0.409	0.061	23.63	5.96	1.086	0.038	21.48	25.82	37844.96	55103.24	1
12	52	29314	0.490	0.046	23.93	3.15	1.031	0.032	11.72	17.65	16694.34	34450.85	1
13	71	21114	0.427	0.024	24.28	0.66	1.002	0.003	5.51	8.36	5938.57	12938.56	1
14	52	53956	0.464	0.041	23.57	1.94	1.013	0.017	7.01	10.56	9992.59	18841.11	1
15	71	45640	0.478	0.030	23.66	1.82	1.025	0.014	4.16	4.23	6489.12	10091.28	1
16	52	62906	0.450	0.056	23.22	4.45	1.084	0.039	12.12	19.04	22309.27	38500.74	1
17	52	58341	0.490	0.040	23.51	2.00	1.015	0.013	11.02	15.37	13855.82	25817.41	1
18	42	68791	0.473	0.071	23.73	2.94	1.022	0.015	23.53	26.01	37999.19	52900.25	3
19	71	48316	0.466	0.055	24.02	1.59	1.012	0.010	6.01	10.77	6777.27	16122.49	1
20	52	27252	0.498	0.077	23.32	2.52	1.020	0.015	16.49	19.29	22852.63	35789.26	1
21	42	72889	0.456	0.073	23.22	3.47	1.029	0.019	39.64	23.23	65215.90	51140.19	3
22	42	23030	0.478	0.032	23.76	2.28	1.005	0.010	38.32	17.69	59289.26	36624.68	3
23	42	159183	0.343	0.051	23.32	3.96	1.017	0.017	38.94	22.66	63242.75	50716.30	3
24	42	27912	0.378	0.031	22.30	3.27	1.016	0.019	21.14	18.47	28548.09	34928.18	3
25	52	31802	0.353	0.038	22.55	2.59	1.009	0.017	8.90	8.70	8312.21	11425.16	2
26	42	105654	0.390	0.029	22.84	2.30	1.008	0.016	7.00	6.99	6055.81	8795.58	2
27	42	6335	0.400	0.014	22.64	1.03	1.004	0.007	2.13	3.55	1334.84	3606.07	1
28	52	9045	0.579	0.016	24.15	3.58	1.058	0.024	5.50	10.96	6261.22	15291.73	1
29	42	70176	0.537	0.044	24.01	2.84	1.037	0.029	6.34	12.09	7902.42	18583.90	1
30	42	47571	0.395	0.044	23.41	3.39	1.016	0.019	11.89	13.35	13755.52	20642.89	2
31	42	53530	0.472	0.049	23.22	4.14	1.036	0.033	20.87	24.60	33088.39	45362.09	1
32	42	25018	0.425	0.007	22.65	1.11	1.001	0.004	14.86	15.03	18262.21	22094.65	2
33	42	31906	0.418	0.015	23.63	3.85	1.021	0.020	9.36	14.56	11660.11	23128.72	1
34	42	25027	0.409	0.014	22.37	2.25	1.003	0.014	4.38	5.24	3220.77	6196.15	2
35	42	133539	0.500	0.030	23.88	5.45	1.106	0.028	14.80	19.44	21026.21	32392.10	1
36	42	45897	0.480	0.050	24.06	5.87	1.099	0.035	30.32	22.44	46920.29	41973.13	3
37	42	53928	0.405	0.084	22.59	5.78	1.081	0.041	25.48	19.45	36513.80	33984.80	3
38	42	83237	0.401	0.054	23.76	4.14	1.041	0.034	31.85	23.73	50593.86	46479.19	3
39	42	60599	0.505	0.043	22.88	6.19	1.108	0.036	24.31	21.93	36168.83	40813.26	3
40	42	20114	0.534	0.028	23.32	6.59	1.108	0.020	20.82	23.43	31915.16	44101.77	1
41	42	29433	0.521	0.036	23.25	6.63	1.123	0.025	14.88	18.81	20581.44	31712.53	1
42	42	37955	0.575	0.039	24.12	5.62	1.093	0.035	9.70	15.55	12673.13	23807.58	1
43	42	163176	0.506	0.051	23.30	5.57	1.101	0.033	12.79	20.19	20239.04	40944.64	1
44	42	29424	0.449	0.061	25.12	5.82	1.096	0.018	34.54	27.91	58900.73	64073.70	3
45	42	67736	0.414	0.102	22.79	6.17	1.073	0.038	22.68	17.55	30692.89	30070.41	3

Table 2: Summary of fireshed attributes for Shasta County, California. NLCD indicates the land cover type code from the National Land Cover Database, 2001. Acres indicates the total number of acres in the fireshed. Fire probability values range between 0 and 1 and listed wind speed values are those expected under near-worst case scenarios. Surface flame length is listed in meters, surface fire line intensity is kW/m. Low, medium and high crown fire activity are classified as 1, 2, and 3 respectively.

Fuel Classification System	Intended Use	Intended Scale	Compatible Models/Systems (Customize fuel models?)	Fuel elements characterized	Mapped Data
Fire Behavior Prediction System (in combination with canopy data)	Surface and crown fire behavior prediction	Site Specific	BehavePlus (Yes), FlamMap (Yes), Farsite (Yes)	Dead and down woody material up to 3" diam. Live herbs and shrubs.	Entire US (LANDFIRE), Various state, local, project-based maps (various mapping methods)
National Fire Danger Rating System	Surface fire danger prediction	Broad	NFDRS (No), FEPS (YES)	Dead and down woody material up to 8" diam. Live herbs and shrubs.	Entire US (WFAS)
Vegetation cover -based classifications (in FOFEM)	Fire effects and emissions prediction	Site Specific	FOFEM (Yes)	All dead and down woody material. Live herbs and shrubs. Litter and Duff. Canopy foliage and 0-1/4" branch wood. Rotten logs.	Entire US (LANDFIRE)
Fuel Characteristic Classification System	Fire emissions prediction	Site Specific	FEPS (Yes), FOFEM(Yes), Consume (Yes)	Trees (over-, mid-, and under-story). Class 1,2, and 3 snags. Primary and secondary shrub layers. Primary and secondary herb layers. All dead and down woody fuels (sound). Rotten woody fuels >3". Sound, rotten and pitchy stumps. Piles. Litter. Lichen. Moss. Upper and lower duff layers. Basal accumulations. Squirrel middens.	Western US (LANDFIRE)

Table 3: Summary of different fuel classification systems.

			Preburn Loading (tons/acre)
Project Total			60.08
Canopy			22.46
	Trees (total)		12.54
		Overstory trees	8.28
		Midstory trees	3.77
		Understory trees	0.49
	Snags (total)		8.95
		Class 1 snags with foliage	4.56
		Class 1 snags w/o foliage	0.03
		Class 2 snags (wood)	3.38
		Class 3 snags (wood)	0.98
	Ladder Fuels		0.97
Shrub			2.66
	Primary shrub layer		2.39
	Secondary shrub layer		0.27
Nonwoody			0.20
	Primary nonwoody layer		0.16
	Secondary nonwoody layer		0.04
Woody Fuels			16.67
	Sound woody (total)		8.09
		0 to 1/4 inch	0.48
		1/4 to 1 inch	1.59
		1 to 3 inch	1.80
		3 to 9 inch	1.12
		9 to 20 inch	2.10
		> 20 inch	1.00
	Rotten wood		8.01
		3 to 9 inch	1.95
		9 to 20 inch	2.72
		> 20 inch	3.34
	Stumps (total)		0.57
		Sound	0.02
		Rotten	0.55
		Lightered - pitchy	0.01
	Piles		0.00
Litter-Lichen-Moss			1.93
	Litter		1.91
	Lichen		0.00
	Moss		0.02
Ground Fuels			16.17
	Duff (total)		16.15
		Upper duff layer	3.86
		Lower duff layer	12.28
	Basal Accumulations		0.02
	Squirrel middens		0.00

Table 4: Summary of fuel loading (tons/acre) for forested areas in Shasta County, CA from Consume model simulation. Note that the different entries represent the various fuel strata in FCCS fuel beds.

	Emissions (tons/acre)			
Pollutant	**Flaming**	**Smoldering**	**Residual**	**Total**
PM	0.16	0.15	0.19	0.51
PM_{10}	0.1	0.12	0.15	0.37
$PM_{2.5}$	0.1	0.11	0.14	0.35
CO	0.82	1.39	1.8	4.01
CO_2	24.58	11.09	14.24	49.91
CH_4	0.03	0.06	0.08	0.16
NMHC	0.03	0.04	0.05	0.11

Table 5: Pollutant emissions (tons/acre) for forested areas in Shasta County, CA simulated in the Consume model under a very dry weather scenario. PM is particulate matter. PM_{10} and $PM_{2.5}$ are inhalable particulate matter less than 10 and 2.5 microns in size respectively. CO and CO_2 are carbon monoxide and carbon dioxide respectively. CH_4 is methane. NHMC is nonmethane hydrocarbon.

Kings River

Pollutant - tons/acre

	Local Data	LANDFIRE Data	% Difference
PM	0.18	0.20	11.1
PM_{10}	0.10	0.11	10.0
$PM_{2.5}$	0.10	0.11	10.0
CO	0.56	0.62	10.7
CO_2	27.20	30.32	11.5
CH_4	0.03	0.04	33.3
NMHC	0.03	0.04	33.3

Last Chance

Pollutant - tons/acre

	Local Data	LANDFIRE Data	% Difference
PM	0.18	0.27	50.0
PM_{10}	0.10	0.15	50.0
$PM_{2.5}$	0.10	0.14	40.0
CO	0.56	0.82	46.4
CO_2	27.65	40.52	46.5
CH_4	0.03	0.05	66.7
NMHC	0.03	0.05	66.7

Plumas-Lassen

Pollutant - tons/acre

	Local Data	LANDFIRE Data	% Difference
PM	0.10	0.25	150.0
PM_{10}	0.05	0.14	180.0
$PM_{2.5}$	0.05	0.13	160.0
CO	0.29	0.77	165.5
CO_2	14.28	37.50	162.6
CH_4	0.02	0.05	150.0
NMHC	0.02	0.04	100.0

Sagehen

Pollutant - tons/acre

	Local Data	LANDFIRE Data	% Difference
PM	0.07	0.18	157.1
PM_{10}	0.04	0.11	175.0
$PM_{2.5}$	0.04	0.11	175.0
CO	0.29	0.81	179.3
CO_2	10.18	28.62	181.1
CH_4	0.01	0.03	200.0
NMHC	0.01	0.03	200.0

Table 6: Fire pollutant emissions (tons/acre) for four study sites in the Sierra Nevada mountains, California. Emissions estimates are for flaming front and crown fire activity only, not ground fire or post-frontal combustion. PM is particulate matter. PM_{10} and $PM_{2.5}$ are inhalable particulate matter less than 10 and 2.5 microns in size respectively. CO and CO_2 are carbon monoxide and carbon dioxide respectively. CH_4 is methane. NHMC is nonmethane hydrocarbon. Local data estimates are those made with locally collected, field-based data. LANDFIRE data estimates are those made using only the publicly available LANDFIRE data.
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Flame Length		Fireline Intensity		Crown Fire Activity	
Min	0.13	Min.	3.19	1 (Low)	28.25%
Max	237.16	Max.	839885.25	2 (Med)	14.50%
Mean	9.44	Mean	11714.52	3 (High)	57.25%
St. Dev.	13.05	St. Dev.	22917.61		

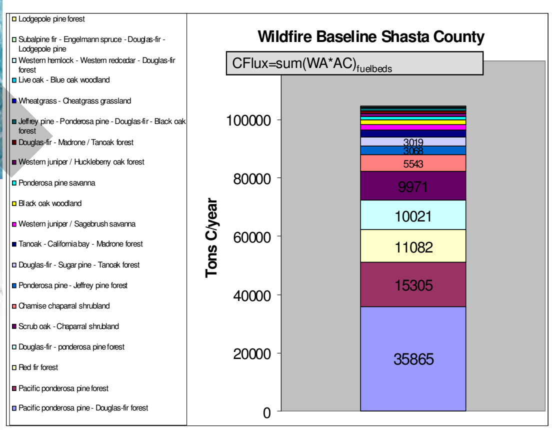
Table 7: Fire behavior characteristics for burnable wildland vegetation in Shasta County, CA. Crown Fire Activity Class is for forested vegetation only.

FINAL REPORT

April 19, 2008

DRAFT PROTOCOL FOR BASELINE FIRE EMISSIONS

Forest Fire Fuels Management for Carbon Sequestration



To: WINROCK International

Sandra Brown and John Kadyszewski, Co-Principal Investigators

By: DV (Sam) Sandberg

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Forest Fire Fuels Management for Carbon Sequestration

I Background

Objective

The objective of this assessment is to conceive a transportable methodology for establishing baseline fire activity and carbon emissions from forest fires and prescribed fires attributable to or affected by fuels management. The intent is to provide a dynamic current and future baseline of expected carbon loss from the un-treated ownerships from which to compare actual or expected future emissions from the treated ownership so that credit for carbon sequestration attributable to the management may be claimed. Context is provided by applying the baseline estimates to a trial demonstration in mixed conifer forests on selected ownership in California. Issues related to the tracking, accounting, and prediction of Carbon offsets are explored and discussed.

The central thesis of this analysis is that it is impossible to directly measure either a baseline or change over time for any area less than many tens of millions of areas. Some form of modeling will be necessary to agree on the expected annual area burned by wildfire or to assess the difference in fire risk over time or as the result of fuels treatment. Wildfire is episodic and rare, with less than a ten percent chance to visit any area within any decade, but certain within centuries. Carbon offsets for fuels treatments will necessarily be gained by demonstration, using agreed-to modeling protocols, that the risk of greenhouse gas (GHG) emissions over time from wildfires plus the sum of emissions from treatments and decomposition, minus the sum of sequestration due to growth, carbon allocation, and wood utilization are expected to be less with treatment than without treatment. The operative word is “expected”, so it is necessary to agree on how to model the effects of fuel treatment on future a) fire risk, b) fire severity, c) ecosystem response, and d) utilization.

This report will focus on treatment of forest fuelbeds and on the influence of altering the physical characteristics of fuelbeds on expected wildfire fire risk (probability of annual occurrence) and severity (GHC emissions). The direct effects of fuel treatments, including prescribed fires, as emitters of GHG’s is easily predicted by using emission models developed for air pollutant emission inventories. (Anderson et al 2004). Effects on decomposition rates, ecosystem response, and utilization are being addressed by others.

Two modeling approaches are possible to establish the current baseline (untreated) risk of fire: 1) calculating a baseline by adjusting from a large reference area to a smaller project area based on comparisons of the risk-causing biophysical characteristics of the two areas and calculating expected treatment effects by a similar comparison of before- and after-treatment fire risk, or 2) employ an intensive, site specific, deterministic fire behavior modeling for the current landscape and alternative futures by utilizing traditional fire management decision support tools such as FLAMMAP (Stratton 2004); This analysis will employ first modeling alternative, relying heavily on the Fuel Characteristic Classification System (FCCS) by Ottmar and others (2007). We believe it has the advantage over the 2nd by being more transportable, scale-independent, and less dependent on subjective expert judgment as an input.

Authority

This assessment is made by David Sandberg, sole proprietor of *Sam's FireWorks*, under contract with Winrock International and with contributions from USDA Forest Service Research. The work is done under the auspices of West Coast Regional Carbon Sequestration Partnership (WESTCARB), led by the California Energy Commission, one of 7 US Department of Energy regional partnerships with the goal of determining the best approaches to capture and permanently store greenhouse gases contributing to climate change. These government/industry partnerships are working to develop technologies, approaches and infrastructure for carbon capture, storage, and sequestration in both terrestrial and geologic systems.

Winrock International is leading WESTCARB terrestrial sequestration efforts. Terrestrial pilots are initially taking place in Shasta County, California and Lake County, Oregon, though opportunities will also be identified in Washington and Arizona. Activities include afforestation of rangelands, improved management of forest fuels to reduce emissions from wildfires, biomass energy, and conservation-based forest management. Overall objectives are to quantify emission reductions/sequestration attributable to each activity; gather information on costs and benefits to landowners; design measurement, monitoring and verification methods; evaluate the practicality of existing reporting protocols to capture verifiable reductions at reasonable cost to landowners and carbon credit buyers; explore questions of market validation for terrestrial activities; and evaluate environmental benefits.

The USDA Forest Service Pacific Northwest Research Station - Pacific Wildland Fire Sciences Laboratory/FERA Team is a key partner in this effort. David Sandberg, a private consultant and scientist emeritus representing FERA, has three decades of experience in air pollutant emissions inventory from fires and in characterizing fuelbeds, fuel consumption, and carbon emissions from fires; and is attempting to apply that experience toward the estimation of carbon baselines and project benefits for forests and fuels management.

Carbon offsets to motivate sequestration

Carbon offsetting is the act of mitigating greenhouse gas emissions by increasing carbon sequestration. Healthy forests sequester carbon as they grow biomass in durable pools such as tree boles and roots, so tree planting to replace shorter-lived vegetation is the most well-known example of a management practice that offsets emissions. Most newly-established temperate or tropical forest ecosystems continue to accumulate carbon for several decades to several centuries, depending on species composition, until they become "carbon-neutral" when mortality and decomposition rates approximately equals photosynthetic rate. Boreal forests are an exception, because the slow rate of decomposition promotes underground carbon storage that can extend sequestration for millennia. Thereafter, the system no longer sequesters carbon at a higher rate than the grassland or scrubland it replaced but it represents the one-time creation of a carbon store represented by total biomass (living and dead; above and below ground) as long as it remains a mature forest.

Harvesting live trees and utilizing the biomass in durable products such as construction materials delays decomposition for many decades and, if the harvested trees are replaced with new growing stock, sustains the forests' ability to accumulate carbon. So the true measure of the carbon store from managed forests would include the carbon sequestered in all wood products. If biomass is removed and converted to energy that reduces consumption of fossil fuels, an offset is accomplished by replacing many thousands of years of carbon formation while maintaining active sequestration by the remaining live biomass.

Fire plays an important role in determining the composition, productivity, and sustainability of most wildland ecosystems. Because fire is only one of many interacting ecological processes, managing fire to reduce carbon emissions is not as simple as preventing or suppressing fires. In fact, fire can either increase or decrease the emission of greenhouse gases over a decade or longer period by influencing other pathways of carbon sequestration and biogenic emissions.

Most wildland ecosystems, with the notable exceptions of boreal and bog ecosystems, do not forever sequester carbon from the atmosphere. Rather, they store carbon in structures during a grand period of growth and development that may last a few years (in grasslands) to a many decades (temperate forests) before mortality and decomposition roughly equals growth and the system becomes carbon neutral. Depending on climate (i.e. moisture and temperature regimes), the biomass directly consumed in mild to moderately severe fires would have decomposed and emitted roughly the same amount of greenhouse gases over those time periods as fire. Fire, by producing some long-lasting charcoal from woody debris and by charring large down logs and stumps, can even slightly reduce future decomposition rates. But all in all, the greatest effect of fire in stable temperate systems in to advance the timing of carbon emissions by a decade or two without substantially changing the carbon balance over time.

The measure of the effect of fires on carbon sequestration rates and storage depends almost entirely on the effect of fire on the health and structure of the mature forest that results after fire, rather than on the emissions or vegetation mortality from fire. Forest fires, in an over-simplistic view, are an anathema to carbon sequestration because they "destroy" forests, consume biomass and sequestered carbon, and emit greenhouse gases. It has been repeatedly proposed that preventing or suppressing forest fires could be credited as a carbon offset. In a few cases, it is true that severe forest fires do consume a significant fraction of living biomass or convert an ecosystem from a forest to a system that supports less standing biomass or even a system with a less productive system that for centuries will store carbon at a slower rate. Or, in boreal systems, create a warmer microclimate where below-ground carbon storage is lost. But the overwhelming fraction of biomass consumed in forest fires is from the accumulation of forest floor and dead fuels that would have otherwise released carbon dioxide as it decomposed over the next decade or two. So the actual effect of forest fires is to advance the release of those emissions by a few years. Tree mortality caused by fire is rapidly replaced in roughly equal measure by regeneration and growth of younger trees or by concentration of growth on the remaining large trees. Less severe fires, such as low-intensity fires in fire-dependent ecosystems of the Western United States, typically improve forest health and eliminate competing undergrowth, effectively transferring carbon stores from shorter-lived species to the boles and roots of trees.

Fuels management, for the purpose of reducing the frequency, size and severity of wildfires and a practice that may also yield useable biomass, has increased dramatically in the past decade on public lands. The increase in costly and destructive "mega-fires" generally attributed to climate change and decades of fuels buildup resulting from prior fire suppression has provided the incentive to invest heavily in restoring forest structure and fuel loading to sustainable levels. Dead biomass loading is almost always either generated through forest stand management or is consumed by fire by prescribed-burn treatments. In any case, fuels management advances either the short-term decomposition or the consumption of biomass in comparison to the unmanaged condition. Whether the advanced emissions or decomposition are offset by increased sequestration depends largely on two secondary effects of fuels management: 1) was the long term health (i.e. sequestration) of the forest ecosystem improved? and 2) was the eventual occurrence of wildfire or other forest disturbance either delayed or made less severe?

Accountability systems for GHG emission baselines

Widely accepted principles have been published for accountability systems for Project Baseline Scenarios for Greenhouse gas emissions (World Resources Institute 2005), In a sense parallel to the development of emission reduction systems for air pollutants over the past four decades, accountability systems based on these principles apply most readily to industrial and transportation sources for which a reasonably constant pattern of emissions can be inventoried and used as a baseline from which to measure future reductions. The obvious and standard methodology is to measure emissions, or inventory parameters thought to be reliable parameters to estimate emissions, over a period of years and simply project the average GHG emissions forward as a constant baseline for comparison to future inventories. Unlike air pollution baseline emissions, however, a GHG emission baseline is a forward-looking and hypothetical estimate of "what would have happened in the future" in the absence of the opportunity to mitigate climate change by offsetting emissions.

GHG emission baselines for Wildland Fire

The emissions baseline for wildfires is the area (acres) that would burn in the absence of a carbon project multiplied by the fuel loading (tons/acre) multiplied by the proportion of fuel consumed by fire (tons/tons) greenhouse gas emissions, or "GHG emission factor" (tons/tons) from each ton of fuel. Simplistically,

$$WGHG_{wildfire\ emissons}^{annual\ basline} = WA_{wilfire\ \ area}^{annual\ baseline} \times WF_{fuel\ load} \times WC_{\%Consumed} \times EF_{CO2}$$

Where

$$WA_{wilfire\ \ area}^{annual\ baseline} = PA_{project\ area} \times W\%_{wilfire\ area\ burned}^{annual}$$

Emission Factors, EF, for greenhouse gases are the most certain term in the equation. Forest fuels almost uniformly contain about 50% carbon (although rotten material can be as low as 35-40% carbon). About 95% of the carbon is released as carbon dioxide and a small quantity released as methane, carbon monoxide, or other greenhouse gases; so it is reasonable to apply an emission factor of about 1835 tons of CO2 per ton of fuel consumed. About 1-2% of the carbon in biomass is left behind as charcoal, sequestered for centuries in that form.

Fuel Consumed, WC, by fires can also be predicted with considerable accuracy on the basis of fuel moisture content at the time of burning. Several fuel consumption models have been published and are in routine use by fire managers.

Fuel load, WF, can range from a fraction of a ton per acre in grasslands to 100 or more tons in forests. Although highly variable, it is measurable directly in the field or estimated from vegetation cover, bioclimatic region, and qualitative description of the biophysical environment using the Fuel Characteristic Classification System, FCCS (Ottmar et al 2007). Forest fuelbeds are complex mixtures dead woody debris on the forest floor, plus a surface layer of moss, lichens, and recently fallen litter, a deeper layer of partially decomposed ground fuels that may burn under dry conditions, low non-woody vegetation, and shrubs (Riccardi and others 2007). In severe wildfires, tree branches and canopies are also significant components of the available fuel (Sandberg and others 2007a). Modeling biomass consumption, GHG emissions, or decomposition cannot be done with one measure of fuel load, but requires the combination of several algorithms that consider the entire fuelbed complex.

The natural (i.e. in the absence of fire management) fire return interval, i.e the inverse of fire risk, both depends upon and expresses itself in the vegetation cover type, and ranges from a year or three in some grasslands to centuries in some forest types. In much of the fire-dependent conifer ecosystems of the West, natural fire return interval would be on the order of 10-25 years, meaning that 4-10 percent of the forest lands would be visited by fire each year. But fires in the Western United States now burn about one-half of one percent per year, suggesting that fire control is approximately 90 percent effective at reducing area burned.

Wildfires are quasi-random, episodic events subject to influence to some extent by fuels management but also to a myriad of intrinsic ecosystem characteristics, weather conditions, ignition probabilities, and the influence of prevention and suppression activities. Consequently, it is extremely difficult to predict what would happen in the absence of fuels management or to assess the marginal effect of increased fuels management. Expected wildfire area burned, WA, is nearly impossible to measure directly.

Trends in wildfire area burned are difficult to establish because of the extreme inter-annual variability. It is simply impossible to measure the difference in fire frequency on any area smaller than a very large bio-region because any local trend is washed out by chance. Attempts have been made to measure the trend in area burned in the United States or other large regions such as Alaska or boreal Canada and even on those large areas the trends are difficult to establish. Nielson and Lenihan (2004) observed a very modest downward trend between 1960 and 1985 in the contiguous United States and a sharp increase (432 thousand acres per year) between 1991 and 2003 that could be due to climate change and or fuel buildup (figure 1). The data were used to tune their simulation model of area burned, which suggests that fire management has excluded 7/8 of natural fire risk.

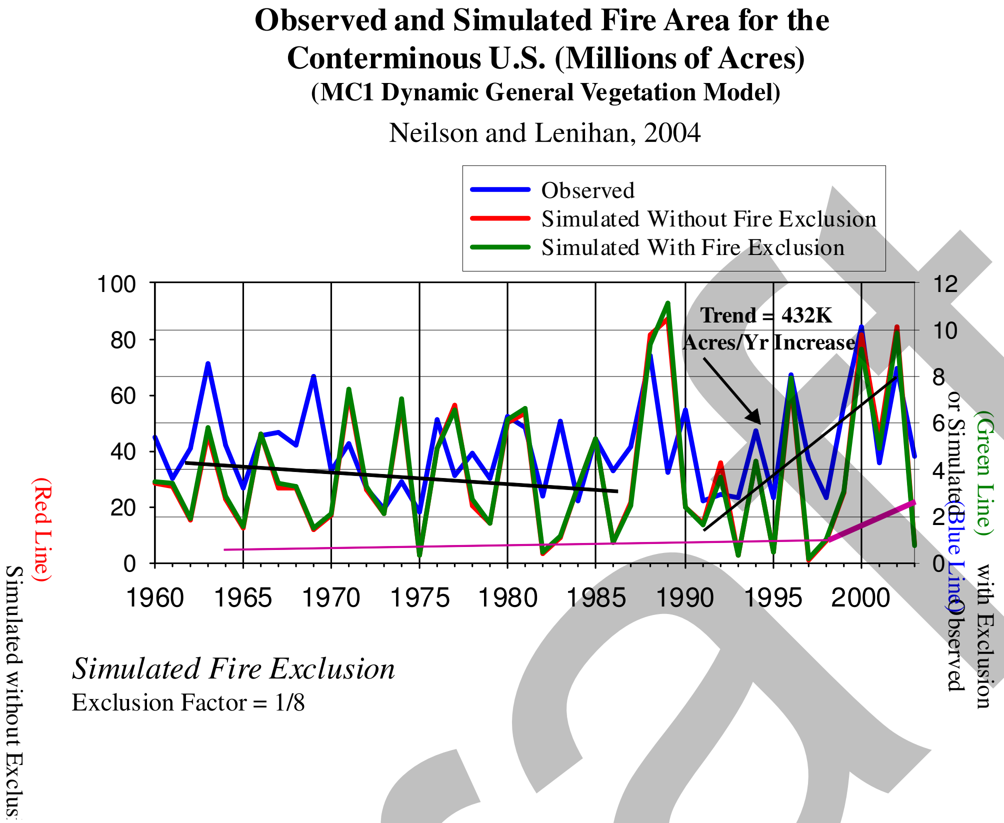


Figure 1. Increase in burned area observed and simulated by Neilson and Lenihan (2004)

Fuels Management, Fire Occurrence, and Fire Severity

Land management agencies and land owners in the United States spend several hundred million dollars per year treating forest fuels to reduce fire occurrence and severity. The effect on area burned is uncertain in part because total area burned and the number of very large fires continues to trend upwards, probably due to climatic change. It is taken on faith that the upwards trend would be even greater in the absence of fuels management, but quantitative proof has been elusive.

Obviously it is easier to suppress fires where fuel loadings and fuel continuity have been altered by fuel treatment, and the severity (biomass consumed and environmental impacts) of those fires is lowered. It is possible to accurately predict the change in fire behavior, biomass consumption, carbon flux, and air pollutant emissions per unit area that result from fuel treatment, but attempts to quantify reduction in burned area have been frustrating.

Central to our approach is our conclusion that annual area burned by wildfire cannot be reliably observed on any small area, i.e. smaller than a state or bio-region. It would be even more impossible to measure the change in fire area burned over any period of time shorter than several decades.   So, there is no hope of establishing an area burned (or carbon flux) baseline on a project area smaller than tens of millions of acres or a period of less than 30 years. The standard practice of measuring carbon flux or the level of activity for a greenhouse gas emitting activity and re-measuring carbon flux at intervals of 5-10 years is not a useful model for evaluating the effectiveness of fire or fuels management efforts.

Instead, some form of modeling must be employed to calculate a baseline for wildfire area burned and carbon flux, and the same form of modeling will be necessary to predict or re-calculate burned area and carbon flux in future decades with and without fuel treatment. That modeling could be done by deterministically simulating fire behavior under assumed weather, fuels, and management scenarios on every “fireshed” in a project area. Federal land management agencies are currently attempting to demonstrate that type of modeling in several areas including parts of the Sierra Nevada region of California.

An alternative approach is presented here that will be to establish a Large-Area historic baseline for wildland fire area burned, and then to adjust the baseline to the smaller Project Area based on differences due to such factors as a) Inflation of wildfire area burned over time, b Vegetation cover distribution, and c) Fuelbed characteristics. It may be possible in the future to also adjust for regional differences in d) Fire Weather, e) Ownership and management, and f) Social and ecological context.

II. DRAFT PROTOCOL for establishing GHG emission project baselines for Wildland Fire Carbon emissions from wildland fire

Step 1—Establish a Historic Large-Area (Reference Area) Burned Area Baseline:

$HFRisk_{ref}$ = Historic Annual Area Burned (in Large Reference Area, A/yr)/Large Reference Area (A)

a) Select a reference area, such as a State, Eco-region, Climate Zone, or other large area that includes the Project Area that has a reliable long history (20+years) of fire occurrence records, including fire size.

b) Compute a 10-year (or other period of between 5 and 20 years) running average of annual burned area. Compute the coefficient of variation of the average area burned, which will represent the minimum standard error of the absolute baseline area burned estimate.

c) Try different combinations of alternate Large Areas and history time periods to attain a satisfactory (or most accurate) historic baseline.

Step 2—Inflate Large-Area Baseline to account for wildfire increases

$TimeHFR_{ref} = HFRisk_{ref} \times 1.007^{(analysisyear - historicbaselineyear)}$, *where*

$TimeHFR_{ref}$ = Time-inflated historic fire risk (1/yr)

1.007=Default annual area-burned inflation factor

a) Inflate wildfire burned-area baseline to current year and future years using annual inflation rate of 0.5-0.9%, or other more applicable value, if known.

b) Adjust the wildfire risk, using other management and sociological factors, if quantifiable.

Step 3—Compare Large-Area Baseline to Project Area Fuelbed or Vegetation Cover:

$$PArea_{i.ref} = Area_{i.ref} \div \sum_{i=1}^{n} Area_{i.ref}$$

a) Determine the area covered by FCCS fuelbed or vegetation cover type, for which historical data or an algorithm exists that enables one to establish the relative fire risk for each fuelbed or type.

b) Using the FCCS mapping capability (McKenzie et al 2007) or other spatial classification of fuelbed or vegetation classification, determine the proportion of area covered by each class in candidate Large (reference) Areas.

c) Using the same classification, determine the proportion of Project Area covered by each class in the Project Area.

$$PArea_{i.project} = Area_{i.project} \div \sum_{i=1}^{n} Area_{i.project}$$

PArea is the proportion of the total area in either the Large Area (ref) or Project Area (project) covered by FCCS Fuelbed i.

$Area_{i.ref}$ = Area of FCCS Fuelbed *i* or Vegetation Type *i* in Reference Area

$Area_{i.proj}$ = Area of FCCS Fuelbed *i* or Vegetation Type *i* in Project Area

Step 4—calculate fire risk by vegetation or fuelbed type in the Project Area

a) Differentiate fire risk for each fuelbed or vegetation cover type using expert judgment based on published guidelines, or employ an algorithm based on fuelbed structure.

b) There are no published algorithms that assign a Relative Fire Risk by fuel or vegetation type, but we offer the following as an example of several that have been proposed: (this subject deserves much more investigation)

    a. Hypothesis 2, h2:

    $RFR_i = {}^{1}/_{RFRI_i}$

    $RFRI_i = 2.0 + 2.3C_{surface.i}$

    RFR_i = Relative fire risk for fuelbed *i*
    (Probability of burning per year, 1/yr)
    $RFRI_i$ =Relative Fire Return Interval (frequency of expected fire, yr)
    $C_{surface\ fuel}$ = Carbon store (fuel load/2) in surface fuel strata (ton/A)
    i = FCCS fuelbed identifier (Ottmar, 2007) or substitute classification.

c) Establish a table of regional-area adjusted fire risk (fire return interval or expected percent annual area burned) such that the product of fire risk multiplied by proportion of area covered for each fuelbed type in the Large Area equals the wildfire burned-area baseline.

$$\text{Adjusted Fuelbed Annual Fire Risk, } AFR_i = Adj \times RFR_i,$$

$$where: Adj = TimeHFR_{ref} \div \sum_{i=1}^{numberoffuelbeds} (RFR_i \times Area_{i.ref})$$

Step 5—Calculate carbon flux (C released per area burned) for each fuelbed or vegetation type.

a) Utilize a recognized fuel consumption model such as CONSUME, FOFEM, FEPS, or FCCS at the moisture scenario appropriate for wildfire to compute carbon flux for each FCCS Fuelbed or type.

$$CFlux_{i.wildfire} = f(fuel.moisture.scenario)_{wildfire}$$

Step 6—Calculate baseline carbon flux (C released per year) for Project Area

a) Multiply carbon flux by adjusted area burned for each Fuelbed, then sum.

$$\text{Project Baseline Carbon Flux} = BCFlux_{project.wildfire} = \sum_{i=1}^{number.of.fuelbeds} (AFR_i \times CFlux_{i.wildfire})$$

III. TRIAL APPLICATION DRAFT PROTOCOL for establishing GHG emission project baselines for SHASTA COUNTY, California

Step 1—Establish a Large-Area Baseline:

Despite extreme variability, there is little choice but to rely on the historical record as starting point for establishing a GCG emissions from wildfires. In order to obtain a reasonable sample of annual burned area one must choose a large enough area and long enough record to be reliable, in most cases larger (and more diverse) than the project area. There are several sources of historical fire records covering large areas. All are secondary compilations of individual fire reports from public agencies. The fire reports have their own accuracy problems, but are the only source currently available. Remote sensing by satellite is slowly replacing individual fire reports as a source of area-burned monitoring, but remains unreliable other than for very large fires.

We explored several possible large area baselines based on Statewide (California and Oregon) fire occurrence records as well as a number of vegetation or fuel classification systems. Few states have as complete or accurate records of wildfires as California. California also shares with Washington and Oregon the best record keeping systems for prescribed fires. In addition to statewide records, there are data bases established to assess fires by ecoregion and land cover types (figure 2).

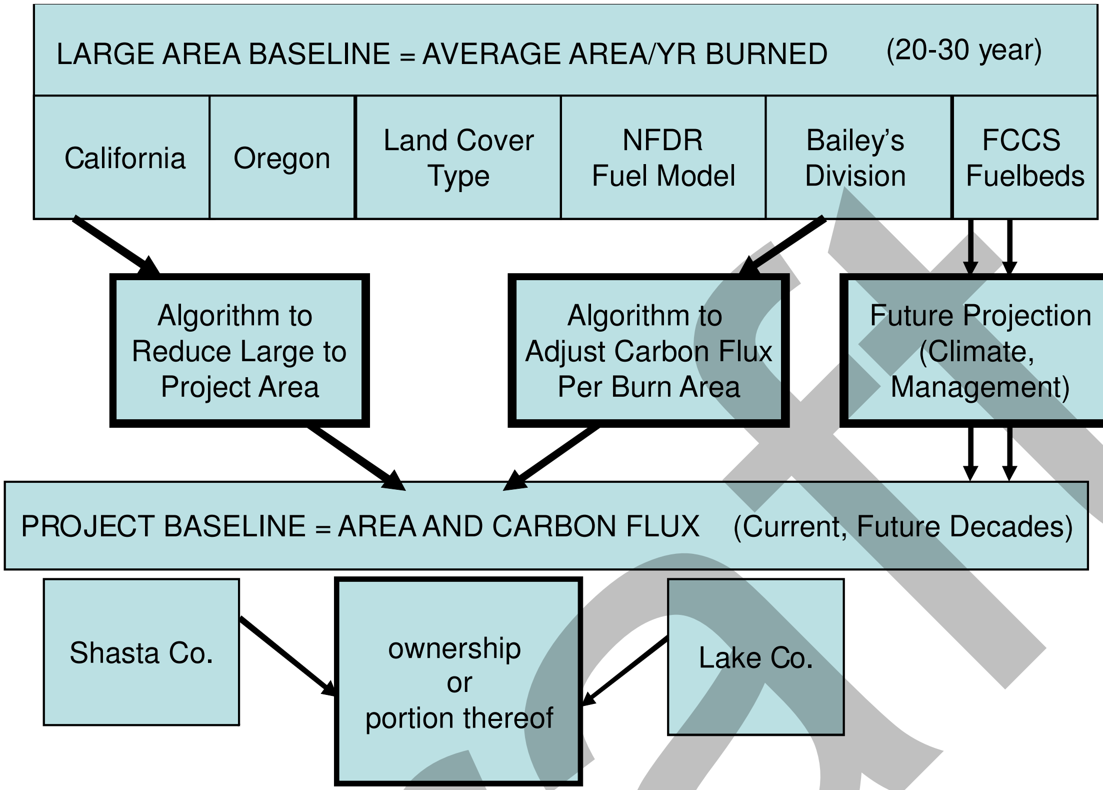
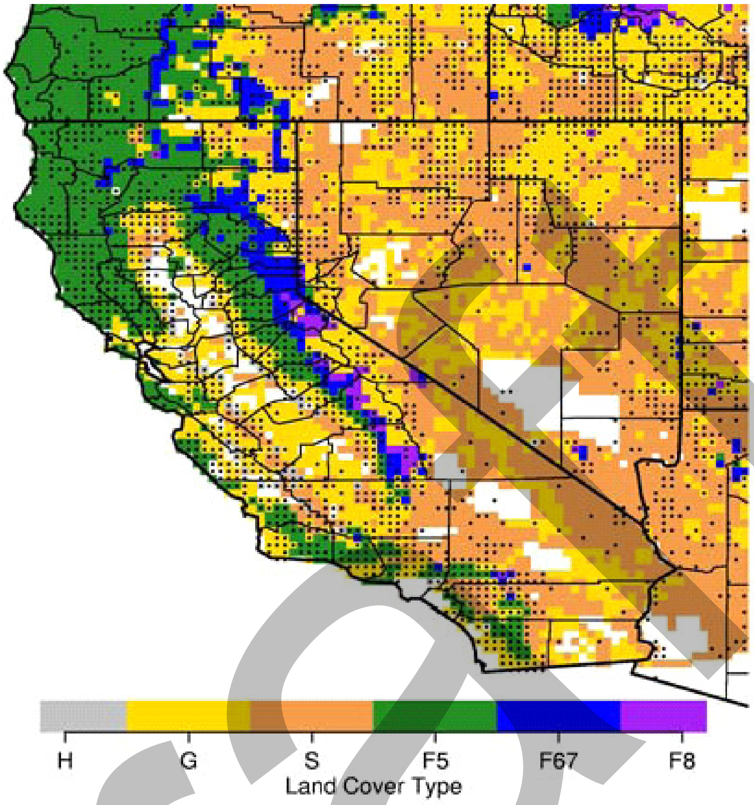


Figure 2. Adjusting large area baseline to project area

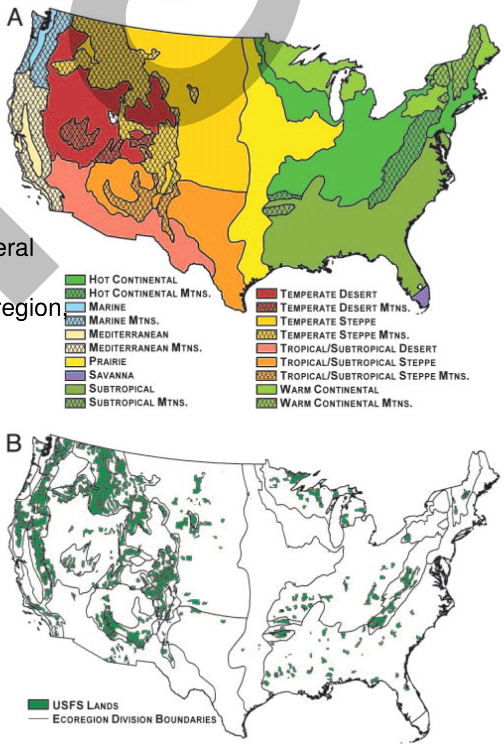
Several assessments have been made of the historical fire record in California and in eco-regions that include California and Southern Oregon by the California Climate Center (Westerling and Bryant 2006) , the Desert Research Institute (Brown 2002, Malamud et al 2006) and CFRAP (CDF 2003, Brown et al 2006). Malamud and others (ibid) examined 30 years of federal fire data to establish an expected area burned by Bailey's eco-region (figure 3).

Westerling, Bryant 2006



DRI-CEFA (Brown 2002; 30 year federal data)

Malamud et al 2005; (Bailey's ecoregion fire return interval)



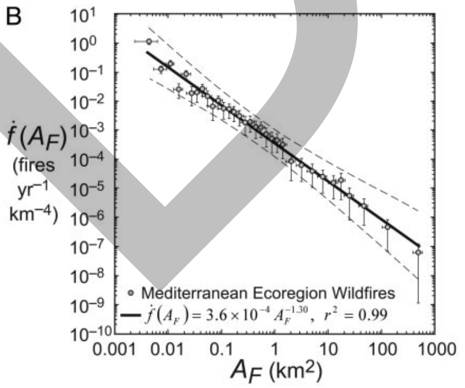
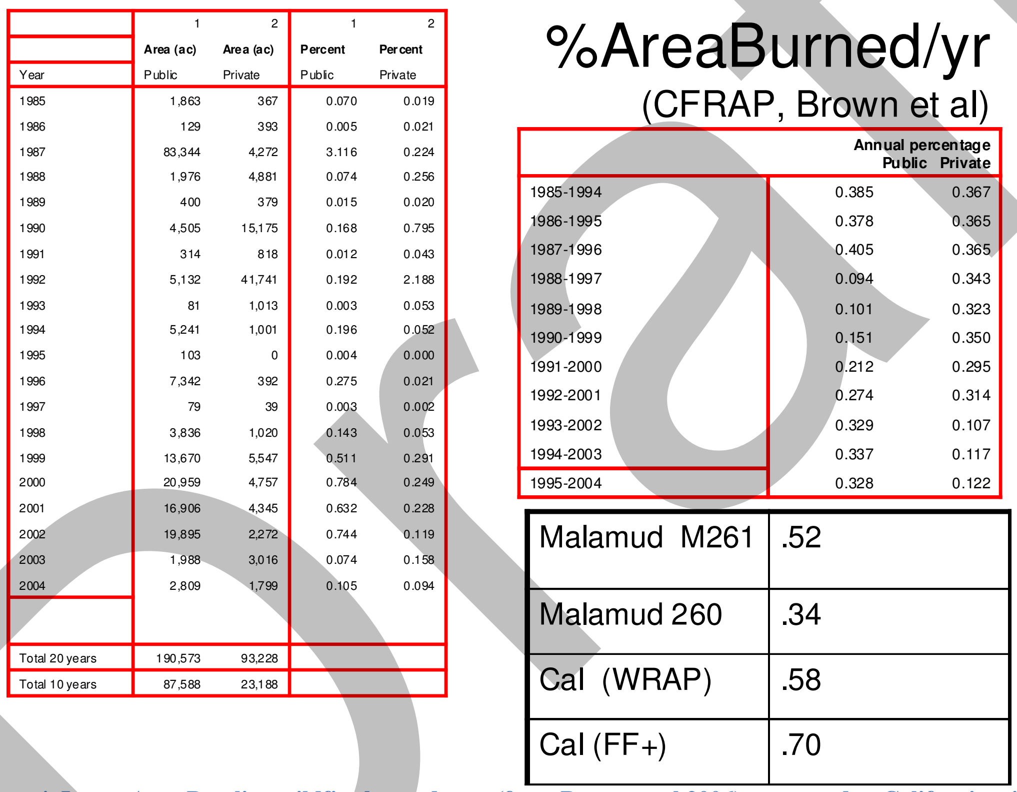


Figure 3. Fire return interval established for Bailey's eco-regions using 30 years of federal fire reports.

Establishing a baseline for wildfire activity has a very weak anchor point in the historical record. It is difficult enough to establish an average or a trend for wildfire area burned annually (or even buy decade) on a national Scale, but almost impossible on any smaller scale. The states of California, Alaska, Montana, Oregon, and Colorado have each recently dominated the area burned in one calendar year; and each have exceeded their previous record for area burned within the past decade. About the most that can be said is that: over the past 20 years in the State of California, or in the mountainous western United States, about 0.3-0.7 percent per year has burned over in an average year, as in figure 4. The two eco-regions that best represent the Sierra Nevada and Southern Oregon project area have experiences .34 and .52 percent per year burned area.



	1	2	1	2
	Area (ac)	**Area (ac)**	**Percent**	**Percent**
Year	Public	Private	Public	Private
1985	1,863	367	0.070	0.019
1986	129	393	0.005	0.021
1987	83,344	4,272	3.116	0.224
1988	1,976	4,881	0.074	0.256
1989	400	379	0.015	0.020
1990	4,505	15,175	0.168	0.795
1991	314	818	0.012	0.043
1992	5,132	41,741	0.192	2.188
1993	81	1,013	0.003	0.053
1994	5,241	1,001	0.196	0.052
1995	103	0	0.004	0.000
1996	7,342	392	0.275	0.021
1997	79	39	0.003	0.002
1998	3,836	1,020	0.143	0.053
1999	13,670	5,547	0.511	0.291
2000	20,959	4,757	0.784	0.249
2001	16,906	4,345	0.632	0.228
2002	19,895	2,272	0.744	0.119
2003	1,988	3,016	0.074	0.158
2004	2,809	1,799	0.105	0.094
Total 20 years	190,573	93,228		
Total 10 years	87,588	23,188		

%AreaBurned/yr

(CFRAP, Brown et al)

	Annual percentage Public	Private
1985-1994	0.385	0.367
1986-1995	0.378	0.365
1987-1996	0.405	0.365
1988-1997	0.094	0.343
1989-1998	0.101	0.323
1990-1999	0.151	0.350
1991-2000	0.212	0.295
1992-2001	0.274	0.314
1993-2002	0.329	0.107
1994-2003	0.337	0.117
1995-2004	0.328	0.122

Malamud M261	.52
Malamud 260	.34
Cal (WRAP)	.58
Cal (FF+)	.70

Figure 4. Large-Area Baseline wildfire burned area (from Brown et al 2006) compared to California wildfire area burned (CDF) and Malamud (2005) area burned in two ecosystem domains.

The simplest baseline area burned would be to project a future where percent of the project area were expected to burn each year would remain constant (represented by the past 30 years)

$HFRisk_{ref}$ = Historic Annual Area Burned (in Large Reference Area, A/yr)/Large Reference Area (A)

$$HFRI_{MalamudM\,261} = 0.52\% / yr$$

Step 2—Inflate Large-Area Baseline to account for wildfire increases

In addition to being extremely variable year to year, wildfires occurrence does not regress over the decades to a historical average. As the climate warms and fire seasons become longer, the area burned by wildfires in the United States is trending upwards at a rate of a few hundred thousand acres per year. One estimate, by Neilson and Lenihan (2004) (see figure 1), is that wildfire area burned in the contiguous United States will grow at about 430 thousand acres per year, or an annual inflation rate of 0.7 %/year. Westerling and Bryant (2006) used a completely different analysis to predict similar inflation (0.5 %/yr) based on scenarios from General Circulation Models (figure 5), and Wilkenson (2002) predicts about an 0.9%/yr increase.

CCI: Climate Change Area Inflation (%/yr) = 1.007 ?

Westerling, Bryant 2006

Figure 6. Standardized annual expected number of 1/8 degree x month voxels with at least one large fire (> 200 ha, or > 494 acres) 1951–2100 for A2 and B1 emissions scenarios and GFDL and PCM global climate models. Bold lines are the result of smoothing with Friedman's supersmoother (Friedman 1984) with a span of 0.3.

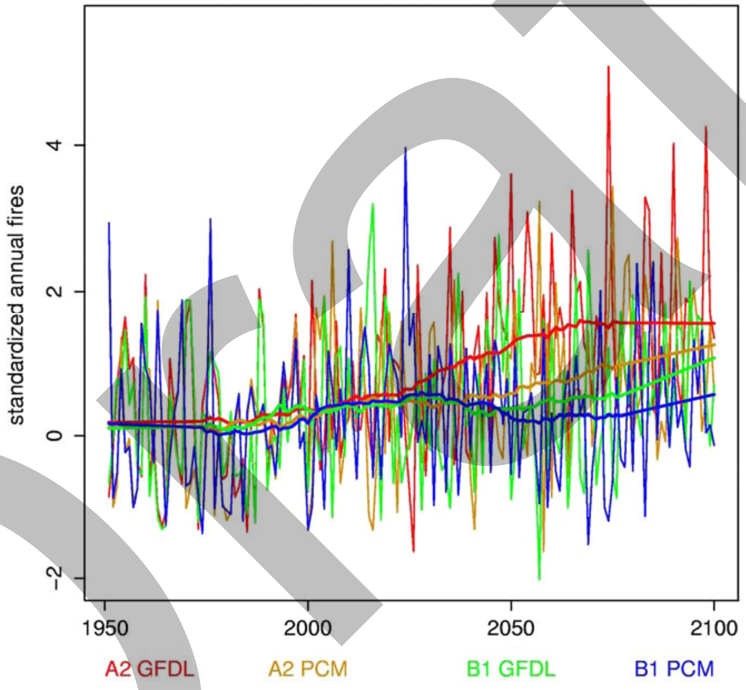


Figure 5. Predicted increase and annual variability in California wildfire burned area by Westerling (2006)

We should consider inflating historic estimates and future baselines by that amount, for example, for 2008 and 2058 baselines:

$TimeHFR_i = HFRI_i \times yrs^{aif}$, *where*

$TimeHFR_i =$ Time-inflated historic fire risk (1/yr)

$yrs =$ years between refernce period and analysis period

$aif =$ annual area-burned inflation factor (default $aif = 1.007$)

$$TimeHFR_{M\,261.2008} = 0.52 \times 1.007^{20} = .60\%/yr, and$$

$$TimeHFR_{M\,261.2058} = 0.52 \times 1.007^{70} = .85\%/yr, and$$

Step 3—Relate Large-Area Baseline to Project Area Vegetation Cover:

a) Using the FCCS mapping capability (McKenzie et al 2007) or other spatial classification of fuelbed or vegetation classification, determine the proportion of area covered by each class in candidate Large (reference) Areas.

b) Using the same classification, determine the proportion of Project Area covered by each class

$$PArea_{i.ref} = Area_{i.ref} \div \sum_{i=1}^{n} Area_{i.ref}$$

$$PArea_{i.project} = Area_{i.project} \div \sum_{i=1}^{n} Area_{i.project}$$

PArea is the proportion of the total area in either the Large Area (ref) or Project Area (project) covered by FCCS Fuelbed i.

Available fuel loading for many vegetation types is uniquely available by accessing the Fuel Characteristic Classification System, or FCCS (Ottmar and others 2007). The system enables land managers and scientists to create and catalogue fuel measurements taken in the field or to choose from a limited library of a few hundred “canned” FCCS fuelbeds selected on the basis of vegetation cover type and Bailey’s eco-region province. Those FCCS fuelbeds have been mapped for the contiguous United States on the basis of remotely-sensed vegetation cover (McKenzie et al 2007; figure 6),

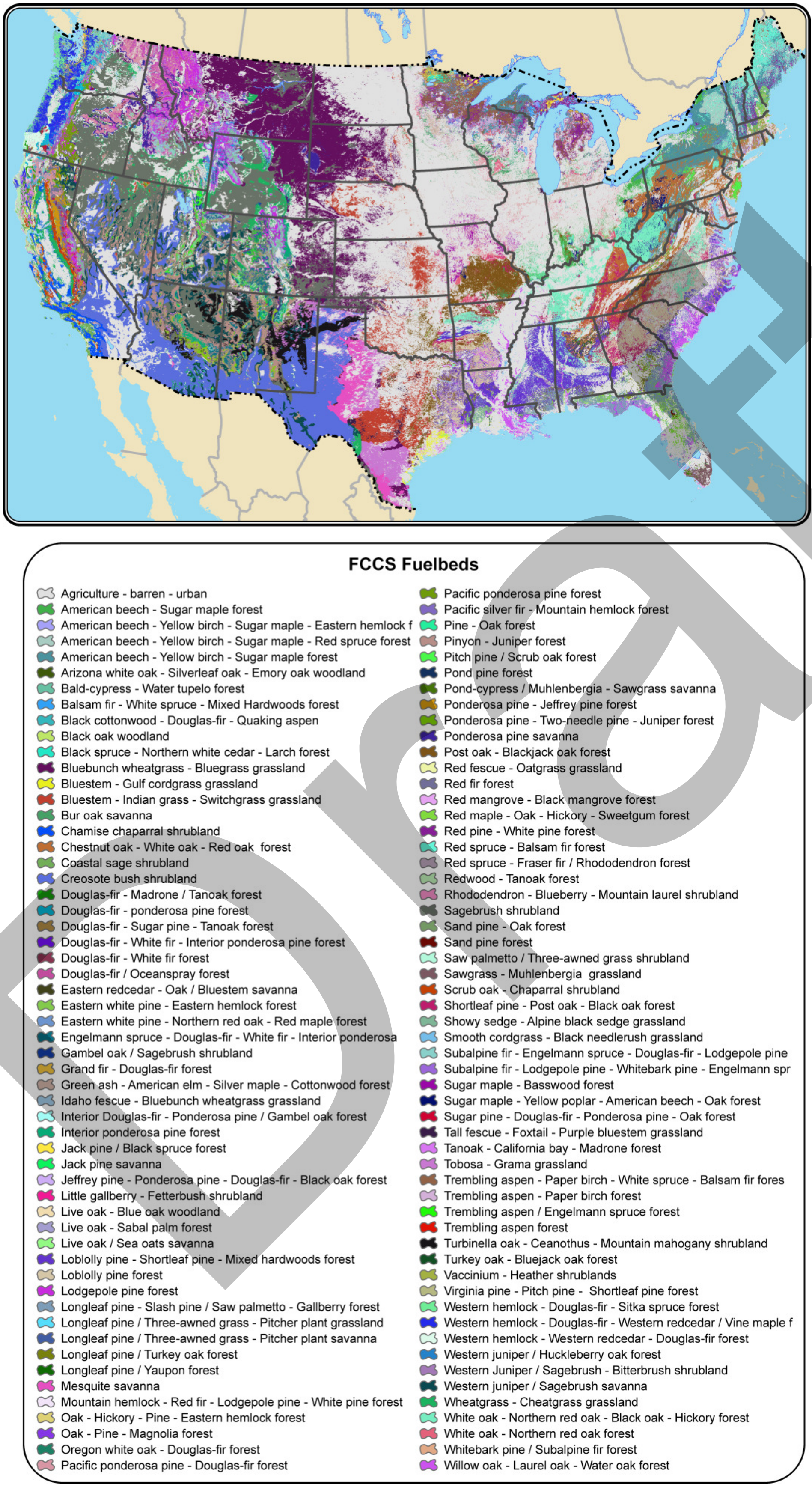


Figure 6. National map of FCCS fuelbeds (McKenzie et al 2007)

and those authors have contributed a breakdown of FCCS fuelbed coverage of the Large Areas (i.e. California, Oregon, and Provinces 260, M261, and 340) and County (Lake Co. OR and Shasta Co. CA) areas considered in this project (figure 7).

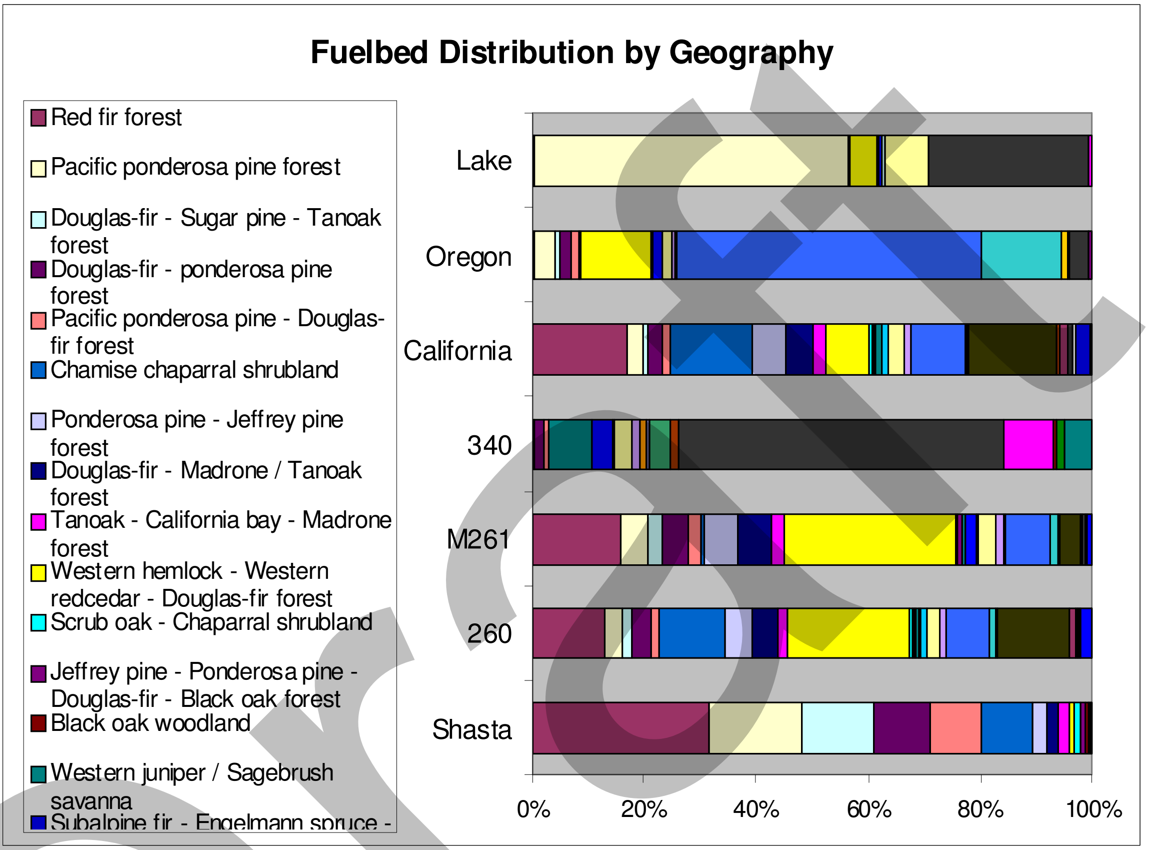


Figure 7 FCCS Fuelbed distribution in Large Area baseline references and in Project Area counties, contributed by McKenzie et. al.

Visual comparison of fuelbed distributions in Shasta or Lake County to any of the Large Area baseline references in figure 6 makes it obvious that some adjustment should be made to the large-area estimates of wildfire area burned and the estimate of biomass available for consumption in a wildfire.

Step 4—calculate fire risk by vegetation or fuelbed type in the Project Area

Adjusting the expected Fire Return Interval (FRI) from the Large Area to the Project area is more problematic. Let me specify up front that there is <u>no</u> published literature that can adjust the FRI based on measured physical attributes of a fuelbed or vegetation structure. While it is clear that fuelbeds such as "wheatgrass" will have a very short FRI relative to "red fir forest", there is no generally accepted algorithm for calculating either on the basis of fuel characteristics. So all we can do now is form hypotheses and see if they look reasonable.

The Project Area will almost differ from the Large Area in two significant ways, unless the distribution of vegetation cover is identical in the two areas because both 1) the Fire return interval (and percentage of area burned per year) and 2) the fuel loading are strong expressions of vegetation cover. In general, the natural fire return interval is very short (on the order of 1-3 years) for grasslands, intermediate (10-50 years) for shrub lands and pine forests, and longer (100+ years) for other coniferous forest lands. The natural fire return interval for many vegetation, not to be confused with return interval for lands under management, is extensively available in the literature.

Conversely, the shorter fire-return interval vegetation types typically have less available fuel loading (i.e. fuel load that would burn in a fire than the longer-interval types. Does that mean, as sometimes assumed, that the two factors offset? That over any long period of time, the product of accumulated available fuel loading and probability of fire each year is constant? No, because ecosystems with a longer fire return interval sequester a greater proportion of carbon in structures that are unavailable for consumption by fire. So, the longer Fire Return Interval ecosystems types can be expected to yield less carbon as a result of fire on an average annual basis.

a) Differentiate fire risk for each fuelbed or vegetation cover type using expert judgment based on published guidelines, or employ an algorithm based on fuelbed structure.
b) There are no published algorithms that assign a Relative Fire Risk by fuel or vegetation type, but we offer the following as an example of several that have been proposed:

    a. Hypothesis 2, h2:

$$RFR_i = {}^{1}/_{RFRI_i}$$

$$RFRI_i = 2.0 + 2.3C_{surface.i}$$

RFR_i = Relative fire risk for fuelbed *i*
(Probability of burning per year, 1/yr)

FRI h2: One hypothesis (h2) is that one can differentiate the likelihood of fire during any time period by measuring the buildup of surface fuels, such that risk is roughly inverse to the fuel loading in the surface (i.e. litter, down woody, herbaceous, and shrub vegetation) fuelbed strata. The FCCS system accounts for biomass allocation (Sandberg and others 2007) in such a way that we can calculate that proportion for each FCCS fuelbed. There are alternative hypotheses, but this one results in an expected FRI ranging from 2 to 108 years, as shown in figure 8. These expected, but not regionally adjusted natural fire return interval are not in conflict with the rage of FRI's reported in the ecological literature. Chamise-chaparral fuelbeds, for example, would have an approximate natural fire return interval of 25 years, while wheatgrass would burn every 2 years.

This is only one hypothesis of many possible hypotheses that relate physical fuelbed characteristics to fire risk or historical fire return interval. It has never been tried before. But it is reasonable that any algorithm based on the allocation of carbon to grasses and other flash fuels increasing fire risk and on the allocation of carbon to coarse fuels and canopy fuels will have some value in explaining the variation in fire return intervals among ecosystems.

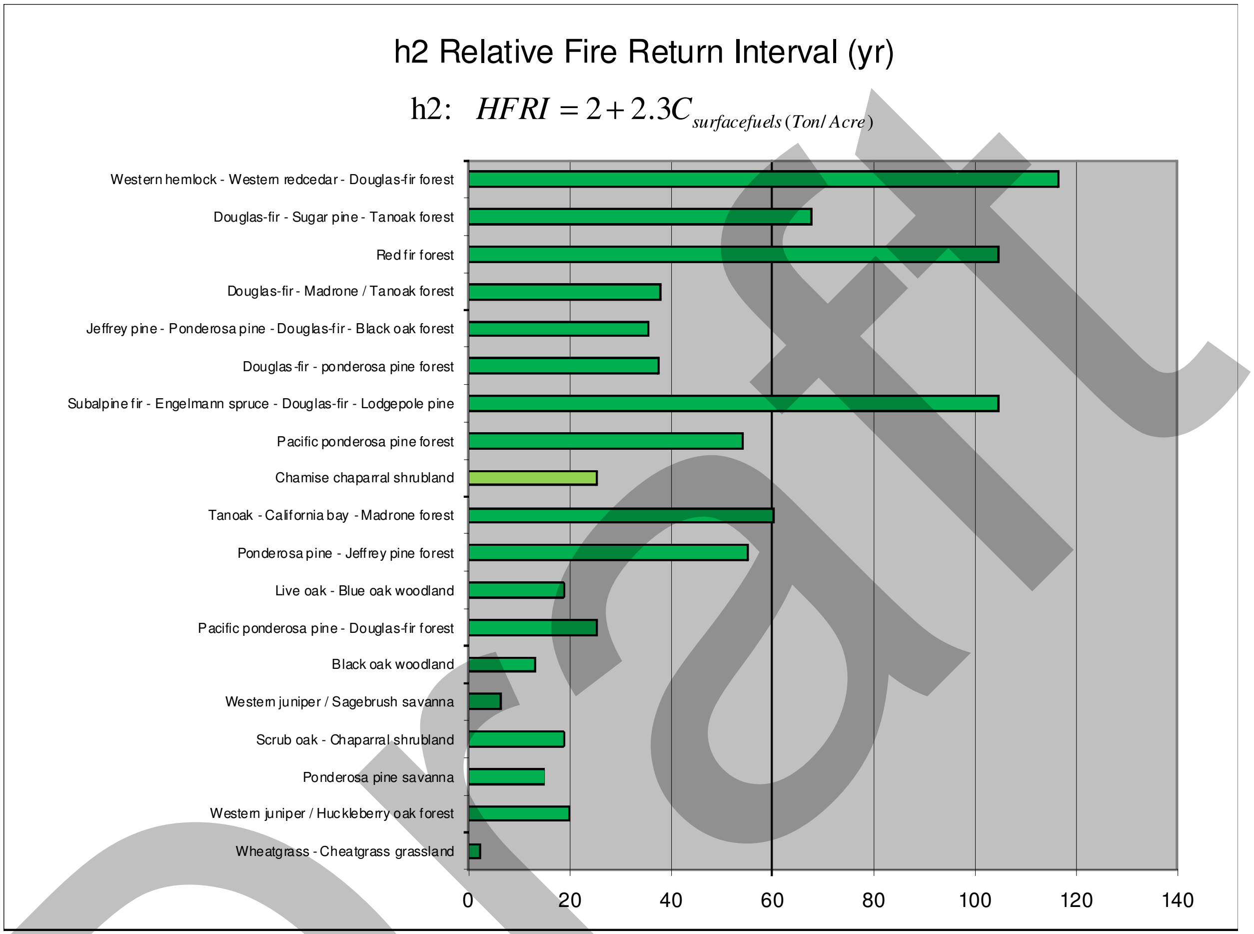


Figure 8. Relative Fire Return Interval (inverse of the annual probability of wildfire on any area) based on the hypothesis that fire return interval is directly proportional to the carbon (C) storage in the surface fuels.

Relative Fire Return Interval, RFRI, is an rough approximation of the natural fire return interval for each Fuelbed. RFRI must be adjusted regionally, by normalization, to the observed historic (or time-inflated) Large Area baseline area burned in order to calculate an expected area burned for the Project Area. At this point, I assume the Project Area will be the entire of Shasta County, although the same procedure would be used for any size project.

As a test, I normalized the relative values by constraining the sum of the products of 1/RFHI x Fuelbed Area for each fuelbed to the observed 30-year average area burned in the Large (reference) Area (figure 9). As validation, I used three Large Area reference areas to test h1 and multiplied the expected (i.e. baseline) area burned by the wildfire carbon flux for each FCCS fuelbed (from figure 8). There is a variance of about 20% among the three estimates which I accept as a reasonable, if not perfect, validation. Perfect validation would result in identical estimates of expected area burned regardless of the Large Area used as reference.

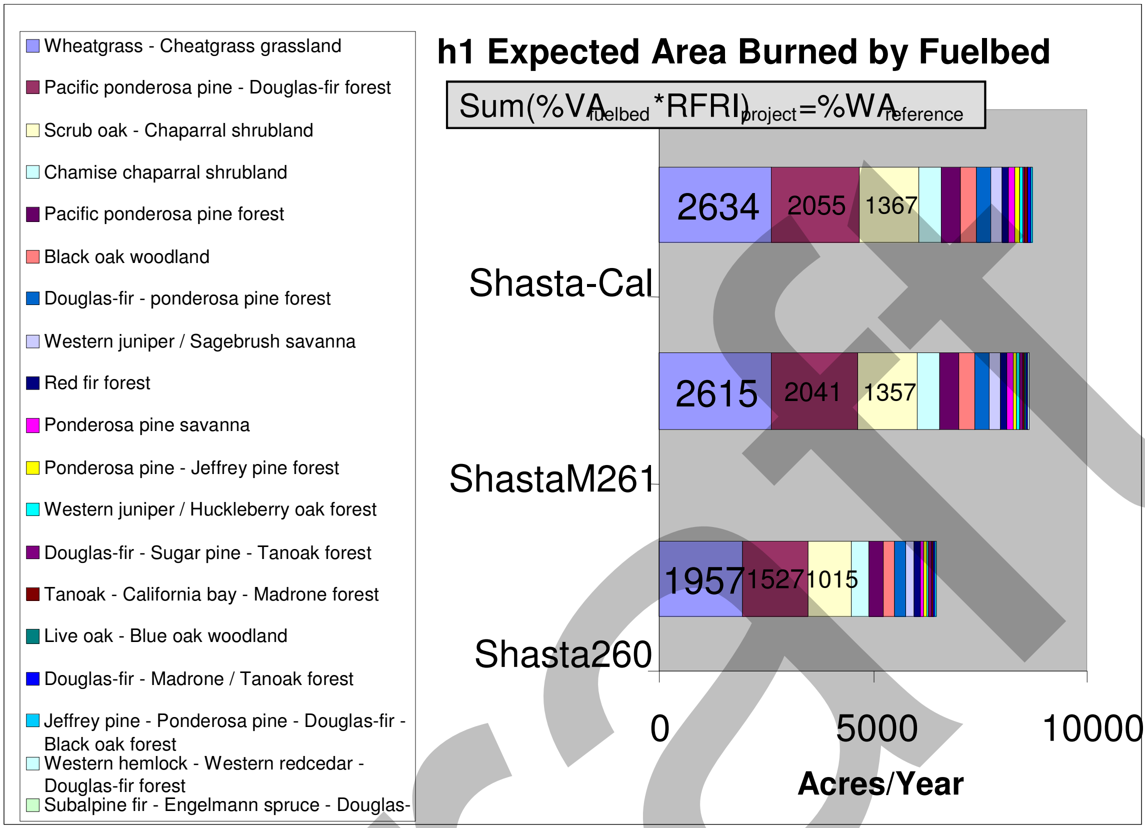


Figure 9. Expected (historic baseline) area burned annually by in Shasta County CA by FCCS, normalized on the basis of Relative Fire Return Interval, to the area burned in California and in two Provinces (M261 and 260) of Bailey's ecoregion classification. Wheatgrass –cheatgrass fuelbeds account for the largest contribution to wildfire baseline burned area.

I accepted Bailey's Province M261 as the most representative Large Area for the Project Area, based on the relative similarity of vegetation cover, and adjusted the h1 Relative Fire Return Interval for each FCCS Fuelbed in that Province (from figure 8) and forced (i.e. normalized) the sum of products to yield the observed historic fire burned area in that province. The calculated fire risk (inverse of fire return interval) for each Fuelbed (figure 10). As expected, the adjusted annual fire risk is greatest for grasslands (3.6%/yr) and lowest for coastal and high elevation coniferous forests (.07-.08% /yr) . Mid-elevation forest lands (where timber management is most often practiced) are estimated to have an average fire risk of 0.07% (Red fir) to 0.29% (Ponderosa pine-Douglas-fir).

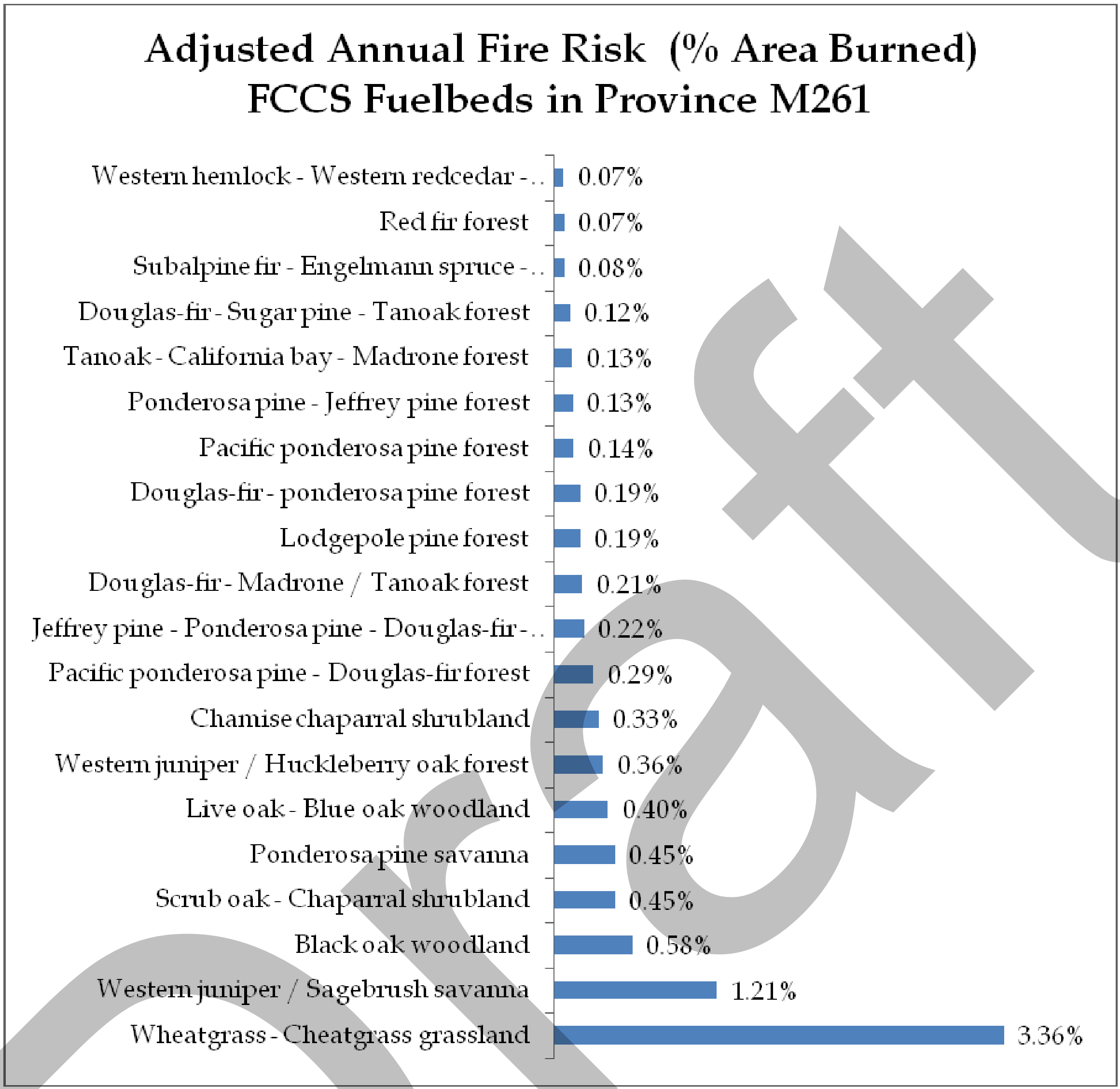


Figure 10 Historic annual fire risk for FCCS fuelbeds in ecosystem province M261. The individual fire risk are assumed to be the same for any Project Area (including Shasta County) in the Province

There are other ways to approach a calculation of baseline area burned. Under a separate subcontract with Winrock, scientists at the University of California, Berkeley (UCB) compiled a detailed fire history in Northern California using a vegetation classification system independent of Bailey's classification and FCCS. The two baseline estimates are illustrated in figure 11. There is no crosswalk currently that allows detailed comparison of the results other than to make a couple of gross observations 1) the UCB estimates an annual area burned in Shasta County to be about 10,000 acres while the h2/FCCS method estimates 8700 acres, and 2) a greater share of the estimate in the h2/FCCS is in grasslands. Shasta County covers 2472470 Acres, so the two methods yield an annual fire risk of 0.041 (UCB) and 0.035 (FCCS).

Comparison of Shasta County Baseline Area burned estimates from UCB (10021) andFCCS(8701) Acres/year. It would be useful, but take a few days of effort, to assign an FCCS fuelbed to each vegetation type in the UCB analysis. The two bars on the Sandberg data reflect baselines derived from the California and M261 ecoregion-wide fire histories.

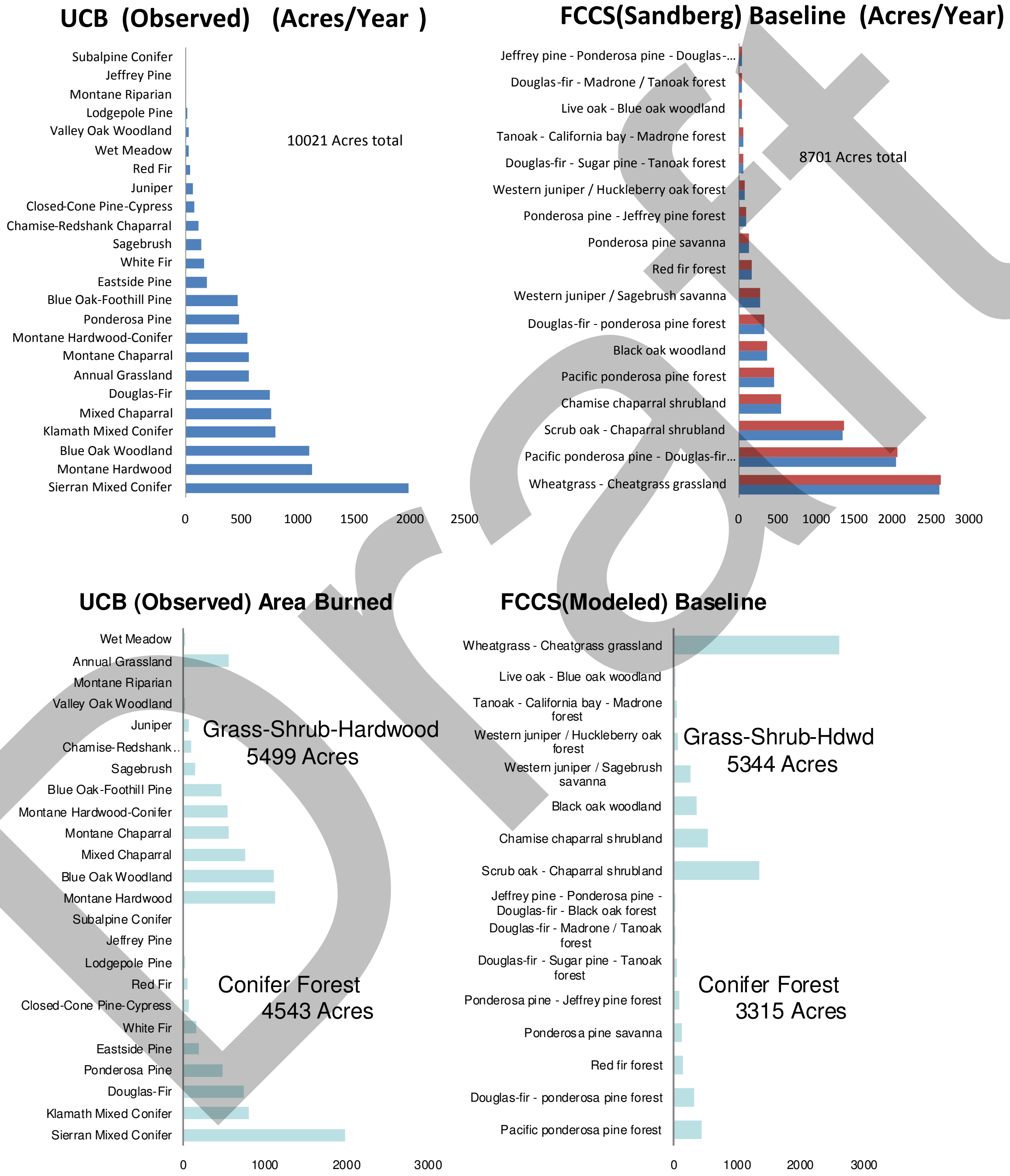


Figure 11 . Comparison of expected (historic baseline) area burned annually by in Shasta County CA using the University of California (observed) and the FCCS (modeled) methods. , Fuelbeds and vegetation classes grouped by life form.

Step 5—Calculate carbon flux (C released per area burned) for each vegetation of fuelbed type.

Each of the FCCS fuelbeds imputed to the geographic areas in figure 6 have a distinct fuel loading. FCCS includes measured values for each size class (0.1-hr, 1-hr, 10-hr, 100-hr, and 1000-hr) and category (foliage, nonwoody vegetation, shrub, woody, litter, and duff) in each fuelbed. Several fuel consumption models, with fuel moisture profiles as inputs, are available to estimate biomass consumption from any FCCS fuelbed or directly measured fuelbed profile. I ran one of these models, i.e. model now integral to FCCS software, to calculate total fuel consumption (expressed at tons/acre carbon flux) at three fuel moisture profiles based on the 1000-hr moisture content (figure 12). The lowest fuel moisture would be representative of wildfire conditions, while the two other moisture scenarios span the typical range of prescribed fires. Several other models are available whose use would be justified, including CONSUME (Ottmar et al 2005), FOFEM (Reinhardt et al 2001), and FEPS (Anderson et al 2004).

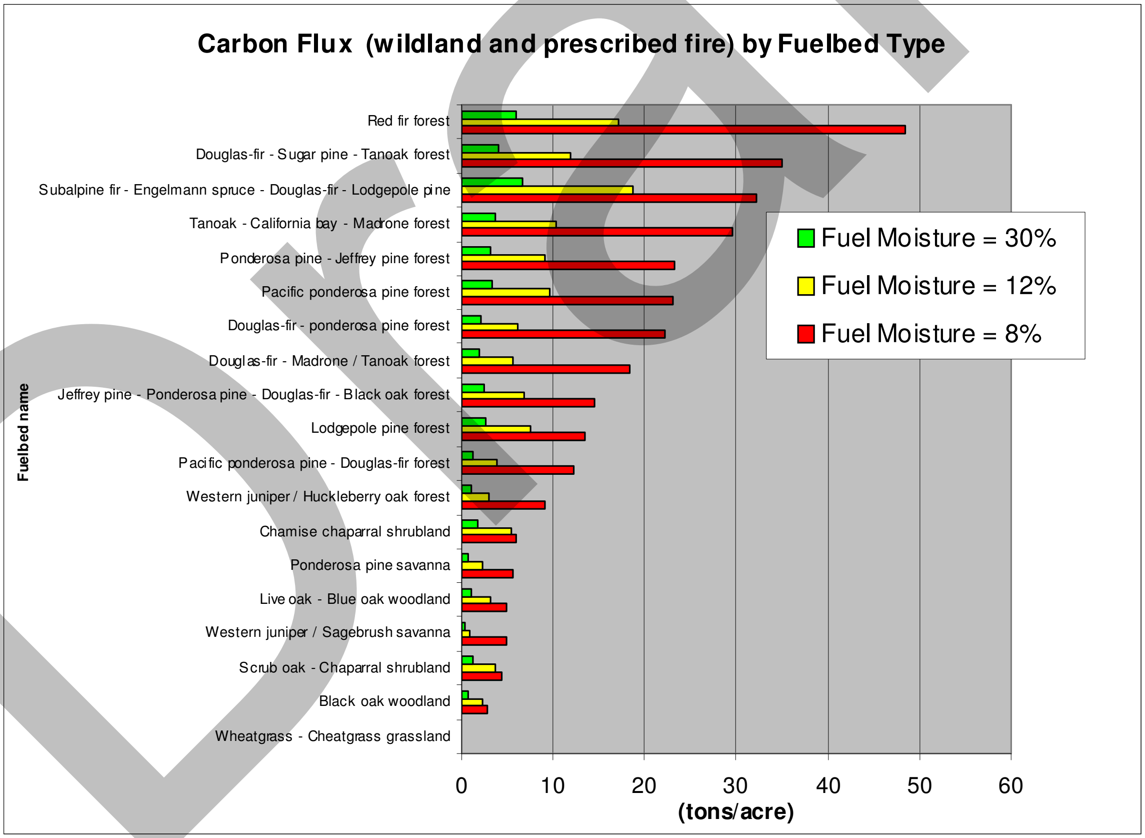


Figure 12. Carbon Flux (tons/acre C) for FCCS fuelbeds in Oregon/California at three 1000-hr moisture content profiles. The "8%" moisture profile represents an average wildfire; 12% and 30% represents a range in fluxes expected from prescribed fire in each fuelbed.

Step 6—Calcualte historic baseline carbon flux (C released per year) for Project Area

a) Multiply carbon flux by adjusted area burned for each Fuelbed, then sum.

$$\text{Project Baseline Carbon Flux} = BCFlux_{project.wildfire} = \sum_{i=1}^{number.of.fuelbeds} (AFR_i \times CFlux_{i.wildfire})$$

Finally, the expected (historic baseline) annual area burned for Shasta—M261 (figure 11) was multiplied by the expected carbon flux from wildfires (figure 12) for each FCCS fuelbed to yield a historic baseline annual carbon flux for Shasta County (figure 13). Although a grass fuelbed (Wheatgrass-cheatgrass) is the greatest contributor of annual expected burned area (2600 acres), the type contributes only 300 tons per year to the carbon flux baseline. There are 11 Conifer-forest FCCS fuelbeds identified in Shasta county that contribute a total of 81000 tons per year to the Carbon flux. Shrub and deciduous forest fuelbeds contribute another 20100 tons per year to a total carbon flux of 104,443 tons C per year.

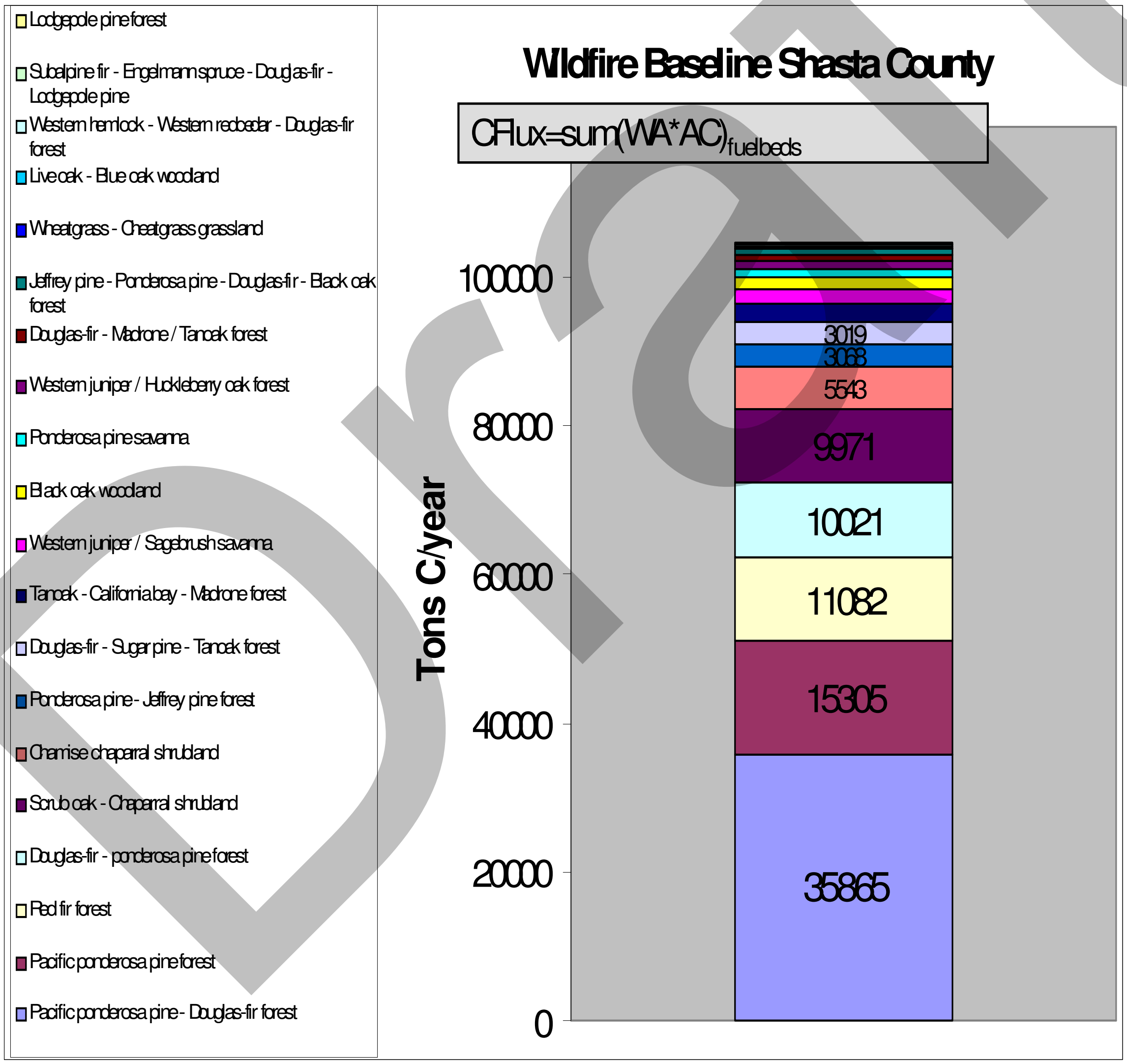


Figure 13. Historic wildfire carbon flux in Shasta County by FCCS Fuelbed type, i.e. the expected annual area burned by the wildfire carbon yield from each fuelbed present in the county. The greatest contribution to the baseline carbon flux are 4 coniferous forest types (Ponderosa pine-Douglas-fir, Ponderosa pine, Red fir, and Douglas-fir-Ponderosa pine). Total historic baseline wildfire carbon flux is 104,443 Tons per year.

Steps 4 and 6 in this test case were based on the Historic Fire Risk rather than a time adjusted risk (Step 2) Returning to the issue of the observed and predicted inflation of annual wildfire area burned, one could apply an factor of 1.007/year to the carbon flux in figure 13. Assuming that no increase in area carbon flux (tons/acre) occurs simultaneously, the 104 thousand tons per year can be expected to have increased to at least 120 thousand tons per year by 2008 and to 170,000 tons by 2058.

IV. SUMMARY and CONCLUSION: Draft protocol for establishing GHG emission project baselines for Wildland Fire Carbon emissions from wildland fire.

- Establishing Project baselines and measuring offsets for fuel management to reduce wildland fire greenhouse gas emissions must rely on modeling. Direct measurement is an unreliable baseline because of the episodic nature and extreme annual variability of fires.
- The baseline for wildfires is not a historic baseline, but is what would have occurred in the absence of fuel treatment in a future also affected by climate change, vegetation land use patterns, and cultural trends. The annual fire risk in most of the United States is increasing at between 0.5% and 0.9% per year.
- The same methodology and assumptions must be used both for establishing a baseline and for measuring the success of mitigating treatments, because any methodology used is likely to be less accurate than the magnitude of the offsets measured. The selected methodology must be precise enough to detect change and be repeatable by different analysts at different times.
- The draft protocol described in this report is based on quantitative algorithms that require no subjective or expert input. However, the assignment of relative risk based on vegetation or fuelbed characteristics is speculative. The example provided is based on an unpublished and narrowly-validated algorithm for that step. This represents a promising avenue for additional research.
- This analysis is intended to be fully transportable and can be used with a minimum of intensive data inputs. All information used for the baseline calculation exists in the public domain. Results could be improved with some specific site data characterizing the fire environment including better fuels, topographic, weather, and management influences.
- Alternatives to this approach include accomplishing a data-intensive and expert-system driven “fireshed” analysis under trial by several federal land management agencies. It is unknown whether that approach will provide adequate precision or repeatability, but it may prove a better alternative where its expense is justified.

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VI. WORK LEFT UNDONE

Establishing a baseline is an essential but an early step in establishing protocols for measuring offsets for forest fuels management, and the proposed methodology presented here is still imperfect. But the modeling framework used to measure baseline emissions can be extended to predict future baselines as well as the impacts of fuel treatments on wildfire and prescribed fire emissions. Next on the agenda:

1. LIFE-CYCLE FLUX ANALYSIS.: Develop the protocols to represent long term forest life-cycle analysis of carbon fluxes from under natural and alternative management scenarios.

Challenging addition work should be done to fully express baseline emissions from managed forests in order to represent the integral of all natural and anthropogenic sources of GHG emissions and sequestration over a forest life cycle (figure 14)

- 100-year, harvest cycle, or biological rotation baseline scenarios accounting for natural and management processes
    - Decomposition
    - Fuel accretion
    - Risk of non-fire disturbance (insects, windthrow, etc)
    - Succesional Change in forest structure (allocation to trees, shrubs, herbaceous, ground fuels)
    - Intermediate harvest
    - Fuel Treatments
    - Prescribed fire
    - Silvicultural treatments
- Recalculation of fire risk resulting from each process at each time interval

2. FUELBED-BASED FIRE RISK QUANTIFICATION: Improve on Step 4: Correlate annual fire risk to physical fuelbed characteristics.

Published statistical correlation between fuelbed characteristics and fire risk is absolutely essential to provide an automated, objective prediction of the effects of fuelbed changes on fire risk. This project provided a proof of concept that biomass production rates and the relative allocation of carbon by ecosystems into various fuelbed strata is useful for predicting natural fire return intervals and annual fire risk.

3. TREATMENT "SHADOW" EFFECT: Develop a simple, automated method for assigning an area-effect multiple for reduction in fire risk.

Spatial patterns of fuelbeds, including treated and untreated areas can be analyzed analytically or statistically to provide measures of percolation or resistance to fire spread. Fire behavior potentials (Sandberg and others

2007) provide a measure of fire spread and extreme fire behavior based on fuelbed characteristics that could be developed into a simple and automated default for the multiplying "shadow" effect of fuel treatments. The US Forest Service intensive "Fire-Shed" analysis is a data rich and expert-judgment based methodology that can be applied in some specific high value cases with good results, but is too subjective and area-limited to be widely transported.

4. INTEGRATION AND APPLICATION: Fuel Characterization Classification System and Consume; R5 Life-Cycle Analysis and SPLATS, Winrock policy development; California

The Winrock-lead contribution to the West Coast Regional Carbon Sequestration Partnership is a groundbreaking demonstration effort involving several agencies, institutions, and private entities. Many advances have been made in a healthy collaborative environment, but there has been no true coalescence into a clear team effort with clear expected application and outcome. The opportunity presents itself in California to apply specific local projects and Statewide programmatic strategies whose value in carbon offsets are measured by jointly developed and accepted set of protocols.

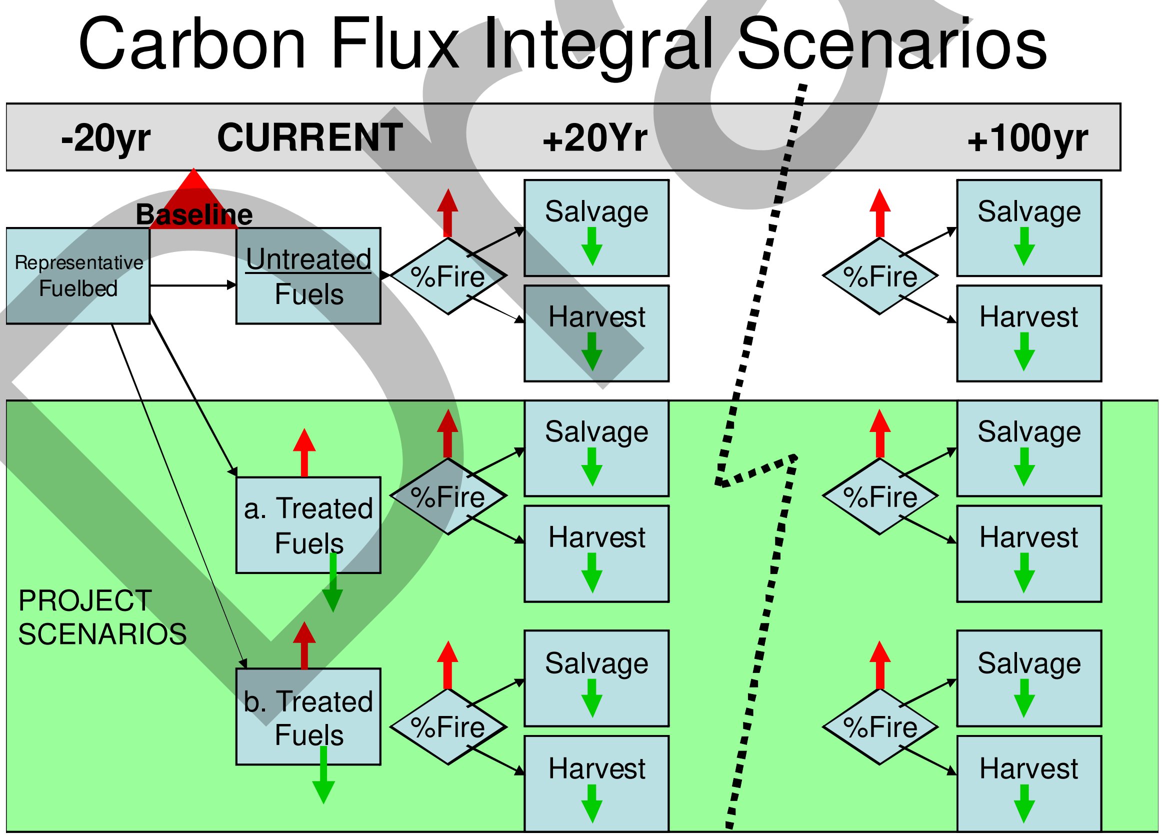

Figure 14. Carbon flux in managed forests consists of several management entries, vegetation succession, and natural events that each have an effect on fire risk as well as emitting or sequestering carbon.

APPENDIX D

A.

RATES OF DECOMPOSITION OF WOODY DEBRIS IN WESTCARB REGION (Northern CA and Southern OR)

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RATES OF DECOMPOSITION OF WOODY DEBRIS IN WESTCARB REGION
(Northern CA and Southern OR)

Introduction

This report was requested in support of methodology for determining carbon credits for improved fuel management. As specified in the statement of work, the report contains literature review and analysis of data on rates of decomposition of woody debris of species and sizes typically found in the mixed conifer forest type of northern CA and southern OR.

The key for understanding and managing woody debris in forest ecosystems is an understanding of the rate this material decomposes. Given this information one can plan the silvicultural, fuel treatment and other practices required to maintain dead wood at desired levels. Unfortunately decomposition rates have been determined for very few species and in a limited number of locations and site conditions. In the Pacific Northwest, the main species that have been reported are Douglas-fir and western hemlock (Graham 1982, Grier 1978, Means et al 1985, Sollins et al 1987). Other species such as lodgepole pine have also been published (Fahey 1983, Busse 1994), but most species remain without this level of examination. Preliminary data on 17 species occurring in the western United States (five locations in Oregon, one in California, one in Colorado, and one in Washington) has been posted on the web at http://www.fsl.orst.edu/lter/pubs/webdocs/reports/decomp/cwd_decomp_web.htm . These data sources and unpublished results from a branch decomposition experiment form the basis of this report. While none of the study sites are within the boundaries of WestCarb project pilot studies, eleven of the sites described in Appendix 1 are near enough to provide relevant decomposition data.

Methods and Sources of Data

The source of the data used in this report was taken from the peer-reviewed literature and from a preliminary report on decomposition rates for 17 species growing in the western Unitied States. Data on wood decomposition was obtained from eleven different sites with different climatic characteristics across the Western US (Table 1). The general approach used at each of the sites differed (Table 2). The three methods used (i.e., chronosequences, time series, and decomposition vectors) are defined below. Each estimate method has a level of uncertainty associated with it.

Chronosequence Approach

The chronosequence approach was used at Frasier, Sequoia, Olympic, Medicine Bow, and Central Oregon to determine decomposition rates from logs in which the sampling occurred only once. In a chronosequence one ages many pieces in various states of decay and examines how a parameter such as density changes through time. This is a substitution of space for time, and while not as precise as a time series experiment (where individual pieces are followed through time) it provides a good first approximation of decomposition rates (Harmon et al. 1998). The uncertainty with this method is intermediate.

Table 1. Climatic characteristics for each site.

	Mean annual temperature		Mean annual precipitation	
Site	Degrees C	Degrees F	mm	Inches
Cascade Head Experimental Forest (CHEF), OR	10	50	2489	98
Fraser Experimental Forest (FEF), CO	0.5	34	737	29
H.J. Andrews Experimental Forest (HJAF), OR	10	49	2500	98
H.J. Andrews Experimental Forest (FRIS), OR[a]	6.7	44	2221	87
Klamath Ranger District (KRD), OR	4	40	1054	42
Pringle Falls Experimental Forest (PFEF), OR	7	45	813	32
Sequoia National Park (SQNP), CA	8	46	1255	49
Wind River Experimental Forest (WREF), WA	8.7	47	2467	97
Warm Springs Reservation (WSR), OR	8.3	47	1778	70
Olympic National Park (ONP), WA	10	50	4000	157.5
Medicine Bow National Forests (MBNF), WY	5	41	600	24
Central Oregon			280	11

[a] FRIS plot in upper elevation.

Table 2. The type of measurements made at each study site.

Location	Type of measurement	Number of Measurements
CHEF	Decay classes, decomposition vector	2 times
FEF	Chronosequence	2 times
HJAF	Time series	5-9 times depending on sp.
FRIS	Chronosequence	1 time
KRD	Chronosequence	1 time
PFEF	Time series	3 times
SQNP	Decay classes, decomposition vector, chronosequence for Abco	2 times
WSR	Time series	1 time
WREF	Decay classes, decomposition vector	2 times
ONP	Chronosequence	1 time
MBNF	Chronosequence	1 time
Central OR	Chronosequence	1 time

Time Series

In a time series a cohort of fresh logs is placed out and individual pieces are followed through time (Harmon et al .1998). Typically a log is sampled once, after a planned interval expires. As different logs are sampled over time the trend in decomposition is revealed. It is more accurate than the chronosequence approach, but takes a lot more time to examine the full range of changes. This method was used at H. J. Andrews, and Pringle Falls. This method has the lowest uncertainty.

Decomposition Vectors

The final method used to study decomposition rates is the decomposition vector method which involves resampling pieces after a set period of time (Harmon et al. 2000). If the age of the piece being sampled can be determined it represents a combination of the chronosequence and time series methods. It is also possible to make estimates of decomposition rate for decay classes. This method allows one to quickly and accurately determine changes in both density and volume over the full range of decay conditions. We used this method at Cascade Head, Fraser, and Sequoia. This method has high certainty when the age of the pieces is known, but the lowest uncertainty when decay classes are resampled.

Methods used to determine density of coarse woody debris

Aside from determining the age of a piece, the key measurement to determine decomposition rates is density of the bark and wood. Density is expressed as a dry mass divided by green volume in most cases, although density can be determined in alternative ways. Pieces are subsampled with a chainsaw to remove cross-sections along the stem. Key characteristics such as presence of leaves, twigs, branches, bark, cross-sectional shape, wood hardness, and strength are typically recorded to help assign the piece to a decay class. Volume is determined either by displacement in water or a particulate solid (e.g., millet seed), taking a known volume using a core, or by measuring external dimensions. While volumes determined by external dimensions are less accurate, they can take quite rapidly in the field on very large volumes and have been the most frequently used.

Mass of samples is typically determined by drying in an oven, often at temperatures ranging between 55 and 75 ˚C until mass remains constant. This can take a extended period of time of weeks for even small cross-sections. To speed up drying times, smaller subsamples are often used. This entails weighing the entire sample and then subsampling for moisture determination. The ratio of oven dried mass to the fresh mass of the subsample is used to convert the fresh mass to dry mass of the entire sample.

In addition to determining the density it is important to determine the volume lost during decomposition. While some of this loss is due to fragmentation, some of it is due to the total respiration of some parts of logs (e.g, sapwood and stem tops). In cases where this correction has not been made the density can be overestimated and the mass loss underestimated (Harmon et al. 1987).

Decomposition rates for small diameter wood

This experiment was conducted in Pringle Falls. Fresh branchwood and twigs of four different size classes (1, 4, 8, and 15 cm) were cut into short lengths, weighed, tagged and placed on the forest floor. The original dry weight was estimated by subsampling fresh pieces. A small subsample was taken from each piece, but they were pooled to provide an average moisture content for a species and size class.

Statisitical analysis

The primary statistical analyses used for the chronosequence and time series data was linear regression. To calculate the decomposition rate constant, the estimated age of the logs was used as the independent variable and the density of the log (adjusted for fragmentation losses) was used as dependent variable. The form of the regression equation used to calculate the decomposition rate constant was:

$$\ln (\mathrm{Density}_t)= \ln (\mathrm{Density}_0) -k\ t,$$

where ln is the natural logarithm of $\mathrm{Density}_t$ or $\mathrm{Density}_{0,}$ the density at time t and 0, respectively and k which is the decomposition rate constant.

In the case of time series without enough sample times for regression analysis (N<3) and decomposition vector samples we used a modification of the regression equation:

$$-k = (\ln [\mathrm{Density}_t/\mathrm{Density}_{t-i}])/i$$

where $\mathrm{Density}_t$ or $\mathrm{Density}_{t-1,}$ the density at time t and the initial sampling time t-i, respectively and i is the interval between samples. The values of k calculated were then averaged to estimate the overall species rate of decomposition. The k estimated for each decay class was weighted by the relative residence time of the decay class.

To estimate the decomposition rate of fine woody detritus we calculated the ratio of decomposition rates for pieces of a given diameter by the decomposition rate for pieces with a diameter of 30 cm. One can estimate the decomposition rate of any species by multiplying this ratio by the decomposition rate of coarse woody detritus.

Results

A comparison of decomposition rates derived from the different methods indicates that for three of the best studied species (*Abies*, *Pseudotsuga*, and *Tsuga*) the rates are generally similar (Table 3). In contrast *Thuja* at HJAF and *Abies*, *Calocedrus*, and *Pinus lambertiana* at SQNP in which the regression estimate of decomposition rate was about half that of the decomposition vector approach. For some species, this difference was caused by the small sample size used in the regression. However for the better sampled species (*Abies* and *Thuja*) it is likely caused by a nonlinear decomposition pattern. In the case of a steady loss of mass the two methods should give identical methods. However, when decomposition accelerates and then slows, the regression method may fail to detect the period of rapid mass loss. This indicates that average rates of decomposition need to be taken as an approximation and a non-linear model with a changing decomposition rate may be required.

Table 3. Best estimate of decomposition rates using all methods.

Site	Species	*k*	Uncertainty
CHEF	Alru	0.055	medium
CHEF	Pisi	0.023	medium
CHEF	Tshe	0.023	medium
FEF	Abla	0.035	medium
FEF	Pico	0.023	medium
FEF	Pien	0.028	high
FRIS	Abpr	0.023	medium
HJAF	Abam	0.051	low
HJAF	Alru	0.083	low
HJAF	Psme	0.007-0.016	medium
HJAF	Thpl	0.007	low
HJAF	Tshe	0.008-0.026	medium
KRD	Abco	0.035	medium
KRD	Abma	0.043	medium
PFEF	Abgr	0.038	medium
PFEF	Pico	0.042	medium
PFEF	Pimo	0.035	medium
PFEF	Pipo	0.011	high
SQNP	Abco	0.051	medium
SQNP	Cade	0.02	high
SQNP	Pije	0.042	medium
SQNP	Pila	0.036	high
WREF	Psme	0.014	medium
WREF	Tshe	0.018	medium
WSR	Abpr	0.030	medium
ONP	Pisi	0.011	medium
ONP	Tshe	0.010	medium
MBNF	Pico	0.012	medium
Central OR	Pico	0.027	medium

Based on all the likely estimates (reasonable sample size, preference for regression estimates) of decomposition rates it would appear that the decomposition rate of tree boles can range and order of magnitude between 0.007 to 0.083 year^{-1}. The two highest rates were for *Alnus*, which was consistent at the two sites it was examined (0.087 and 0.089 year^{-1}). *Abies* at SQNP was estimated to have rates as high as 0.087 year$^{-1,}$ but a long-term average is more likely to be 0.044 year^{-1}. This would mean that the range for conifers is most likely to be from 0.007 to 0.044 year^{-1}.

The rates of decomposition estimated generally correspond to the general classes of decay resistance developed in forest products analysis. Conifer genera with very low decay resistance such as *Abies* had decomposition rates ranging from 0.035 to 0.051 year^{-1}. However, for other genera with low decay resistance, there was considerable variation with *Picea* ranging between 0.018 to 0.028 year^{-1} and yellow pines ranging between 0.011 and 0.023 year^{-1}, and *Tsuga* being 0.026 year^{-1}. The high range in yellow pines is likely caused by and underestimation with *Pinus ponderosa*. *Pseudotsuga* and white pine species, which have moderate decay resistance had decomposition rates ranging between 0.014 and 0.035 year^{-1}. The two genera with high decay resistance (*Thuja* and *Calocedrus*) had decomposition rates ranging between 0.007 and 0.02 year^{-1}.

Decomposition rates for small diameter fuels are faster than for CWD (Figure 1). A 1-hour fuel decays about 10 times faster than a 10,000-hour fuel (Table 4). The relationship between fuel size classes and decomposition rate is hyperbolic (i..e., 1/time) indicating that it requires longer to decomposition larger fuels.

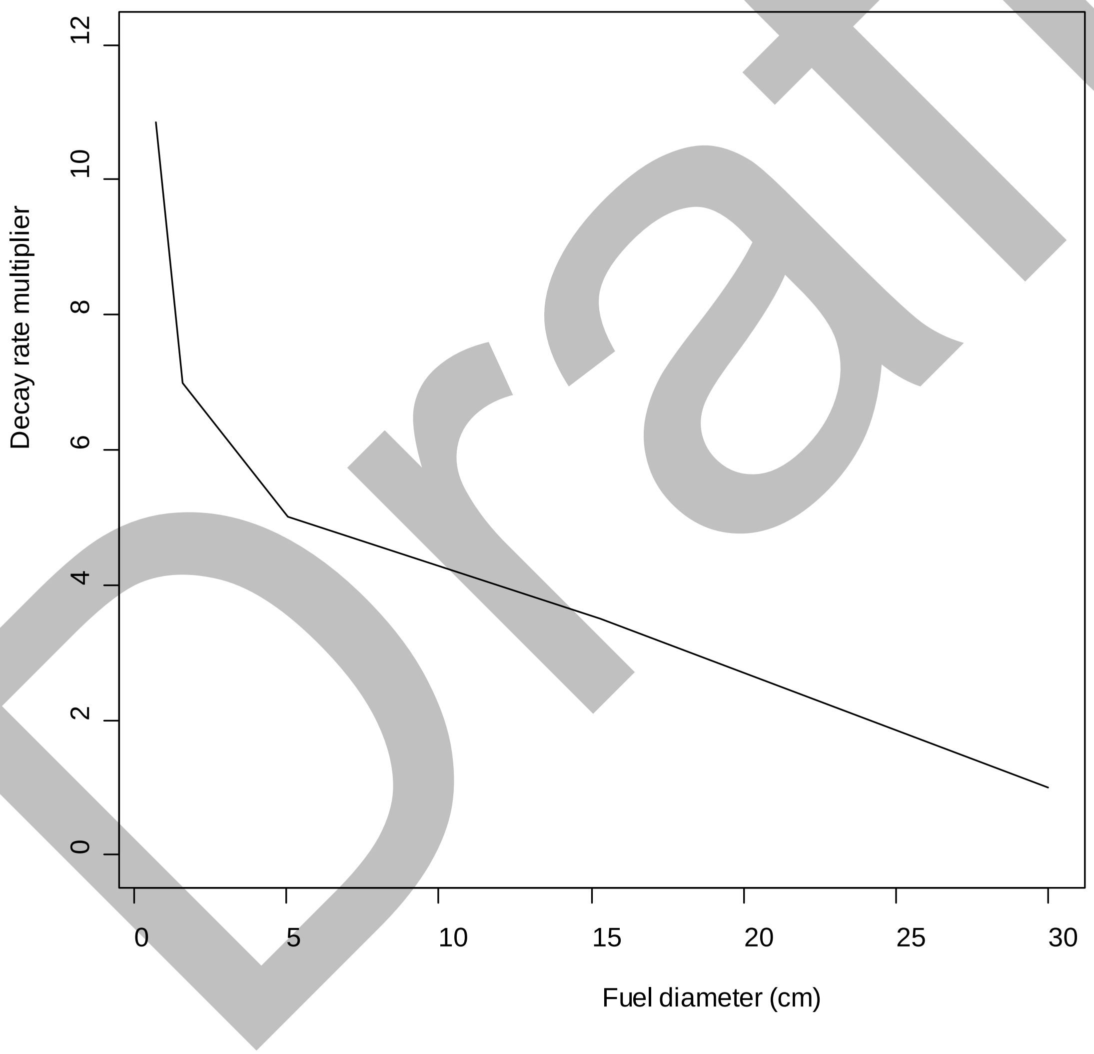

Table 4. Decomposition rate multiplier for time-lag fuels small size woody debris.

Fuel class	Diameter range	Decomposition rate multiplier
1 hour	$D < 7$ mm	10.85
10 hour	7 mm< D < 25 mm	7.00
100 hour	25 mm < D < 76 mm	5.02
1000 hour	76 mm< D< 23 cm	3.50
10,000 hour	23 cm < D*	1

* value for a CWD of 30 cm *D*

Uncertainty in decomposition rate estimates

The data presented in this report were not collected from the pilot study area and that introduces uncertainty in the decomposition rate values. While the species might be the same, the environment is unlikely to be the same. There is little understanding how temperature and precipitation interact to control decomposition rates. Temperature increases decomposition rates in theory, but it also increases evaporation rates and reduces moisture available to decomposers. Given that moisture in the pilot study area is likely lower than the study areas found in the review, it is possible decomposition rates are lower than estimated from the literature.

The effect of size is not completely understood. There is a lack of data on fine wood decomposition (despite its importance as a fire fuel). In part it is due to the fact that fine wood decomposition rates are highly influenced by the position of the piece relative to the forest floor. Pieces on the forest floor are more likely to decompose faster than those suspended above the forest floor. As our preliminary numbers are for pieces on the forest floor these estimates are likely to be high if the decomposition rates of pieces are suspended is being predicted.

All the decomposition rates reported have been for downed wood. Given the dry nature of the pilot study area it is likely that suspended or standing dead wood decomposition rates will be extremely low relative to that of downed wood.

The effects of burning on decomposition rates are not known. Fire is likely to slow decomposition, but this may only be true for wood that is in the intermediate stages of decomposition (Harmon 2001). Fire charred trees are typically attractive to wood boring insects and many species specialize in finding fire-killed trees. Wood fully colonized by decomposers is also likely to be little affected by charring, although increasing albedo is likely to heat the wood and lead to faster biological activity. Charring is most likely to slow decomposition in woody pieces that have the decayed portions fully removed by fire, thus eliminating the normal colonization sequence.

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Appendix 1. *Description of study sites*

Cascade Head Experimental Forest (CHEF), Oregon

Cascade Head is located on the north-central coast of Oregon, 8 km north of Lincoln City. It lies entirely within the Hebo Ranger District of the Siuslaw National Forest. The site is in the Oregon Coast Range region and the forests are representative of the Sitka spruce-western hemlock (*Picea sitchensis-Tsuga heterophylla*) and Douglas-fir (*Pseudotsuga menziesii*) zones of the region. Soils, derived primarily from tuffaceous siltstones, are fine textured, moderately well drained, and deep (up to 100+ cm). Because of the Pacific Ocean influence, CHEF has a moderate and very wet climate. Mean annual temperature is 10˚C (50 F) with minimal seasonal variation. Average yearly rainfall is 2489 mm (98 in.), although fog drip through the forest canopy can add 500 mm or more precipitation a year.

Fraser Experimental Forest (FEF), Colorado

Fraser Experimental Forest is located in the heart of the central Rocky Mountains, about 50 air miles from Denver. FEF includes subalpine forests typical of the area, with Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) predominating at higher elevations and lodgepole pine (*Pinus contorta var. latifolia*) predominating at lower elevations and on drier upper slopes. Soils are generally derived from gneiss and schist and typically contain angular gravel and stone with very little silt or clay. These soils are very permeable and can store considerable water during snowmelt. Climate varies strongly with elevation. Overall, the climate is cool and humid with long, cold winters and short, cool summers. Mean annual temperature at the Fraser Forest headquarters is 0.5°C (34 F) and mean annual precipitation over the entire FEF is 737 mm (29 inches).

H. J. Andrews Experimental Forest (HJAF and FRIS), Oregon

H. J. Andrews Experimental Forest is located approximately 5 miles east of Blue River, Oregon, within the Willamette National Forest. The HJAF plots are primarily located in lower elevation forests that are dominated by Douglas-fir, western hemlock, and western redcedar (*Thuja plicata*). The FRIS plot is located in upper elevation forest that contains noble fir (*Abies procera*), pacific silver fir (*Abies amabilis*), Douglas-fir, and western hemlock. Throughout the experimental forest soils are mainly Inceptisols (some undoubably Andisols) with local areas of Alfisols and Spodosols. The maritime climate has wet, mild winters and dry, cool summers. The average temperature at lower elevation is 9.5°C (49 F) and the average precipitation is 2500 mm (98 inches). The average temperature at higher elevation is 6.7°C (44 F) and the average precipitation is 2221 mm (87 inches).

Klamath Ranger District, Winema National Forest (KRD), Oregon

The Klamath Ranger District of the Winema National Forest is located in south-central Oregon, 35 miles northwest of Klamath Falls and south of Crater Lake National Park. Elevations on this Ranger District range from 1,277 to 2,430 m (4,200 feet to 8,000 feet). The topography is mountainous and dissected. Conifer forests are the dominant vegetation, and fall within the mixed conifer, white fir (*Abies concolor*), Shasta red fir (*Abies magnifica*), and mountain hemlock (*Tsuga mertensiana*) zones of Franklin and Dyrness (1973). Mixtures of white fir, ponderosa pine (*Pinus ponderosa*), and Douglas-fir occur at the lowest elevations and red fir, mountain hemlock, western white pine (*Pinus monticola*) and lodgepole pine occur at the highest elevations (Hopkins 1979). Soils are generally well-drained, gravelly and cobbly fine sandy loams to loam, with 10-75% coarse fragments (Carlson 1979). The climate is characterized by cold, snowy winters and warm, dry summers (Carlson 1979). The mean annual temperature is 4.4°C (40 F). Mean annual precipitation is 1054 mm (41.5 inches).

Pringle Falls Experimental Forest (PFEF), Oregon

Pringle Falls Experimental Forest is located in central Oregon, about 6 miles west of LaPine, within the Deschutes National Forest. The forests are characteristic of low elevation forests within the High Cascades physiographic province and are comprised of ponderosa pine, lodgepole pine, and higher elevation mixed conifer. Soils are derived from aerially deposited Mount Mazama pumice and ash with only a thin weathered surface layer. Most of the soil profile is undeveloped, with low organic matter content and high porosity. The climate at PFEF is continental, and most precipitation occurs as snowfall. Annual precipitation averages 813 mm (32 inches) and the average temperature is 7°C (45 F).

Sequoia National Park (SQNP), California

Sequoia National Park is located in the Sierra Nevada mountain range of East-Central California within Tulare and Fresno Counties. The sample plots for this study were located in the Giant Forest region of the park. Vegetation in this region is typical for midelevation mixed conifer forests in the Sierra Nevada. The forests of this area are dominated by white fir, red fir (*Abies magnifica*), incense cedar (*Calocedrus decurrens*), sugar pine (*Pinus lambertiana*), Jeffrey pine (*Pinus jeffreyi*), and giant sequoia (*Sequoiadendron giganteum*). Soils are primarily Pachic Xerumbrepts, derived from granodiorite. The climate of this area is Mediterranean, with wet, snowy winters and long, dry summers. The mean annual precipitation is 1255 mm (49 inches), with approximately half occurring as snow. The mean annual temperature is 8°C (46 F).

Wind River Experimental Forest (WREF), Washington

The Wind River Experimental Forest is near Carson, Washington in the Gifford Pinchot National Forest. The forest is classified as a western hemlock/salal (*Gaultheria shallon*) cover type, and is estimated to be ~500 years old. Dominant tree species are Douglas-fir and western hemlock. Dominant understory shrub species are vine maple (*Acer* *circinatum*), salal, and dwarf Oregon grape (*Berberis nervosa*). Soils are of the Stabler series, coarse textured and developed on 2 to 3 meters of volcanic ejecta over basalt bedrock. Texture ranges from shotty loam to clay with coarse particles in the top 1 m averaging 3% of the soil volume. The climate is characteristic of a temperate winter-wet, summer-dry climate. Annual precipitation totals 2467 mm with less than 10% occurring between June and September. Mean annual temperature is 8.7°C.

Warm Springs Reservation (WSR), Oregon

The Warm Springs reservation plots are located in north central Oregon, approximately 8 miles from the town of Government Camp and bordering the Mt. Hood National Forest. The forests are characteristic of mid to high elevation forests within the High Cascades physiographic province and are comprised of Douglas-fir, western hemlock, noble fir, pacific silver fir, and higher elevation mixed conifer. The climate is characterized by cold, snowy winters and warm, dry summers. The mean annual temperature is 8.3°C (47 F). Mean annual precipitation is 1778 mm (70 inches).

Olympic National Park (ONP), Washington

The Olympic National Park is located in the Olympic Peninsula, WA. The study area was located 5 km inside the National Park along the south fork of the Hoh River on the west side of the peninsula. Forests in this area consist of massive, widely spaced Sitka spruce and western hemlock with scattered bigleaf maple trees and large vine maple shrubs. The climate of the region is characterized by winter rains and summer drought. There may be intermittent snowpacks in this area during the winter. Precipitation exceeds 250 cm per year (Graham and Cromack 1982).

Medicine Bow National Forest (MBNF), Wyoming

The Medicine Bow-Routt National Forests extend from north central Colorado to central Wyoming. The study sites were located in Wyoming about 50 km west of Laramie. The climate of the Forests ranges from semi-arid at low elevations to cold and humid in the high country. Mean annual precipitation is about 600 mm, mostly in the form of snow from October to May. Large annual variation in precipitation (over two fold) is a characteristic of the study site. In July the mean daily maximum temperature is 20°C and the mean minimum is 4°C. Forests are dominated by *Pinus contorta*.

Central Oregon

The study area was located on the high lava plains of Central Oregon, about 30 km east of LaPine. The average elevation is 1670 m asl, and the landscape is gently rolling, with scattered volcanic cones and buttes. Most of the precipitation falls in the form of snow during November through April. Forests are dominated by lodgepole pine with an understory dominated by bitterbrush (*Purshia tridentata*) and western needle grass (*Stipa occidentalis*).

APPENDIX D.

B.

MODELING STUDY OF CARBON DYNAMICS

FOR SELECTED TREATMENTS OF FOREST FUELS IN SOUTHERN OR

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Introduction

This report was prepared to present the results of a simulation study of forest carbon dynamics with and without different fuel treatments (stand thinning) and for different wild fire severities. As planned for TASK 4, the STANDCARB 2.0 model was used to examine changes in carbon stores over time for these scenarios:

> control and 2 different levels of thinning (high and low intensity)
>
> regeneration after wild fire (3 levels of burning severity for the above fuel treatments)

Additional scenarios were also examined to assist in the analysis of the impact of thinning and wild fire on carbon stores and on forest fuels. The report includes the description of methods and assumptions used to frame the model simulations, results of simulation runs and their analysis, and preliminary conclusions at the end.

Methods and Assumptions

STANDCARB Model

STANDCARB 2.0 is a simulation model that accounts for the regeneration, growth, death, decomposition, and disturbance of forest stands (Harmon and Marks 2002). The pools of carbon accounted for in this model include live (separated into various parts such as leaves, branches, stems, and roots), dead (all the types of live parts that have died), and stable (soil) pools. The model has been parameterized for the major tree species in the PNW and used for analysis of the impact of forest management activities on carbon stores in forest ecosystems (e.g., Cohen et al. 1996, Harmon and Marks 2002, Krankina and Harmon 2006).

The model can be set up to assess the effects of different types of forest disturbance on carbon pools. The timing and the impact of disturbance can be defined by the user. The default definitions of burning severity in STANDCARB for the four vegetation layers (Herbs, Shrubs, Lower trees, and Upper trees) include: percent killed which represents the amount of biomass for each layer killed by fire, percent burned is the proportion of killed biomass that is incinerated, and percent charcoal is the proportion of killed biomass that is converted to charcoal (Table 1).

Table 1. Definition of burning severity in STANDCARB

Fire severity	Layer	% killed aboveground	%killed belowground	% burned aboveground	% burned belowground	% charcoal aboveground	% charcoal belowground
High	Herb	100	100	99.5	50	0.5	2.0
High	Shrub	100	100	99	5	1.0	2.0
High	LTree	100	100	10	5	2.0	1.0
High	UTree	100	100	5	2	4.0	1.0
Medium	Herb	90	90	99	25	1.0	1.5
Medium	Shrub	75	75	75	5	1.0	1.0
Medium	LTree	90	90	7	2	1.5	0.0
Medium	UTree	50	50	2	1	1.0	0.0
Low	Herb	80	80	99.5	0	0.5	0.5
Low	Shrub	50	50	50	0	0.5	0.5
Low	LTree	80	80	5	0	1.0	0.5
Low	UTree	5	5	1	0	2.0	0.5

The proportion of different dead biomass pools **left on site** following wild fires of low, medium, and high severity is shown in Table 2, along with the “fuel weighting factor” parameter which defines the likely contribution of various fuels to fire severity. The level of burn severity is based on the amount of fuels present (unless the user prescribes a specific burn severity).

Table 2. Proportion of different dead biomass pools left on site following wild fires

Pool	**Light Burn**	**Medium Burn**	**Hot Burn**	**Fuel Weighting Factor**
Dead Foliage	75	50	0	0.65
Dead Fine Root	100	75	50	0.213
Snag SapWood	100	85	70	0.3
Log SapWood	95	75	50	0.65
Snag HeartWood	100	95	80	0.2
Log HeartWood	100	90	70	0.413
Dead Branch	75	50	0	0.75
Dead Coarse Root	100	100	70	0.138
Stable Soil	100	100	100	0
Stable foliage	100	50	25	0.713
Stable wood	100	50	25	0.713
Charcoal	10	5	0	0.2
Herb	n/a	n/a	n/a	0.325
Shrub	n/a	n/a	n/a	0.675
Lower Trees	n/a	n/a	n/a	0.8

For the dead pools, the proportions of burned mass (percentages) that is transformed into charcoal are presented in Table 3.

Table 3. Percent of burned mass that is transformed into charcoal

Pool	**Light Burn**	**Medium Burn**	**Hot Burn**
Dead Foliage	2	3	0
Dead Fine Root	1	2	0
Snag Sapwood	1	1.7	2.5
Log Sapwood	2	3.5	5
Snag Heartwood	0	0	1.2
Log Heartwood	0	0.4	1.5
Dead Branch	5	10	1
Dead Coarse Root	0.5	1	2
Stable Soil	0	0	0
Stable foliage	2	3	1
Stable wood	2	3	1

Charcoal in STANDCARB is composed of two pools. The first is the surface charcoal pool, which represents charcoal input from live, dead, and stable pools when there is a wild fire. These pools are subject to loss from wild fires and can be transferred to the second pool which is buried charcoal. The latter is not subject to loss via fires and has a very low decomposition rate (essentially zero).

The model outputs the stores of carbon in all pools. For purposes of WestCarb Project we created two additional outputs: (1) total harvest which is the sum of all biomass removals by thinning for a given scenario and defined time interval and (2) "fuel levels" which we calculated using the "fuel weighting factor" above and grouped into the following five categories:

Fine fuels= Dead foliage + Dead Branches

Coarse woody fuels = Snagsapwood + Snagheartwood + Logsapwood + Logheartwood

Belowground fuels=Fine roots + Coarse roots + Stablefoliage + Stablewood

Live fuels = Herbs + Shrub leaf + Shrub branch + Lower trees leaf + Lower trees branch

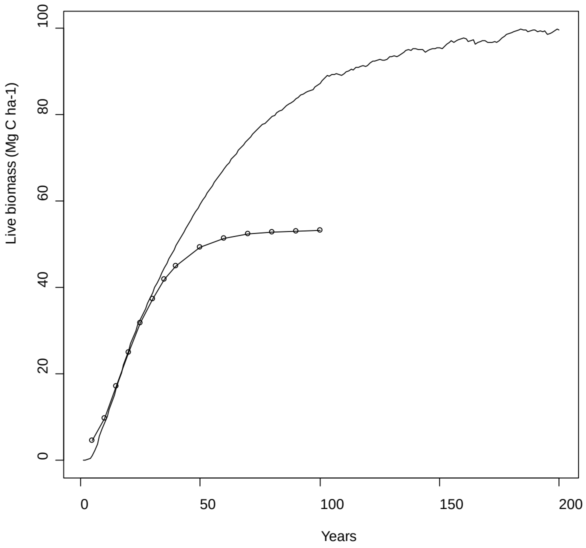
Charcoal.

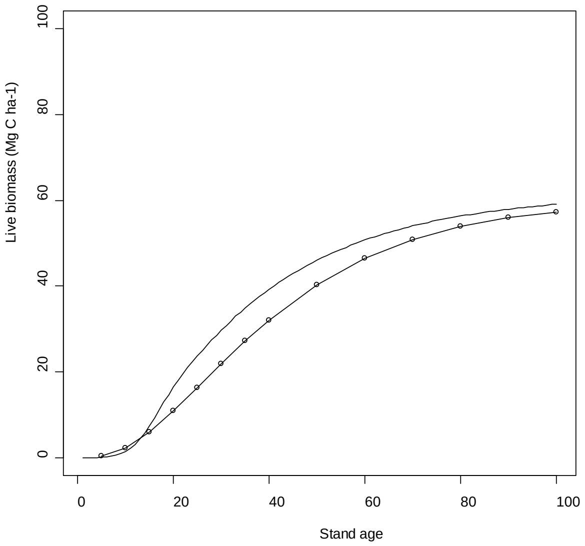
Model calibration.
To approximate the growth patterns of major forest types in Southern Oregon we calibrated the model to make the output consistent with FIA data. We generated the reference data using the Carbon Online Estimator (COLE, http://ncasi.uml.edu/COLE/), which is an online package that was developed under a cooperative agreement between NCASI and the USDA Forest Service, RWU-4104 in Durham, NH. We retrieved data from USDA Forest Inventory and Analysis plots current as of March 18, 2005 for Klamath and Lake Counties in Oregon. Even though the Lake County is the primary

focus we felt that pooling data from 2 adjacent counties would increase the number of plots and produce more robust reference data. The full COLE report for two counties is appended.

Only forest types represented by >20 plots were analyzed by the COLE report; those forest types include Ponderosa pine (155 plots), Fir/Spruce/Mountain Hemlock Group (27 plots), White Fir (28 plots), Lodgepole pine (100 plots). Ponderosa pine Lodgepole pine types were selected for the modeling and analysis.

While the report provided information on a full set of forest carbon pools, we focused the calibration on live tree carbon which is expected to be the most accurate of all reported pools. The chronosequence of live tree biomass shows little or no accumulation beyond stand age class 70-80 years (Figure 1 and Appendix-Table 3) for Ponderosa Pine while for Lodgepole pine accumulation continues through age 100 years. The lack of biomass accumulation in older stands of Ponderosa pine is likely an artifact of chronosequence method as it reflects the impact of thinning and also the selective removal of high-biomass stands from the older age cohort by past clearcut harvests. This impact can be expected to be greater in more productive and valuable Ponderosa pine type than in Lodgepole pine. Thus for Ponderosa pine we used the values from age classes 5-50 as a basis for model calibration, while for lodgepole pine the entire chronosequence of biomass accumulation with age of forest stands matched closely the model output (Figure 1).


Live biomass (Mg C ha-1)
0
20
40
60
80
100
0
50
100
150
200
Years


Live biomass (Mg C ha-1)
0
20
40
60
80
100
0
20
40
60
80
100
Stand age

	50%			x	x

The effects of fire were simulated using the same starting point as for thinning scenarios and the model was run for 1000 years for the following wild fire scenario matrix:

		Frequency			
		0	20 yrs	100yrs	200yrs
Severity	No	x			
	Low		x	x	
	Moderate			x	
	High			x	x

While the model is best suited to simulate long-term impacts of different disturbance regimes we recognize the need to examine shorter-term effects, and produced a set of outputs that focus on short-term simulation results as well.

In the combined thinning and wild fire model runs we used a subset of thinning scenarios including one scenario with aggressive thinning (50% thinning every 25 years) and two moderate thinning scenarios (35% and 20% every 25 years). The timing of fires was selected randomly to average a 100 year fire return interval. We assumed that thinning reduces wild fire severity and not the frequency of fires (Sam Sandberg, pers. comm.). The scenario with no thinning and high burning severity was used as a control against which scenarios with thinning were compared. In a separate round of simulations we allowed the model to define the burning severity based on the amount of fuel present at the site. To assure meaningful averages of resulting carbon stores the scenarios were run to year 1400.

Results

Thinning scenarios

Model calibration resulted in reasonable agreement for the calibration ages between COLE live tree biomass estimates based on FIA data and those simulated by STANDCARB for two selected forest types: Ponderosa Pine and Lodgepole Pine (Figure 1). Because forest floor and organic soil are reported as constant values in COLE report we did not consider those in the calibration exercise. Dead wood carbon pool also shows reasonable agreement between the simulations and data. While there is no precise match between reference data and calibrated model output we feel we were able to achieve realistic results. Because the overall approach is to estimate the effects in relative rather than absolute terms the differences between the simulation results and the reference data appear insignificant.

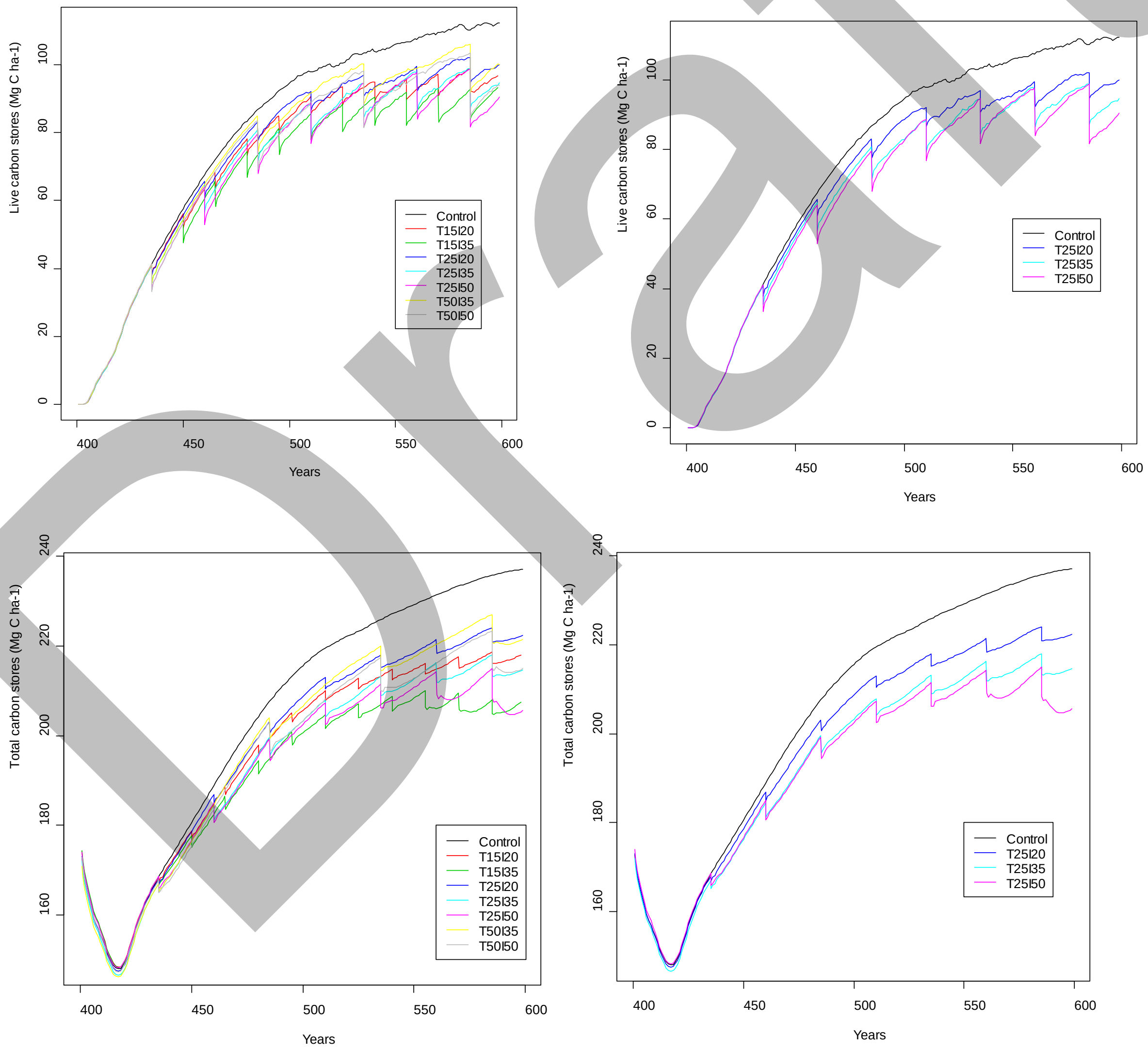


Figure 2. Effect of thinning on live (top) and total (bottom) biomass stores in Ponderosa Pine forest type (Legend: T is thinning frequency in years; I is thinning

intensity in percent of stem wood harvested, color-coding of individual scenarios shown on graphs).

Model outputs for Ponderosa Pine (Figure 2) suggest that at year 600 of the simulation (or after 165 years of application of aggressive thinning e.g., 35% removal every 15 years or 50% removal every 25 years) carbon stores in live biomass and total biomass stores declined by about 20 and 30 MgC/ha, respectively. This loss of carbon stores represents 15-20% of the business as usual scenario (control). Moderate scenarios resulted in smaller losses of carbon at the end of the simulation, but live biomass declined at least by 12 MgC/ha and total carbon stored by 15 MgC/ha. The overall pattern of impact was similar for Lodgepole Pine, but because of lower productivity the losses of carbon were lower in absolute terms (but represented a similar percentage of live and total carbon store on site; graphs not shown).

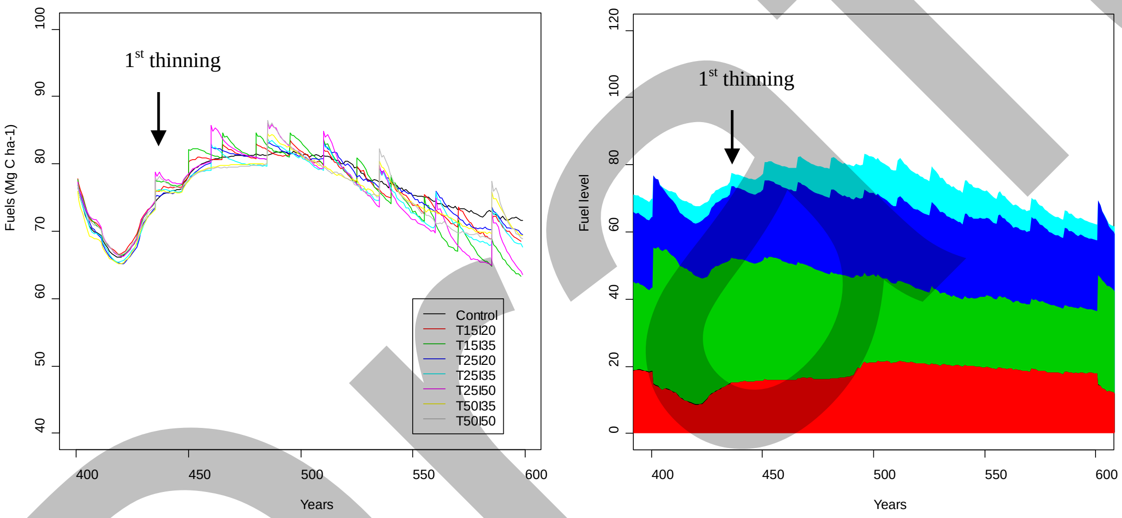


Figure 3. Effect of thinning on forest fuel level over time in Ponderosa Pine forest type: changes in total fuel loads for all scenarios (left) and changes in fuel composition for 35% thinning every 15 years (right; light blue - live fuels; blue - fine fuels; green - coarse woody fuels; red - belowground fuels).

All thinning scenarios in both forest types initially increase the amount of fuels on site (i.e., 50-80 years after the start of thinning regime), but over long term these treatments tend to cause a small reduction of fuel levels. Specifically, aggressive thinning in Ponderosa Pine reduced forest fuel level by up to 8 MgC/ha (or 12%) by the end of simulation. Thinning caused fluctuations in the amount and composition of fuels and fine fuels fluctuated the most: there is a sharp increase in fine fuels as the slash is left on site followed by reduction as this material rapidly decomposes. The proportion of live fuels increases over time as the canopy opens and allows understory vegetation to accumulate more biomass.

On average over the 165 years of applying these thinning treatments the losses of live biomass ranged from 7 to 15 MgC/ha compared to the no-thin scenario. The effect of thinning on the average fuel levels was small being about 1 MgC/ha or 1.3% of the forest fuel level in no-thin scenario (control). This average reflects the initial increase in fuel level and subsequent decline primarily due to the reduced level of coarse woody fuels towards the end of the simulation.

Carbon removed by harvest was by far the greatest effect of thinning and the greatest difference among thinning scenarios. The total amount of carbon moved off site with harvested biomass ranged from 42 to 87 MgC/ha in Ponderosa Pine and 32 to 68 MgC/ha in Lodgepole Pine indicating significant potential for biomass fuels offsets.

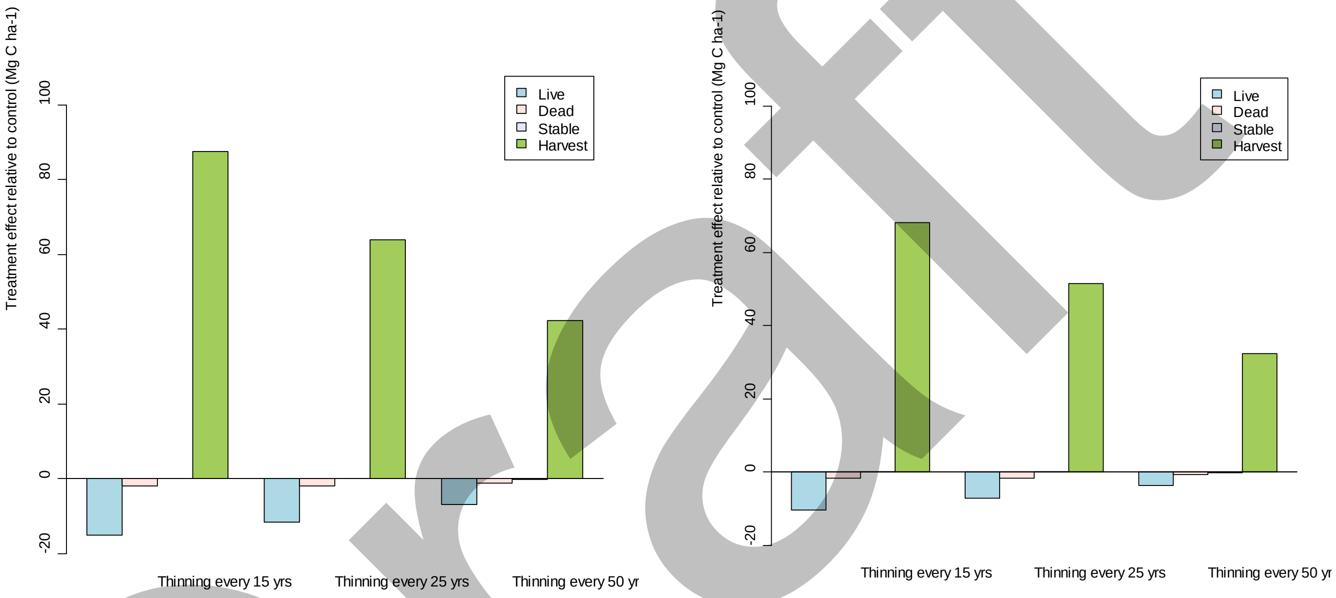


Figure 4. Summary of Thinning Effects in Ponderosa Pine (left) and Lodgepole Pine (right) over 165 years: comparison with control

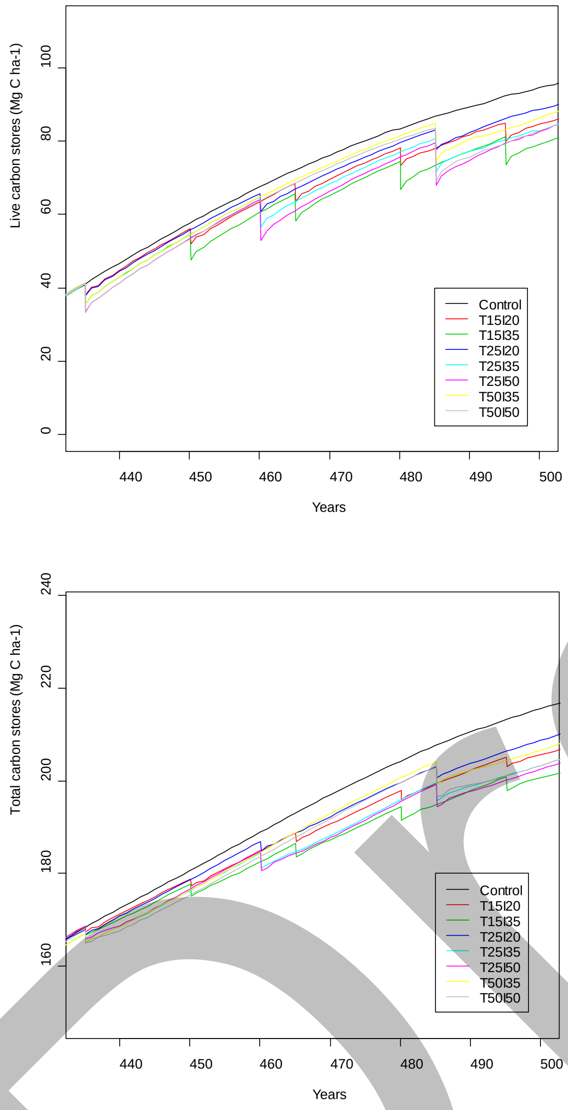


Figure 5. Short-term effect of thinning on live and total biomass stores in Ponderosa Pine forest type.

Carbon pools undergo significant short-term changes (in the year of thinning and during the first few years following thinning): it takes 4-6 years to recover the pre-harvest levels of live and total biomass, but in comparison to the control the stores of carbon in live trees and the total stores do not recover before the next round of thinning. Due to the input of slash the fuel level is the highest immediately following thinning; then it declines gradually as the slash decomposes (Figure 3). While these losses are partially offset by accumulating live fuels, the overall fuel level is the lowest prior to the next thinning.

Fire scenarios

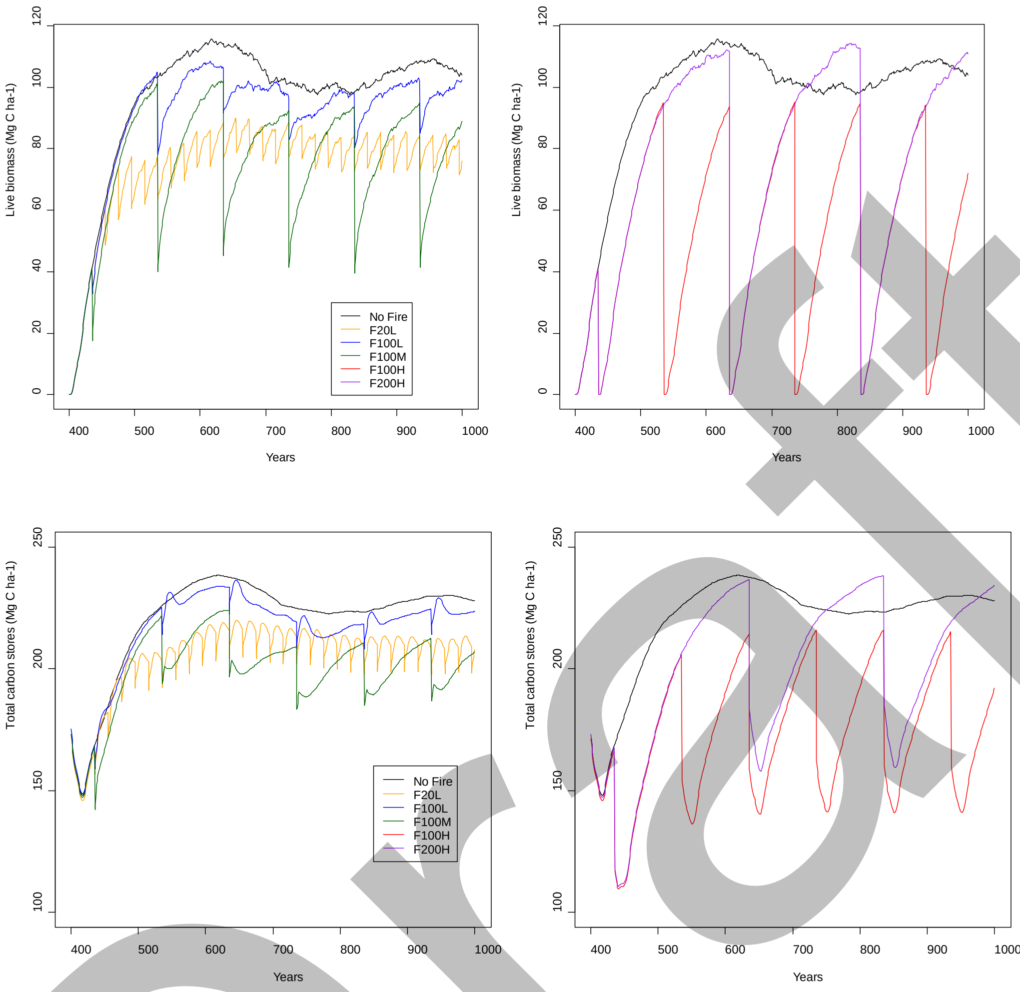


Figure 6. Effect of wild fire on live and total biomass stores in Ponderosa Pine forest type (Legend: F is Frequency; L, M, H are Low, Medium, and High Severity; for example:
F20L = Frequency 20 years, fire severity Low).

Wild fires caused greater fluctuations in the amount of C stored on site than did thinnings. On average wild fires reduced live and total carbon stores. The long-term average reduction in live stores caused by fire in Ponderosa Pine ranged from 8 to 53 MgC/ha, the reduction in total C stores on site was between 17 and 50 MgC/ha. Among the examined fire scenarios, high severity fire every 100 years made the greatest impact and low severity fire every 100 years – the smallest for both forest types.

Wild fires had relatively small impacts on long-term averages of fuel levels: low and medium severity fires had virtually no effect in Ponderosa Pine forest type, while high-severity fires increased fuel levels slightly (by 4-7 MgC/ha or 6-10%). A fire regime with low-severity frequent fire is expected to reduce fuel loads, and while in our simulations this regime did reduce the long-term average fuel level slightly in Lodgepole Pine forest type, it did actually increase it by 2.5 MgC/ha compared to no-burn scenario in Ponderosa

Pine forest type. The increase occurred in fine and belowground fuels (duff), while the live fuels were significantly lower compared to no-burn scenario (by 2 MgC/ha or 40% of the control).

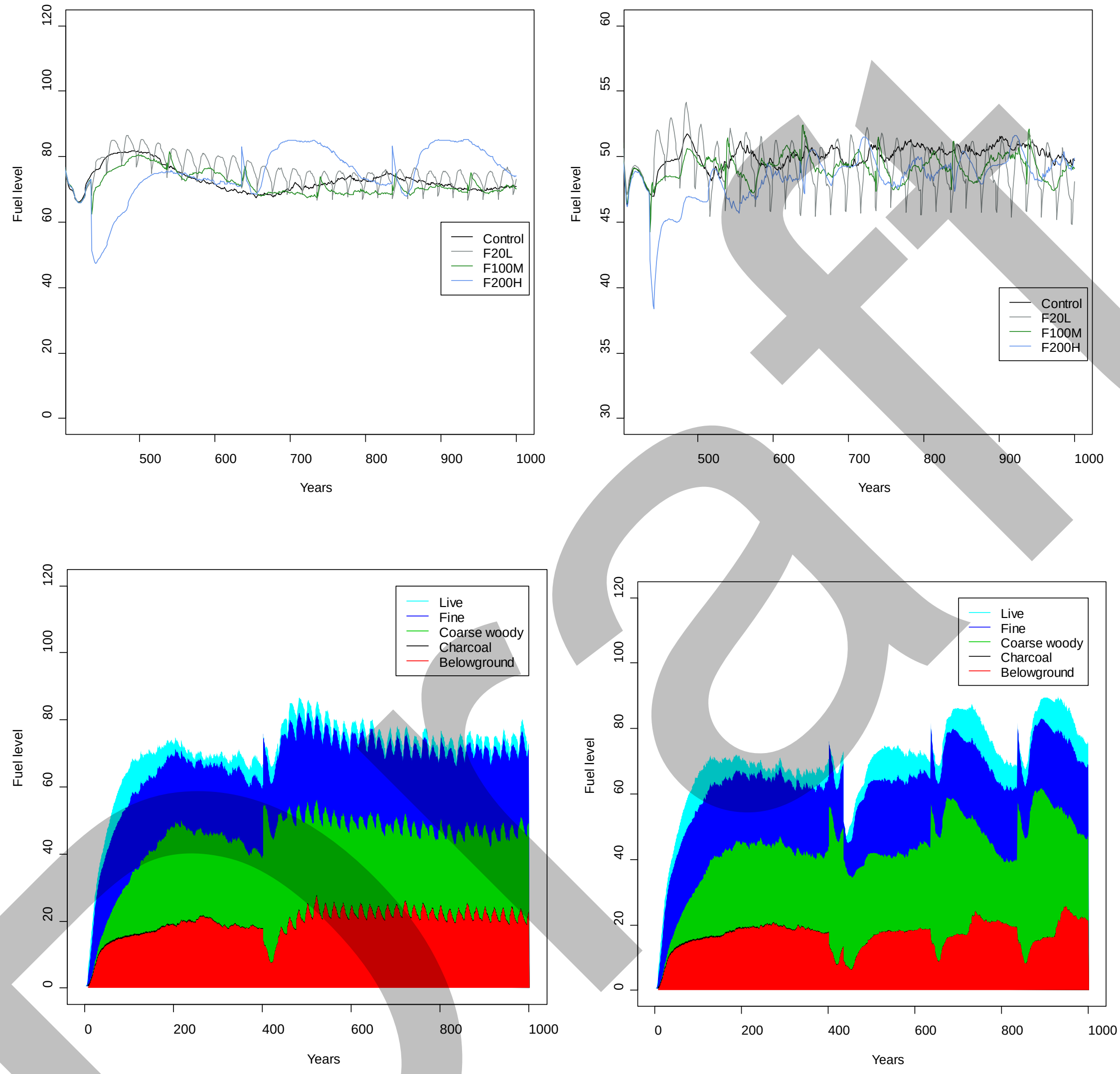


Figure 7. Effect of different wild fire scenarios on fuel stores (Ponderosa Pine – upper left, Lodgepole Pine - upper right) and composition in Ponderosa pine (light severity fires every 20 years – lower left, high severity fires every 200 years - lower right).

Short-term impacts are highly variable and are quite different from effects on long-term averages. For example, the first burn was simulated to occur in a relatively young and low-biomass forest and in case of a high-intensity burn a significant proportion of fuels was consumed by fire which also reduced fuel production for several years while the site regenerated. This lead to greatly reduced fuel levels for several years (in fact, the first wild fire temporarily reduced fuel to the lowest level found in all simulation results). However, fuel level increased following a high severity burn of a 200-year-old, high biomass forest. In this case, the initial pulse of added fuel came from the large mass of live trees as they were killed by wild fire and there was an additional increase in fuel level several years after the fire as snags began to fall and live fuels accumulated.

Combined thinning and fire scenarios

In combined model runs we first assumed that aggressive thinning reduced wild fire severity to low level while moderate thinning resulted in moderate level of fire severity. In the second round of simulations we allowed the STANDCARB model to define the burning severity based on the level of fuel present at the site.

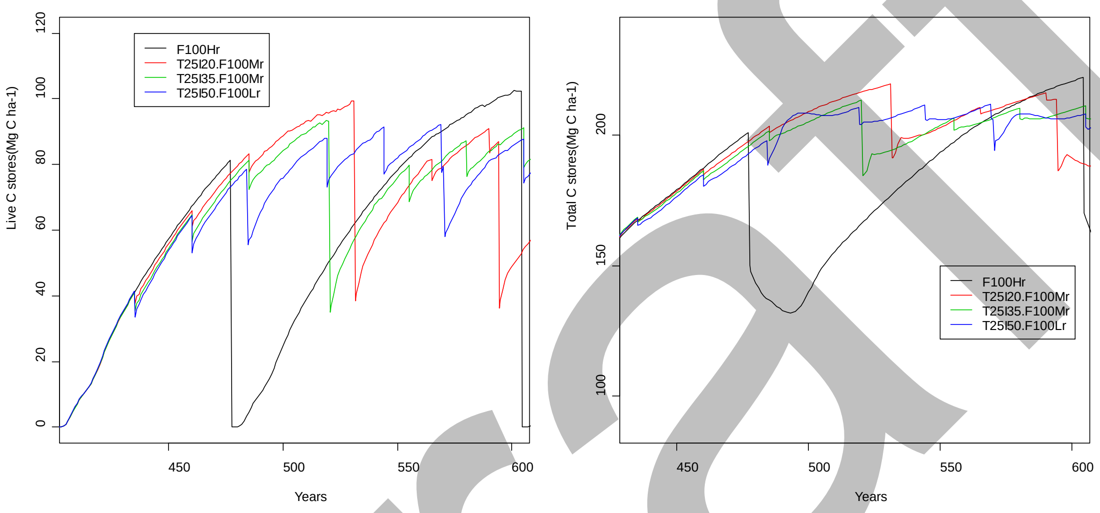


Figure 8. Combined effect of wild fire and thinning on live and total biomass stores in Ponderosa Pine forest type.

Our simulations indicated that wild fire had a much stronger impact than thinning on carbon stores in Ponderosa Pine forest type. The no-thinning scenario with high severity fire resulted in the lowest average carbon stores (Table 4). Note that both live and total stores for this scenario are lower than for all other scenarios while the dead pool is higher. Compared to this (burn/no-thin) scenario, the total fuel levels were lower in all thinning scenarios but there was there was virtually no difference among them. This result appears to call into question the potential for greater reduction of fuel levels (and consequently burning severity) by aggressively thinning rather than by moderate thinning schedules.

In Lodgepole pine forest type the difference between the impact of thinning and wild fire was small: minor increase in live biomass in thinning scenarios was offset by reduction in dead stores so that the overall impact of thinning treatment on total carbon store was virtually zero and the level of fuels was not different from control.

Table 4. Long-term average carbon stores (MgC/ha) for thinning + wild fire scenarios. In all scenarios the interval between thinnings is 25 years and the average wild fire return interval is 100 years.

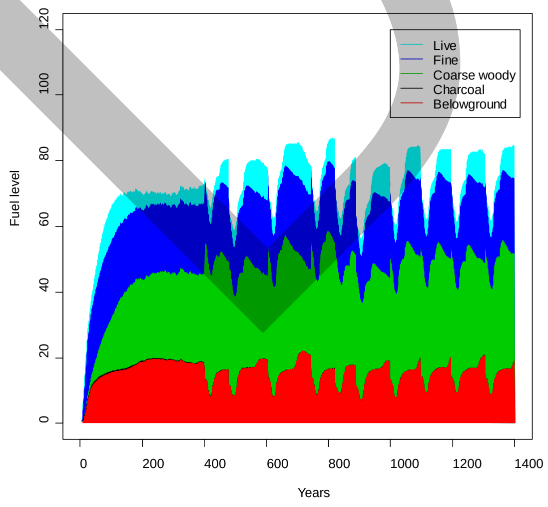
Ponderosa Pine

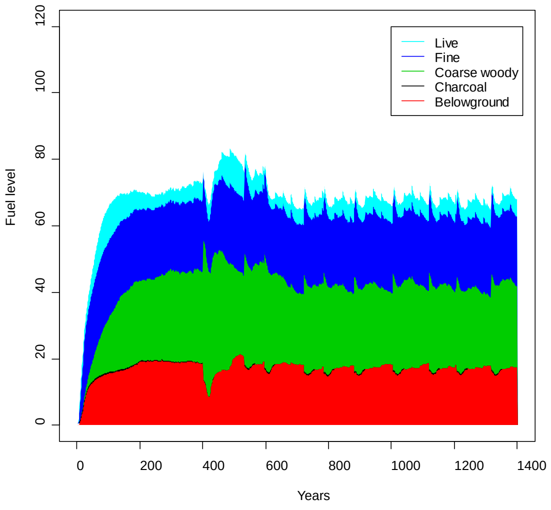
	No thinning, high-severity fire (baseline)	Thinning 20%, moderate fire	Thinning 35%, moderate fire	Thinning 50%, low-intensity fire
Live	54.99	73.57	70.87	80.01
Dead	74.69	67.25	65.77	63.89
Stable	49.65	54.00	53.88	56.19
Total	179.33	194.81	190.52	200.09
Fuel levels	75.50	69.80	69.06	69.39

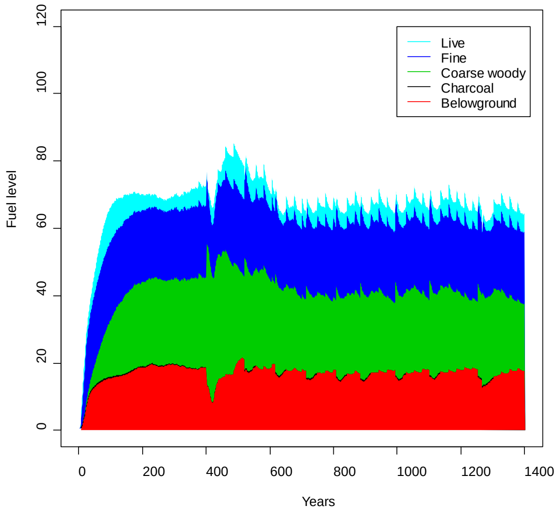
Lodgepole pine

	No thinning, high-severity fire (baseline)	Thinning 20%, moderate fire	Thinning 35%, moderate fire	Thinning 50%, low-intensity fire
Live	28.37	31.02	29.86	32.29
Dead	31.94	29.69	28.83	27.48
Stable	12.17	11.76	11.77	12.33
Total	72.49	72.48	70.46	72.10
Fuel levels	29.15	29.33	28.77	28.69

Thus, relative to the baseline scenario (a high-severity wild fire averaging every 100 years), thinning can be expected to increase long-term averages of total C stores on site by about 10-20 MgC/ha for Ponderosa Pine. For Lodge-pole pine thinning does not significantly change the total amount of C stores compared to wild fire as live biomass takes longer to recover between thinning treatments in this low productivity forest type. This result reflects the working assumption that aggressive thinning reduced fire severity to low level while moderate thinning results in moderate level of fire severity.







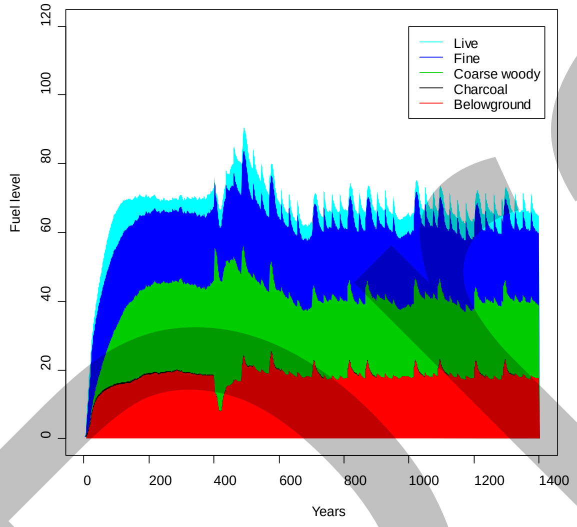
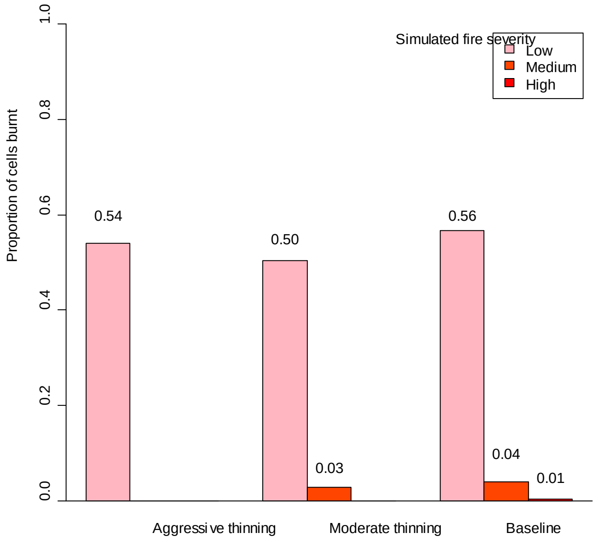


Figure 9. Combined effect of different wild fire scenarios on fuel levels and composition

Combined thinning and burning scenarios reduced the average level of fuels on site by 4-6 MgC/ha in Ponderosa Pine forest type primarily because of the reduction in coarse woody fuels level. In Lodge-pole pine virtually no reduction in fuel level was found.

The STANDCARB simulation experiment with wild fire severity determined by the model for the same set of combined thinning-fire scenarios and baseline (burn-no-thin scenario) indicated that the scenario assumptions are valid overall for



Ponderosa pine forest type, but different fire severity occurred in all scenarios and in the control as well (Figure 10).

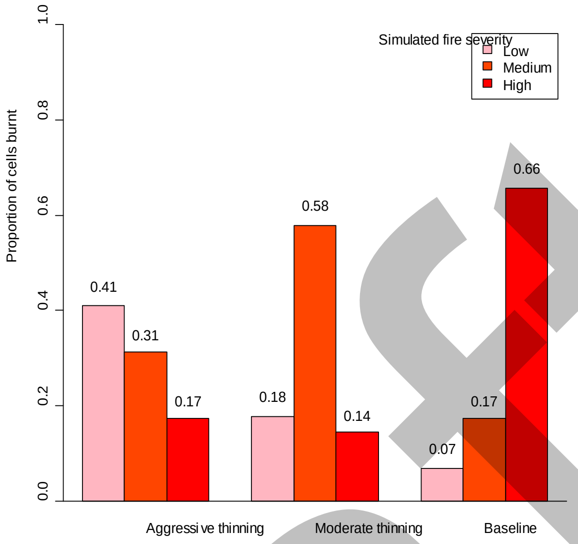


Figure 10. Proportion of wild fires at different severity levels projected by STANDCARB for combined thinning and wild fire scenarios in Ponderosa Pine (left) and Lodgepole Pine (right) forest types. Thinning intensity was 50% and 35% in aggressive thinning scenarios and 20% in moderate thinning scenario; thinning interval was 25 years for all scenarios. Baseline scenario did not have thinnings. Note that proportions do not add up to 1.0 because a small fraction of STANDCARB cells was projected not to burn.

In the baseline scenario for Ponderosa Pine, high-severity fire was projected in 66% of cases, 24% of fires were of moderate/low severity, and 10 % of cells did not burn at all. In the aggressive thinning scenario not all fires were projected to remain at the low severity level; moderate to high fire severity level was projected in 48% of the cases. While we acknowledge that the severity levels were set by us, the simulated proportion of wild fires at different severity levels seems realistic.

The levels of fuel projected for Lodgepole pine suggested low probability of medium to high severity fire in all scenarios and the distinct prevalence of low-severity fire. This however may not be a realistic projection because high-severity fires are common in Lodgepole Pine forests. The STANDCARB model settings for fuel levels corresponding to different levels of fire severity need to be adjusted to reflect the differences in fire behavior that is characteristic for individual forest types (this effort is beyond the scope of the current project).

Table 5. Long-term averages of carbon stores (MgC/ha) for thinning + fire scenarios with wild fire severity defined by STANDCARB. In all scenarios the interval between thinnings is 25 years and the average wild fire return interval is 100 years.

Ponderosa pine

	No thinning, (baseline)	Thinning 20%,	Thinning 35%,	Thinning 50%
Live	62.78	72.81	70.30	70.54397
Dead	73.47	67.69	66.19	64.35037
Stable	51.07	53.60	53.60	53.76243
Total	187.31	194.10	190.03	188.6568
Fuel levels	74.83	70.38	69.52	68.23997

Lodgepole pine

	No thinning, (baseline)	Thinning 20%,	Thinning 35%,	Thinning 50%
Live	37.44	35.03	33.55	32.82
Dead	29.86	28.51	27.58	27.21
Stable	12.11	12.01	11.99	11.99
Total	79.41	75.55	73.12	72.02
Fuel levels	30.56	29.43	28.75	28.55

Combined thinning+wild fire scenarios for Ponderosa Pine forest type with burning severity defined by the model show that aggressive thinning may result in smaller gains in on-site C stores than assumed initially (Table 5). Because the severity of burning in the baseline scenario was in some cases lower than the assumed high severity, the baseline stores of live biomass and total carbon were higher. Relative to this higher baseline, the long-term averages of live biomass stores increased by 8-10 MgC/ha, while dead stores are reduced by 6-9 MgC/ha, and the average total stores are increased by only 1-7 MgC/ha (< 4%) in the examined thinning scenarios. The largest increase in the long-term average total C stores on site was found in the moderate thinning scenario.

In the Lodgepole pine forest type, the same set of scenarios resulted in lower live, dead, total and fuel stores in thinning scenarios compared to baseline. The productivity in this forest type is too low to adequately rebuild carbon stores following thinning is the likely explanation for this result.

The projected effect of thinning on wild fire severity in combined thinning+wild fire scenarios for Ponderosa Pine forest type appears greater than simulations of fuel level following thinning would suggest (Figure 3). This is likely because effects of wild fires and thinnings on fuel loads are synergistic in that fires tend to reduce fine and belowground fuels, while thinning reduces the coarse woody fuels over long term.

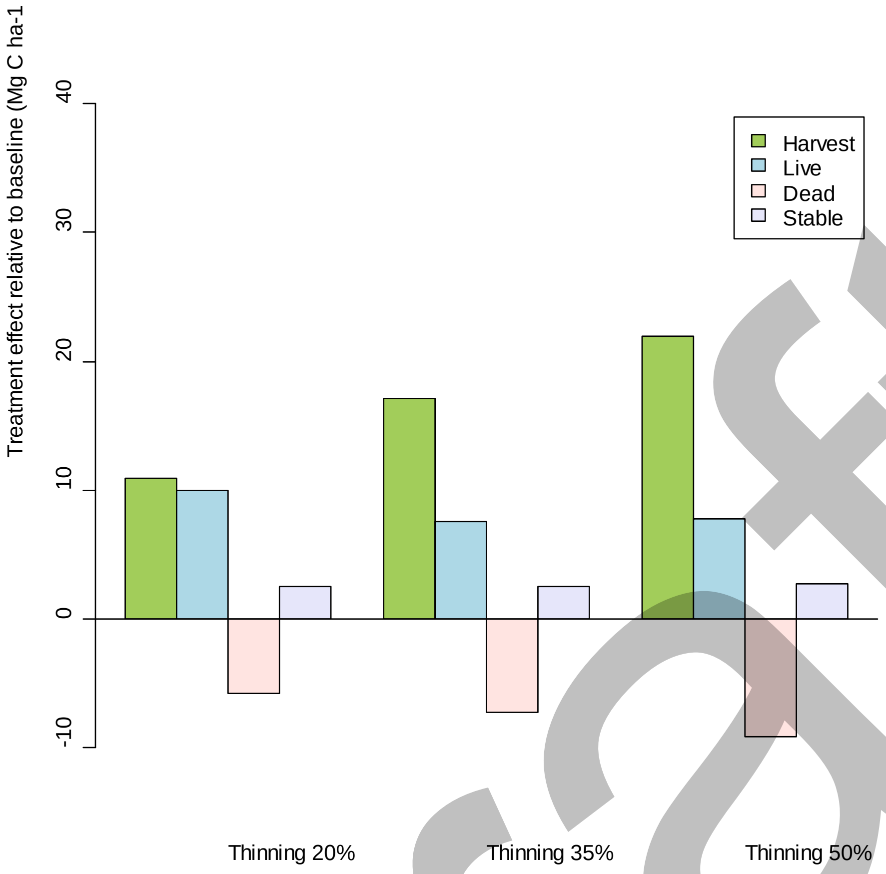


Figure 11. Summary of Combined Thinning + Wild Fire Effects in Ponderosa Pine forest type: comparison with baseline (fire-no-thinning). Average C stores on site over 965-year simulation and total harvest over the first 165 years (for comparison with Figure 4).

Removal of carbon with harvested wood plays a smaller role in combined thinning+fire simulation results because wild fires destroy some of potentially harvestable wood (Figure 11). Nevertheless including harvested material in the comparison of scenarios makes aggressive thinning scenario more attractive.

The difference between near-term and long-term effects is especially significant in combined thinning+wild fire scenarios (Figure 12). After hundreds of years in aggressive thinning, the fuel levels are gradually reduced and wild fire severity declines leading to higher average live biomass stores and significantly reduced dead stores in comparison with baseline scenario.

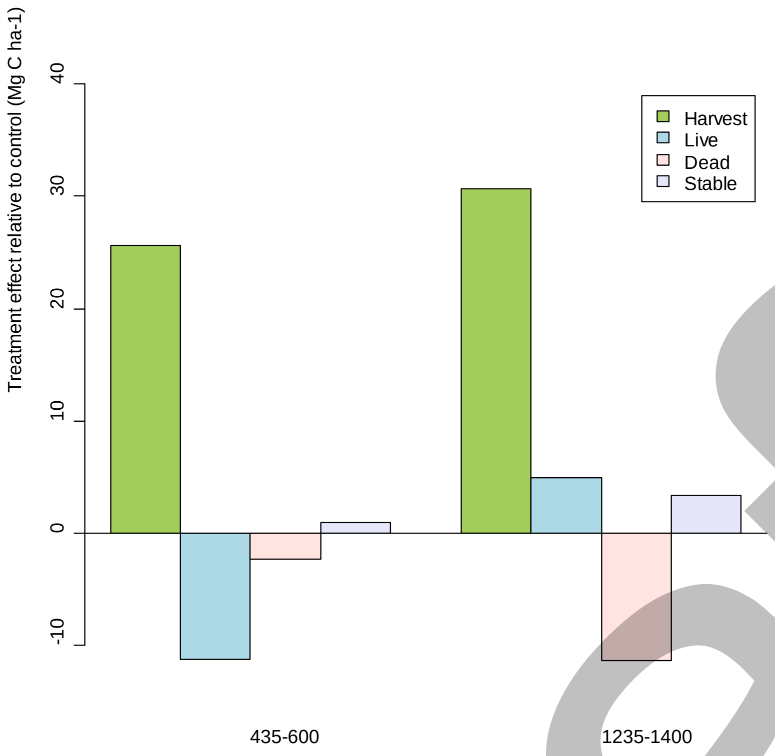


Figure 12. Near-term and long-term effects of aggressive thinning + wild fire scenarios (severity 50% every 25 years) for Ponderosa Pine forest type: comparison with baseline (fire-no-thinning). Average C stores on site and total harvest over the first 165 years and the last 165 years.

Discussion and Conclusions

1. For thinning to be an effective measure to reduce the impact of wild fire, the impact of thinning on forest fuels has to be significant. The model simulations suggest that in the short term (for several decades after the start of the thinning treatments) the periodic addition of slash to the forest floor actually increases the level of forest fuel above the level found in the control (i.e., stands that are not thinned). This agrees with some recently published results of field studies that suggest that thinning may increase rather than reduce the fuel load, at least in the short term (e.g., B. Bormann presentation). Over time the examined thinning scenarios do reduce the level of fuels, but this reduction develops gradually over 100+ years. Moreover, for all thinning scenarios the reduction of on-site C stores was projected suggesting that thinning forest stands leads to additional C emission compared to control. Thus, based on consideration of on-site carbon stores “carbon credits” for thinning do not appear feasible in the short term.

2. The total amount of carbon moved off site with harvested biomass over 165-year simulation significantly exceeds on-site losses due to thinning. To what extent this removed C can be counted against the losses on site depends on the accounting method used. If the harvested wood replaces fossil fuels in energy generation then as much as 90% of the harvested carbon can be counted as “credit” and this would exceed significantly the losses of C on-site and create a potential for assessing C credit.

3. The short-term effects of thinning and wild fire depend on the initial condition of the stand being treated. In this report we used a 35-year-old stand initiated by a high-severity wild fire in an old forest as the initial condition. Without disturbance or thinning treatment this stand accumulates C stores and thinned stands are projected to follow a similar general pattern of C accumulation, but at a slightly lower level. Over time the difference between thinned and control stands increases, a result of the fact that the same percent thinning intensity removes greater absolute amount of C with harvested wood while older stands are less capable in recovering carbon after thinning. This general pattern was projected in both examined forest types.

4. If low severity burns repeat at a 20-year interval as simulated, the average fuels level remains higher than in the no-burn scenario. Live fuels are the only fuel type that is significantly reduced by frequent burns. Among all wild fire simulations the lowest level of fuels was predicted at the beginning of our high severity fire scenario (e.g. Figure 7). This low level of fuels occurred following 2 high-severity burns at 35-year interval (a high-severity fire 35 years prior to the starting point of simulations, then the first fire of high-severity scenario). Repeated high severity wild fire is not unusual (Thompson et al. 2007) and may create an impression that frequent burns result in low fuel loads, but our modeling results indicate that for low-severity fires at 20-year interval this is not the case. While general pattern was similar in both examined forest types, more productive Ponderosa Pine type had nearly twice as high a fuel level as a low-productivity Lodgepole pine type.

5. Reducing wild fire severity from high to low caused a significant increase in long-term averages of C stores on site (up to 45 MgC/ha or 25% for 100-year fire return in simulation for Ponderosa pine forest type). While thinning alone does not seem to reduce average fuel levels in the short term, other methods of fuel treatment (prescribed burning, removal of ladder fuels, removal or accelerated decomposition of slash) could reduce fuel levels to the point where burn severity is reduced. If the losses of C associated with these fuel reduction measures are smaller than gains associated with lower burning severity, then treating on site fuels appears a feasible way to increase the average on-site carbon store.

6. **Significance of baseline.** The simulation results for thinning scenarios alone and for combined thinning and fire scenarios are not directly comparable because they use

different baselines. Compared to the no-burn/no-thin baseline, all thinning scenarios reduce on-site carbon stores. When the baseline includes high-severity wild fire with average fire return of 100 years, then thinning scenarios do not reduce average C stores on site over long-term in Ponderosa pine forest type, but for Lodgepole pine type there is small reduction.

7. **Near-term vs. long-term effects.** Near-term effects of thinning include (1) fluctuations in live and dead biomass and fuel levels , (2) increase in average fuel levels and decline in average live and total biomass on site at the scale of several decades to a century. The some extent this decline can be offset by carbon credits if harvested biomass substitutes fossil fuels in energy production. Thus in the short term it does not seem feasible to generate carbon offsets by forest thinning aimed at wild fire control. The long-term effects at the scale of several centuries to a millennium include reduced fuel loads and burning severity, slightly higher live biomass stores and reduced dead stores.

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AN ANALYSIS OF WILDFIRE FUEL TREATMENTS AS A CARBON OFFSET PROJECT TYPE

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(The Climate Trust and Oregon Department of Forestry

DOE Contract No.: DE-FC26-05NT42593

Contract Period: October 1, 2005 - May 11, 2011

Public Interest Energy Research (PIER) Program

FINAL PROJECT REPORT

An Analysis of Wildfire Fuel Treatments as a Carbon Offset Project Type

Prepared for: California Energy Commission

Prepared by: The Climate Trust and Oregon Department of Forestry

SEPTEMBER 2010

CEC 500-02-004

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Subcontract Numbers: MR-06-O3G and MR-06-03K

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ACKNOWLEDGMENTS

The authors would like to thank the following contributors to the case study simulation of wildfire risk, fuel treatments, and carbon stocks: Alan Ager, USDA Forest Service, Pacific Northwest Research Station, Western Wildlands Environmental Threat Assessment Center; Drew McMahan, SofTec Solutions; Mark Finney, USDA Forest Service, Rocky Mountain Research Station, Missoula Fire Sciences Laboratory; and Brian Watt, (formerly with) USDA Forest Service, Fremont-Winema National Forest.

The authors would also like to thank the West Coast Regional Carbon Sequestration Partnership's (WESTCARB) fire methodology panel and Center for Fire Research and Outreach for their discussion and guidance in interpreting the case study analysis results. We would like to thank in particular WESTCARB fire methodology panel members Sandra Brown, Katie Goslee, and Tim Pearson, of Winrock International; David Saah, of Spatial Informatics Group; and Max Moritz, of University of California, Berkeley. Finally, the authors would also like to acknowledge and thank the following people for their insight and advice: Rick Brown; Guy Pinjuv, Ptarmigan Forestry and Carbon Consulting; and Amy Phillips, Monica Thilges, and Peter Weisberg, of The Climate Trust.

The authors are solely responsible for the entire content of this report, including any errors or omissions.

PREFACE

The California Energy Commission Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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- Renewable Energy Technologies
- Transportation

An Analysis of Wildfire Fuel Treatments as a Carbon Offset Project Type is the final report for the West Coast Regional Carbon Sequestration Partnership – Phase II (contract number MR-06-03G, work authorization number MR-045) conducted by The Climate Trust and Oregon Department of Forestry. The information from this project contributes to PIER's Energy-Related Environmental Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

ABSTRACT

Fuel treatments involve the removal of biomass from targeted areas in the forested landscape to reduce the risk of uncharacteristically severe wildfires caused by excess biomass in the forest. This report describes a landscape-scale case study in southern central Oregon that modeled the impact of fuel treatments on wildfire behavior and associated carbon dioxide emissions and assesses the project's ability to generate carbon offsets that meet the quality criteria identified by the Offset Quality Initiative. The report makes two primary findings. The first is that the case study is likely a carbon-neutral project, meaning that few or no offsets would result from the project activity. The second is that, while this project type could generate quality offsets, the adoption rate would likely be low due to the current inability to implement quality offset projects on federal lands and the expense of the activities required to ensure that the carbon benefit is real and permanent. For these reasons, fuel treatment projects are unlikely to be a viable source of quality offsets. This report recommends that a federal policy decision be made to determine if offset projects can involve federal lands. This is important not only for this project type but for others that hope to utilize waste biomass (e.g., biochar and energy generation projects). This report also encourages the development of fuel treatment projects because the risk of uncharacteristically severe wildfires is likely to increase with climate change and such projects provide a host of climate change adaptation and mitigation benefits.

Keywords: Carbon offsets, fuel treatment, wildfire risk, restoration, carbon credits, carbon dioxide emissions

Please use the following citation for this report:

Kelly, Peter, Jim Cathcart. (The Climate Trust, Oregon Department of Forestry). 2010. ***An Analysis of Wildfire Fuel Treatments as a Carbon Offset Project Type.*** California Energy Commission. Publication number: CEC-500-02-004.

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EXECUTIVE SUMMARY

Introduction

State and federal policies to suppress wildfires on forestlands in the United States have caused many federally owned forested landscapes to hold more biomass, both living and dead, than they would under a natural fire regime. This greater fuel load increases the likelihood of an uncharacteristically severe wildfire, which would emit an abnormally large amount of carbon dioxide (CO_2).

Fuel treatment projects are actions to reduce the risk of wildfire on a given landscape by removing biomass from specific forest stands to limit a fire's spread and intensity. There is hope that these projects could also reduce CO_2 emissions—primarily through the avoidance of CO_2 emissions from uncharacteristically severe wildfire—and could therefore be eligible to sell carbon offsets to help overcome funding barriers to implementation.

Purpose

This report presents findings from a landscape-scale case study in southern central Oregon that modeled the impact of fuel treatments on wildfire risk and associated CO_2 emissions; it then provides an assessment of the project type's ability to generate quality carbon offsets.

Project Objectives

The overall goal of WESTCARB Phase II is to validate and demonstrate the region's key carbon sequestration opportunities through pilot projects, methodology development, reporting, and market validation. WESTCARB research will facilitate informed decisions by policy makers, communities, and businesses on how to invest in carbon capture and storage technology development and deployment to achieve climate change reduction objectives. The sequestration opportunity presented here is the avoided loss of forest biomass due to uncharacteristically severe wildfire.

Project Outcomes and Conclusions

The case study indicates that it is possible to model both the baseline and project scenarios in a way that enables an accounting for the carbon benefit (or cost) of the fuel treatment project. It also indicates that:

- Fuel treatment projects may provide net gains in carbon emissions because the biomass removed from the landscape acts as a debit on the project that must be overcome before the project can accrue carbon offsets.
- Extrapolation of the case study results on fuel treatments, wildfire risk, and avoided CO_2 emissions indicates that this class of projects is more likely to be carbon-neutral than to provide significant emissions benefits.

Analysis of this project type indicates that even if the project provides quality offsets, the adoption of the project type may be limited due to the following project design requirements:

- The risk of reversal is high, which requires significant contributions of some of the offsets to buffer pools to insure against this risk.
- The need to continue to implement fuel treatment practices periodically on the landscapes for an additional 100 years after a project is completed can be a disincentive when recruiting project participants.
- The cost of third party verification will be high due to the need for verifiers to have specialized experience in wildfire ecology, forestry, and probabilistic simulation models.
- The cost of monitoring and verification will be high due to the long span of time that both activities are periodically required to occur (project life plus 100 years).

This report's analysis also concludes that in order to provide certainty that the emissions event would have happened, fuel treatment projects should be considered as a subset of the improved forest management (IFM) project type; in effect, a fuel treatment project is a commitment to manage the risks of wildfire on a forested landscape. This allows the project lifetime to be defined so as to include an uncharacteristically severe wildfire occurrence in the baseline case with near certainty.

Recommendations

This report finds that fuel treatment projects are likely to be near carbon-neutral and therefore do not make good offset projects. However, fuel treatment projects could be critical to long-term climate strategies, because changes in climate will likely increase the risk of uncharacteristically severe wildfires. In addition, there is potential to use the biomass removed by fuel treatment practices to create energy or biochar, both of which could benefit the climate and rural economies.

This report recommends that federal policy makers provide clarity about the appropriate role for private financing on public lands, because additionality concerns for projects on public lands is such an important issue for this project type. It is also recommends that studies be conducted to properly define how the CO_2 emission benefits (or carbon neutrality or even a carbon cost) from the fuel treatment projects are linked with either the biochar or energy creation project activities. It is the overall net reduction of CO_2 emissions to the atmosphere—both from the forestland as a result of treatment and from the power plant or other end use as a result of utilization—that will define the potential of the combined activity to provide a climate benefit. Projects will need to be carefully constructed so that the offsets are of high quality.

In conclusion, although fuel treatment projects face significant barriers to providing quality offsets, they continue to have the potential to play an important role in both climate change mitigation and climate change adaptation.

Benefits to California

Results of WESTCARB fuel treatment case study and evaluation will inform voluntary efforts, such as those by California Climate Action Registry members interested in offsetting greenhouse gas (GHG) emissions through forestry. WESTCARB will also inform regulatory developments, such as the process now underway by the California Air Resources Board (ARB) to design a GHG regulatory program under the California Global Warming Solutions Act of 2006 (California Assembly Bill 32). Projects demonstrated to be cost-effective, verifiable, environmentally beneficial, and attractive to both regulated entities and landowners/carbon credit suppliers may become eligible for trading under the market-based compliance program ARB adopts.

CHAPTER 1: Introduction

Formed in 2003, the West Coast Regional Carbon Sequestration Partnership (WESTCARB) is a collaborative research project bringing together scientists, foresters, and engineers from more than 90 public agencies, private companies, and nonprofit organizations to identify and validate the best regional opportunities for removing or otherwise keeping carbon dioxide (CO_2) out of the atmosphere—either through geologic sequestration and related capture and storage technologies or through terrestrial sequestration practices on agricultural, range, and forestlands.

Phase I of WESTCARB conducted regional assessments and baselines for terrestrial carbon sequestration for the states of California, Oregon, and Washington and identified promising practices and other opportunities for increasing terrestrial sequestration. One terrestrial sequestration opportunity identified for Oregon was to conduct wildfire fuel treatment and thinning projects (henceforth referred to as "fuel treatment projects") in forests at risk of uncharacteristically severe wildfire ("problem wildfire") as a means to reduce CO_2 emissions from these forests during such problem wildfires.

1.1 Definition of fuel treatment projects

Fuel treatment projects involve selectively removing woody material (e.g., down logs, standing dead trees, and live tree stocking) in fire-prone forests as a means to reduce the severity and extent of wildfire should the forest burn. Treatments are conducted through mechanical harvesting methods, sometimes followed by prescribed burning. The goal of fuel treatment projects is to improve the health and resiliency of the treated forest area and to slow the progression of wildfire to surrounding untreated forest areas. Fuel treatment projects do not eliminate the risk of wildfire from the forest. Rather such projects reduce wildfire intensity, reducing the amount of woody material and vegetation burned and thereby decreasing the amount of CO_2 emitted.

The majority of the material removed in fuel treatment projects has little or no commercial value. For example, of Oregon's 67 wood combustion facilities, only 10 use woody residues to generate power and of those 10, only four sell power to the public energy grid. Most of these facilities rely on sawmill residues and wood waste for fuel supply; only two facilities provide direct markets for the utilization of forest residues. A 2006 study named "Biomass Energy and BioFuel from Oregon's Forests[1]" estimates that the economics necessary to make this material pay for itself in energy production is not competitive with the current values of electricity. As a result, at best only a portion of the area in need of fuel treatment would be economically recoverable if additional biomass energy facilities were built.

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[1] Mason, Bruce and Girard, Inc.; Pacific Energy System, Inc.; Oregon State University; and Jim Bowyer. 2006. Biomass energy and biofuel from Oregon's forests. Portland, Oregon: Oregon Forest Resources Institute. [Unconventional pagination.]

1.2 Climate mitigation potential

The lack of commercial value (or the high cost relative to that value where commercial end uses do exist), provides a financial barrier to conducting fuel treatment projects. With the emergence of voluntary carbon offset markets and the anticipation of compliance-driven offset markets, foresters and landowners began wondering if carbon offset revenues from fuel treatment projects could make these projects financially viable.

Recognizing the lack of markets for the material removed in fuel treatment projects, the Oregon Governor's Advisory Group on Global Warming identified "reduce wildfire risk by creating a market for woody biomass from forests" as a key greenhouse gas (GHG) mitigation strategy. The strategy premised that if more end-use markets for woody material removed from fuel treatment projects existed (e.g., more biomass energy facilities), then more fuel treatment projects could be conducted. The ability of these projects to also generate revenue from the sale of carbon offsets would further expand the number of fuel treatment projects conducted. However, the advisory group's recommendation is premised on the assertion that fuel treatment projects lead to lower amounts of CO_2 reaching the atmosphere than the amount of CO_2 in the atmosphere absent the fuel treatment project.

1.3 Purpose of this report

This report aims to evaluate the viability of fuel treatment as a high quality carbon offset project type. Chapter 2 outlines the criteria used to evaluate offset quality. Chapter 3 examines the results of a case study simulation of a landscape fuel treatment project in Lake County, Oregon. Chapter 4 evaluates the specific case study against relevant offset quality requirements, while Chapter 5 evaluates the project type against offset quality requirements to better understand the strengths and weaknesses of this class of projects as an offset project type.

CHAPTER 2:
What Makes a Quality Carbon Offset Project?

2.1 Offset quality criteria

This report uses offset quality criteria established by the Offset Quality Initiative (OQI) as an evaluative framework. OQI, a consortium of six national nonprofit organizations working to provide leadership on GHG offset policy and best practices, states that offsets should:

1. Be real
2. Be additional.
3. Be based on a realistic baseline.
4. Be accurately quantified and monitored.
5. Be independently validated and verified.
6. Be unambiguously owned.
7. Address leakage.
8. Address permanence.
9. Do no net harm[2].

In the following sections The Climate Trust interprets each of the OQI criterion as it relates to the fuel treatment project type (further discussion can be found in Chapter 5).

2.2 Interpretation of criterion "Be real"

Project-based offset credits should represent actual emission reductions and not simply be artifacts of incomplete or inaccurate accounting (OQI, p.3).

The fuel treatment project must demonstrably increase the store of carbon on the forested landscape when compared with the store of carbon on the forested landscape absent the project. It is critical to the integrity of the offset market that the carbon benefit not simply be due to misleading accounting. All relevant carbon pools must be accounted for in both the baseline and project scenarios.

Fuel treatment practices remove biomass, which actually reduces the amount of CO_2 sequestered in the project boundary. Any emission benefits earned by the project must exceed

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[2] For a more general discussion of these criteria, see *Ensuring Offset Quality: Integrating High Quality Greenhouse Gas Offsets Into North American Cap-and-Trade Policy* (2008), available at http://www.offsetqualityinitiative.org/briefings.html

this loss of carbon stores within the project lifetime in order for the project to earn offset credits. Emission benefits earned from biomass that leaves the forested landscape but remains sequestered as long-living harvested wood products may be credited to the project so long as the eventual decomposition or combustion of the wood is accounted for. However, biomass used to generate energy is considered outside the boundary of the project and may not be credited.

Fuel treatment projects present a unique issue for the criterion "be real" because the avoided emissions event (the problem fire in the baseline case) is probabilistic, meaning there is a chance that it will not occur. Since the baseline case of an offset project is a counterfactual (it does not happen because the with-project scenario takes its place), it is impossible to determine through observation whether the problem fire would have occurred. However, the fuel treatment project type can remain eligible for offset credits if it can provide certainty that the problem fire that the project is designed to avoid would have occurred in the absence of the project. It is possible to provide this certainty using statistical methods outlined in Chapter 5.

2.3 Interpretation of criterion "Be additional"

Because offsets are used to compensate for emission reductions that an entity operating under an emissions cap would otherwise have to make itself, the reductions resulting from offset projects must be shown to be "in addition to" reductions that would have occurred without the incentive provided by offset credits. The revenue from selling the project's emission reductions should be reasonably expected to have incentivized the project's implementation for an offset project to be considered additional (OQI, p.3).

Additionality requires that the fuel treatment project prove that it would not have been executed without carbon offset funding. In order to do so, it must demonstrate that the fuel treatments were not required by law or contractual obligation and that offset funds helped overcome some other barrier to implementation such as a lack of financial viability.

The additionality criterion is complicated by the fact that the carbon market has not yet come to consensus on whether to implement projects on public lands. This is a major issue for this project type because most of the anticipated demand for fuel treatments is on federally owned forestlands, which are required to be managed for the public good, including climate change mitigation. Fuel treatment projects would not be considered additional if fuel treatments are viewed as within the mandate of public land management agencies.

However, such forest management efforts are underfunded and offset funding could be used to overcome this financial barrier. The risk is that using carbon funding to implement CO_2 reduction projects on public lands would decrease the likelihood that governments would ever provide sufficient public funding. In order to avoid this risk, the carbon market has determined that offset projects should not be implemented on federal lands until legislation or rulemaking clarifies the appropriate relationship between private financing and public management activities and priorities.

2.4 Interpretation of criterion "Be based on a realistic baseline"

A GHG emission baseline must be established in order to quantify an offset project's GHG reductions. A baseline represents forecasted emission levels in the absence of the offset project; this is sometimes referred to as the baseline scenario, or the "without-project" case. The difference between the baseline and the actual emissions after the offset project is implemented represents the reductions achieved by the project, and this amount is credited as an offset. Offsets are only as credible as their baselines (OQI, p.3).

The baseline scenario for the fuel treatment project—an untreated landscape that has a higher risk of problem wildfire—must be modeled to produce a realistic estimate of the specific landscape's carbon stock, including pre-fire and post-fire conditions. In addition, the quantification of both baseline and "with project" scenarios must explicitly account for any significant forest management changes within the project boundary.

The baseline calculation must apply a principal of conservativeness that overestimates carbon stocks, because an underestimated carbon stock in the baseline scenario would inaccurately increase the quantity of carbon offsets generated by the project activity.

2.5 Interpretation of criterion "Be accurately quantified and monitored"

Emission reductions from offset projects must be accurately quantified. Each project must have a unique monitoring plan that defines how, when, and by whom data will be collected and emissions quantified (OQI, p.4).

A fuel treatment project must include a unique monitoring plan that defines how, when, and by whom data will be collected and emissions quantified. Both the avoided emissions and the project-related emissions must be quantified according to an industry-accepted method. The principle of conservativeness must be applied so that at each point of quantification the carbon emission benefits will be underestimated rather than overestimated.

Because an avoided problem wildfire cannot be monitored directly, the monitoring plan must focus instead on assuring that landscape and wildfire conditions are below any thresholds that have been defined as triggering such an emissions event.

2.6 Interpretation of criterion "Be independently validated and verified"

All GHG reductions should be verified by an independent, qualified, third-party verifier according to approved methodologies and regulations. Verifiers should be entities whose compensation is not in any way dependent on the outcomes of their decisions. Regulatory regimes should have an approved list of offset project verifiers and should have procedures in place to ensure that conflicts of interest are avoided. Ex post monitoring and verification reports should be used as the basis for issuing offset credits (OQI, p.4).

A qualified independent third party must validate the modeling technique, or how the baseline and project case were calculated, and the resulting baseline carbon stocks. Modeling techniques and parameters must be transparent, publicly available, and have gone through a stakeholder consultation process. Also, a third party must verify that the fuel treatment activities took place and that the carbon stocks on the land have been accurately reported. Verification of the increased carbon stocks is required for both the project lifetime and for the commitment period following it to ensure that more carbon than expected has not been emitted.

2.7 Interpretation of criterion "Be unambiguously owned"

Clear and uncontested title to offset credits should be established by contractual assignment and/or government recognition of ownership rights. Furthermore, the transfer of ownership of any and all offset credits must be unambiguous and documented. Once sold, the original seller of the offset credit (and the project owner) must cede all rights to claim future credit for the same reductions in order to avoid double counting. Finally, offsets must be serialized and accounted for in a registry or other approved tracking system (OQI, p.4).

The landowner must clearly own the rights to carbon stored on the land or must have clearly transferred those rights to an appropriate party (such as the party performing the fuel treatment). This is evaluated on a project-by-project basis. All issued offsets must correspond to a unique serial number that is stored on a public registry.

2.8 Interpretation of criterion "Address leakage"

Leakage is defined as an increase in emissions outside of the project's emissions boundary that occurs as a result of the project's implementation. For example, avoiding deforestation through an offset project in one area could simply shift forest harvesting (and the resultant emissions) to a different region or country. Offset program design should include monitoring/verification plans and protocols that provide the necessary mechanisms to properly account for potential leakage over the life of an offset project (OQI, p.5).

A fuel treatment project must address and mitigate any activity-shifting leakage or market leakage that may cause higher emissions as a result of the project activities. Leakage is not considered to be a risk for this project type, which is further discussed in Chapter 5.

2.9 Interpretation of criterion "Address permanence"

There is a risk that emission reductions generated by certain offset project types can be reversed, and thus are not permanent. Permanence is a type of project risk most often associated with biological and geologic sequestration of emissions. For example, reductions realized through a forest sector project could be reversed through a forest fire. Regulatory regimes should address permanence through policy mechanisms *that ensure the minimization of loss in the case of project reversal. Such mechanisms include reserve pools, buffer accounts, and insurance, among others (OQI, p.5).*

Observed wildfire behavior within the project area must not exceed expected levels for the project lifetime and the following commitment period.

2.10 Interpretation of criterion "Do no net harm"

Offset projects should not cause or contribute to adverse effects on human health or the environment, but should instead seek to provide health and environmental co-benefits whenever possible (OQI, p.5).

Fuel treatment projects must adhere to all relevant state and federal forestry practices and regulations that protect water quality, endangered species, and biological diversity. Further, projects must only take place in locations that have been identified by existing local and regional needs assessments. Such assessments must have been developed in a transparent way with stakeholder participation and must have explicitly addressed habitat impacts and the drought resistance of the forest (in addition to wildfire risk).

CHAPTER 3:
Case Study: Simulation of Fuel Treatments and Wildfire Emissions

3.1 Description of the project area

The simulated case study area is the Drews Creek watershed located in Lake County in southern Oregon. The Drews Creek watershed was selected because it contains dry ponderosa pine and mixed conifer forest types at risk of problem wildfires and is at the beginning stages of fuel treatment planning by the Fremont-Winema National Forest. The watershed is approximately 169,200 acres, of which approximately 77,500 acres are privately owned and 91,700 acres are owned and managed by the U.S. Department of Agriculture (USDA) Forest Service. The Drews Creek watershed encompasses a relatively narrow band of topographical relief. The forested area of the watershed is 140,526 acres. Stands dominated by ponderosa pine account for about 68% of the forest land in the watershed, about 17% of the area is in juniper woodlands, and western juniper dominates 26% percent of all forested types, encroaching on the hot dry ponderosa pine sites. Stands dominated by white fir represent a minor contingent of the landscape, at around 6% of the forested acres. Dry grasslands, dry shrub lands, and dry meadows comprise nearly 50% of non-forested lands (defined as land with tree cover less than 10%) with the balance being agricultural lands and wet meadows associated with the major streams.

Dead or down wood fuel loadings are variable across the drainage but follow various gradients:

- In the treated low-elevation pine stands, typical fuel loadings range from 2 to 5 short tons of biomass per acre.
- Untreated pine stands tend to be more variable, averaging 3 to 15 short tons biomass per acre.
- As white fir joins the stands at low elevations, loadings increase rapidly, particularly where root disease is present. Typical loadings here can range from 15 short tons to as high as 50 short tons biomass per acre or more if there has been recent disturbance that has killed trees or made them more susceptible to wildfire.

For the period of 1949-1999 the watershed had 688 wildfire ignitions, an average of 14 fire starts per year. The high was 38 ignitions in 1977 and the low was one in 1963. All fires were actively suppressed and 88% were suppressed at less than 0.25 acres, 10% between 0.26 to 9.9 acres, and the balance at larger acreages. Forty-four fires larger than 10 acres occurred over this period; the total area burned for these fires was approximately 9,000 acres.

3.2 Overview of the offset project

The project boundary for the fuel treatment case study was the entire Drews Creek watershed that was assumed to benefit from the project practices (i.e., the project included both the stands treated as well as the remaining untreated stands within the watershed). The proposed offset project was to treat a percentage of the forested stands within Drews Creek watershed (i.e., the landscape) with thinning operations to lower tree stocking and removing associated logging slash and other wildfire fuel. In some cases, thinning was followed by prescribed under burn to further reduce wildfire fuel loadings.

Avoided wildfire emissions were estimated for a single random wildfire ignition that occurred during extreme burning conditions (i.e., high temperature, low-moisture fuel, and prevailing winds). The emissions estimates were based on the probability distribution of wildfire extent and intensity, including the probability of a problem wildfire.

3.3 Spatial modeling of wildfire and effectiveness of fuel treatments

The case study used ArcFuel[3] as the simulation platform for the analyses. ArcFuel is a library of ArcGIS[4] macros developed to streamline spatial modeling of wildfire behavior, stand growth and yield, and fuel treatments for planning purposes. ArcFuel brings together various data layers—gradient nearest neighbor (GNN) treelists, digital elevation grids, stand polygons, Forest Vegetation Simulator[5] (FVS) growth and yield outputs, LANDFIRE[6] fuel model data, slope, and aspect—and processes them in ways that facilitate communication between fire simulation, stand growth and yield, and spatial modeling programs. Carbon stocks were modeled through FVS' Fire and Fuel Extension (FFE) application. Specifically, FVS-FFE accounts for the following carbon pools:

- Aboveground merchantable live biomass
- Below-ground live and dead biomass
- Standing dead biomass
- Dead and down woody debris
- Forest floor (litter and duff)
- Understory (shrub and herb)

FVS-FFE also accounts for the fate of carbon stored in merchantable material removed, specifically the amount of continued storage in wood products and landfills and the amount lost to decomposition. However, the FVS-FFE does not account for soil carbon stores.

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[3] For more information on ArcFuel, see: http://www.fs.fed.us/wwetac/arcfuel/.

[4] For more information on ArcGIS, see: http://resources.esri.com/gateway/index.cfm.

[5] For more information on the Forest Vegetation Simulator, see: http://www.fs.fed.us/fmsc/fvs/.

[6] Landscape Fire and Resource Management Planning Tools Project. For more information, see: http://www.landfire.gov/.

Stands were selected for treatment based on criteria developed by Fremont-Winema National Forest staff. Virtually all stands eligible based on basal area [at least 70 square feet (ft^2) per acre] also met additional distance to road and slope criteria. The area treated was 94 treatment units, averaging 175 acres each, totaling 17,740 acres. The treatment units covered approximately 12.6% of the watershed's forestland. Of the 17,740 acres selected, 12,825 acres met thresholds for treatment (9.1% of the watershed's forestland). The treatment prescriptions called for thinning from below to a residual basal area of 70 ft^2 per acre for mixed conifer or fir-dominated stands and 50 ft^2 per acre for pine-dominated stands, followed by slash removal and under burning. The treatments were simulated with FVS and consisted of a 3-year sequence of thinning from below, site removal of surface fuel, and under burning.

Relatively few burn periods (defined as the period within a 24-hour day where wildfire activity is the greatest) generally account for the majority of the total area burned in large wildfires (e.g. >5,000 hectares) in the western United States, and wildfire suppression efforts have little influence on fire perimeters during these extreme events. Based on input from forest staff and historical data from remote automated weather stations, each fire event was simulated as an 8-hour burn period with a 25 mph wind under the extreme dry fuel moisture conditions. Wind was randomly simulated from three directions for each burn period and ignition locations were random. These conditions resulted in an average targeted simulated fire size of 11,000 acres.

Each stand had estimated conditional burn probabilities (BP_i), which represent the probability of a fire at the i^{th} 0.5 meter (m) flame length wildfire intensity category reaching the stand. Different flame lengths are predicted depending on the direction the fire encounters a stand relative to the major direction of spread (i.e., heading, flanking, or backing fire). The conditional burn probability for a given stand is an estimate of the likelihood that a stand will burn given a random ignition somewhere in the watershed under the weather conditions represented in the simulation.

Random ignitions were also allowed to originate outside the watershed to include wildfire events that burned into the watershed. The treated and untreated landscapes were each simulated with 10,000 wildfires to generate burn probability surfaces at 90m resolution. This represented both the conditional probability of wildfire reaching the stand (given an ignition on the landscape) and the conditional probability of the wildfire's intensity (given that wildfire reached the stand).

3.4 Quantifying effects of wildfire on carbon stocks

To quantify the potential effects of wildfire on carbon stocks, each possible stand condition (as represented by the GNN tree list data, both treated and untreated) for each possible wildfire intensity (as represented by flame length category) was burned through FVS-FFE. Each stand condition in the study area was burned within FVS-FFE under a pre-defined surface fire flame length ranging from 0.5m to 10m in 0.5m increments. The post-wildfire carbon reports in FFE were then examined to determine the amount of carbon in each carbon pool after burning. The result was a carbon loss function for each stand condition representing all the possible post-wildfire carbon stocks by wildfire intensity class including no wildfire.

Carbon loss is defined here as the reduction in post-wildfire carbon stocks for a given wildfire intensity when compared with the carbon stocks present if no wildfire occurred; the amount reduced is equivalent to CO_2 emissions lost to the atmosphere from the fire. As such, it ignores nitrous oxide (N_2O) emissions from fire events and any CO_2 emissions related to fossil fuel combustion during fuel treatment activities. For treated stand conditions, carbon loss included the sum of carbon loss from treatment and from wildfire. Treatment carbon losses occur as a result of non-merchantable biomass removal, the burning or decomposition of non-merchantable material remaining on site, carbon losses associated with the end-use and fate of merchantable material removed, and from the CO_2 emissions from the under burns.

The carbon stocks representing the amount of stored carbon post-wildfire (for untreated stand conditions) and post-treatment/wildfire (for treated stands) was matched with the burn probability data to calculate expected carbon stocks for each stand as follows in Equation 1:

$$E[C]_{LS_j} = \left[\sum_{i=0}^{20} \left[BP_{ij} \times SC_{ij} \right] \right] + WPC_j$$

Where:

$E[C]_{LSj}$ = Expected carbon (mass per unit area) post-wildfire for the *j*th stand and LS = TRT for the treated landscape and NO-TRT for the untreated landscape.

BP_{ij} = Conditional burn probability of wildfire intensity class *i* reaching stand *j*; where:

$\sum_{i=1}^{20} BP_{ij} = BP_j$ where BP_j is the overall burn probability of wildfire reaching stand *j*

BP_{0j} = Conditional probability of no fire = 1-BP_j;

and $\sum_{i=0}^{20} BP_{ij} = 1$

SC_{ij} = total stand carbon, post-wildfire of wildfire intensity class *i* burning in stand *j*; *i*=1 to 20.

SC_{0j} = total stand carbon in stand *j* if no wildfire occurs.

WPC_j = carbon stored in wood products from treatment in stand *j*.

For the untreated landscape, $WPC_j = 0$ for all j. For treated areas on the treated landscape, SC_{ij} represents total stand carbon post-treatment and post-wildfire for intensity class i burning in stand j for $i = 1$ to 20, and for treated stands on the treated landscape, SC_{0j} represents total stand carbon post-treatment if no wildfire occurred.

3.5 Calculating the carbon offsets

The expected carbon offset is calculated for each stand by comparing the expected post-wildfire amount of carbon stored in the stand on the treated landscape with the amount of carbon stored in the same stand post-wildfire on the untreated landscape. (If the stand had been treated, then the post-treatment/post-wildfire conditions are compared with the same stand's untreated/post-wildfire conditions). If the amount of carbon stored in the stand post wildfire on the treated landscape is greater than the amount of carbon stored post-wildfire on the untreated landscape, then carbon offsets would represent the positive CO_2 emission benefit that occurred as a result of undertaking the treatment.

The carbon offset, $E[(\Delta C)]$, for the entire project is calculated as follows in Equation 2:

$$E[(\Delta C)] = \sum_{j=1}^{n} (E[C]_{TRT_j} - E[C]_{NO-TRT_j})$$

where:

n = is the total number of stands in the watershed,

$E[C]_{TRT_j}$ = is the expected carbon stock post treatment and wildfire in stand j; treated landscape

$E[C]_{NO-TRT_j}$ = is the expected carbon stock post-wildfire, stand j; untreated landscape, and

$E[C]_{TRT_J} - E[C]_{NO-TRT_j}$ = the carbon offset occurring in stand j as a result of treatment.

$E[(\Delta C)] > 0$ is a necessary condition for the offset to be used as mitigation for CO_2 emissions from an unrelated source.

3.6 Modeling Results

The simulated fuel treatments were effective in reducing the intensity and extent of wildfire. Fuel treatment had the desired effect of reducing the likelihood of fire reaching a given stand as measured by conditional burn probability. For untreated stands on the treated landscape, the likelihood of wildfire to spread to untreated stands was also reduced as a result of applying the treatments. There was a shift in the conditional burn probability distribution for treated stands, making low intensity fires much more likely than if the stands had not been treated, as well as reducing the overall likelihood of wildfire in those stands. Average fire size on the treated landscape was 32% lower than average fire size on the untreated landscape. Also, the largest fire simulated on the treated landscape was 15,000 acres compared with over 19,000 acres for the untreated landscape. In general, the treated landscape experienced a greater number of smaller wildfires when compared with the untreated landscape.

Thinning from below and fuel move practices removed 716,063 metric tons of CO_2 equivalent[7] ($mtCO_2e$), or 55.9 $mtCO_2e$ per treated acre, representing 19.1% of the total biomass in treated stands. Of this amount, 530,843 $mtCO_2e$, or 74%, was emitted to the atmosphere (41.3 $mtCO_2e$ per treated acre) with the remaining 185,219 $mtCO_2e$, or 26%, remaining stored in long-lived wood products (14.3 $mtCO_2e$ per treated acre). Under burning emitted another 372539 $mtCO_2e$ of CO_2 (29.0 $mtCO_2e$ per treated acre) representing 13.3% of the total biomass in treated stands. In total, carbon lost from the fuel treatment activity totaled -903,383 $mtCO_2e$ (-70.6 $mtCO_2e$ per treated acre). In comparison, only an expected 12,319 $mtCO_2e$ (0.7 $mtCO_2e$ per acre) of avoided carbon loss accrued to the treatment polygons as a result of the treatment's effect of reducing both the likelihood and intensity of wildfire in treated stands. Similarly, only 10,278 $mtCO_2e$ of expected avoided carbon loss accrued to the untreated polygons (0.1 $mtCO_2e$ per acre) as a result of the treatment's effect of reducing the likelihood of wildfire, for a total benefit of 22,597 $mtCO_2e$ of expected carbon loss avoided (0.2 $mtCO_2e$ per forested acre). The net expected carbon benefit accruing to the treated landscape when compared with the untreated landscape is $E[(\Delta C)]=$ -880,786 $mtCO_2e$ (-6.3 $mtCO_2e$ per forested acre) carbon, which indicates an overwhelming net gain in carbon emissions arising from the fuel treatment project.

The case study results show a gain in carbon emissions from conducting the fuel treatment project; that is, carbon stocks on the untreated landscape (the project baseline) are higher than on the treated landscape, even though they provide a lowered chance of problem wildfire. This is due to the probabilistic nature of wildfire and, specifically, the high probability that wildfire does not occur on a given landscape in a given year. Even if an ignition on the landscape occurs, the corresponding risk of wildfire for a given stand is low (usually below 3%). Since the dominant baseline scenario for each stand is that the fire never reaches it, fuel treatments provided no avoided CO_2 emissions benefit in this case study. Further, not every wildfire that does reach the stand, even under severe weather and fuel moisture conditions, is a problem wildfire, and less severe wildfires present significantly smaller carbon losses. And when a problem wildfire does occur, the amount of carbon loss compared with the stored carbon before the wildfire is still relatively small since the immediate effect of severe wildfire is to transfer carbon from the live tree carbon pools to the dead tree carbon pools.

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[7] Emissions and losses are reported here as metric tons of carbon dioxide equivalent ($mtCO_2e$), because some losses are in the solid form of carbon and others are in the gaseous form of carbon, namely CO_2. All outputs of the model were originally expressed as short tons carbon, so the units have been changed using a multiplier of 3.67 to change from carbon to CO_2 and 0.9072 to change from short tons to metric tons.

The case study results show that for any given ignition in the year after the completion of fuel treatments, the expected avoided carbon loss from one wildfire ignition is 22,597 $mtCO_2e$. The Drews Creek watershed experiences 14 wildfire ignitions a year on average; if independence is assumed in the wildfire outcomes from one ignition to another and it is assumed that one-third, say 5, of the 14 ignitions per year for Drews Creek occurred during the severe weather and fuel moisture conditions used in this study, then the expected avoided CO_2 emissions from the same fuel treatment investment would be 112,984 $mtCO_2e$ (the avoided carbon loss of 22,597 $mtCO_2e$ multiplied by an assumed five avoided events for that year). However, even when properly accounting for the number of chances in a given year a problem wildfire could have occurred, the added carbon benefit is still not enough benefit to make up for the 903,383 $mtCO_2e$ lost from the fuel treatment activity.

CHAPTER 4:
Case Study: Evaluation of Offset Quality

The case study simulation results reveal whether fuel treatment projects meet some of the conditions necessary to be considered a quality offset project. The case study focused on quantification and modeling techniques, so it is most applicable to use those offset quality criteria related to baseline and quantification. Therefore, this chapter evaluates how the case study performed against the following three criterion: (1) Be real, (3) Be based on a realistic baseline, and (4) Be accurately quantified and monitored. Chapter 5 discusses all of the OQI offset quality criteria in the context of the project type.

4.1 How the case study performed against criterion "Be real"

For the case study's offsets to be considered "real," the project would have needed to count all relevant carbon pools and determined that CO_2 emissions reductions occurred that could be quantified as offset credits. However, the case study resulted in an initial net loss in carbon stocks to the atmosphere, so no offsets were generated. The estimated net loss is real in that the carbon gains and losses of all the relevant carbon pools (aboveground biomass, below-ground biomass, dead wood, litter, and wood products, and landfills) were accounted for[8]. The project did not attempt to account for transportation fuel combustion or other project-related emissions. Further, the model did not attempt to incorporate anticipated changes to vegetation or wildfire risk as a result of climate change.

In addition, in order for the case study's offsets to be considered "real," the problem wildfire in the baseline scenario must have a probability of one of occurring in the baseline scenario (that is, it must have occurred with near certainty absent the project activity). There was uncertainty that the problem wildfire would have occurred in the baseline case, so there is no certainty that there would have been an emissions event that the project is avoiding.

Conclusion: The Drews Creek watershed case study did not meet the "Be real" criterion because all estimates were expected values (i.e., estimates that reflect the average outcome given the probability distributions of wildfire *including the probability that no wildfire occurs*) and there was not an absolute probability of one that the problem wildfire would have occurred. Also, the project did not account for project-related fossil fuel emissions.

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[8] Soil carbon was not accounted for due to a lack of data and models. This could be a key omission in the case study analysis as areas that are intensively burned by severe wildfire could result in significant losses of soil carbon that would be avoided by the lower intensity burns that follow fuel treatment. This omission is conservative in that it would tend to underestimate rather than overestimate project crediting.

4.2 How the case study performed against criterion "Be based in a realistic baseline"

The case study simulation demonstrated that establishing a realistic "without project" baseline for fuel treatment projects is feasible. The Drews Creek case study estimated the probability of wildfire occurrence and wildfire intensity on both the untreated ("without project") and treated ("with project") landscape, using identical methods and models. This is a significant advancement over previous studies estimating the carbon benefits from fuel treatments that had to rely on knowing in advance where the problem wildfire was going to occur[9] since this approach explicitly took into account the uncertainty inherent in wildfire occurrence, both in terms of extent and severity. As such, the case study modeling approach is realistic in that expected outcomes to carbon stocks—a weighted average of all possible outcomes for all types of wildfire including no wildfire based on the probability of each outcome—are used to quantify emission benefits (or costs).

Conclusion: The Drews Creek watershed case study met the criterion "be based on a realistic baseline" because the baseline modeling approach explicitly took into account the uncertainty inherent in fire occurrence and behavior. As such, the modeling approach is realistic. This is as compared with previous modeling of fuel treatments that assumed advanced knowledge of the occurrence, extent, and severity of the wildfire.

4.3 How the case study performed against criterion "Be accurately quantified and monitored"

The case study simulation results show that wildfire emissions and avoided emissions from fuel treatment activities can be modeled and reported using a sound probabilistic approach to wildfire. However, conservativeness was not applied in estimating the baseline stocks and emissions—both the "with project" and "without project" outcomes were modeled at the same level of accuracy and precision. To be conservative, the emissions from the "with project" case should be higher than the expected value, while the emissions from the "without project" case should be lower than the expected value.

Conclusion: The Drews Creek watershed case study partially met the criterion "be accurately quantified and monitored" because both the baseline and "with project" scenarios were modeled using identical techniques and the quantified offsets is simply the difference between the two. However, it did not provide methods to monitor the quantified reductions.

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[9] See Hurteau and others 2008 for an example.

4.4 Conclusions

The Drews Creek watershed case study does not result in a quality offset project. First, the case study resulted in an increase in CO_2 emissions, so no real offsets can result from the project as described. Further, there is too much uncertainty that a problem wildfire would have occurred during the project lifetime, meaning that there is no certainty that an emission was avoided by the project. In addition, the project did not address the majority of the offset criteria, including permanence, additionality, and ownership.

CHAPTER 5: The Fuel Treatment Project Type: Discussion of Offset Quality and Potential

Due to the limited scope of the case study, quality criterion (1), (3), and (4) were the only offset requirements that could be evaluated. However, it is possible to use the case study as a foundation for discussing whether and under what conditions wildfire fuel treatments may qualify as an offset project type. This chapter discusses the project type more generally within the context of the OQI's quality criteria.

5.1 Be real

In order to "Be real" this project type must provide certainty that the avoided emission event (the problem wildfire) occurred, all relevant carbon pools must be taken into account, and the project must result in an actual carbon benefit.

This project type can meet the "Be real" criterion if the project is properly designed. For example, one reasonable way to provide certainty that the problem wildfire would occur during the project lifetime is to increase the required duration of the project until the certainty of the emission event is 100%. While problem wildfire is probabilistic for a given wildfire ignition in a given year, eventually it is going to happen. "Eventually" can be quantified using the absolute probability (usually estimated based on historical fire frequency data) that an area will incur a catastrophic wildfire. For example, if the absolute annual probability that a problem wildfire event will occur in a given stand is 2% (= 0.02), then this type of wildfire would occur within 50 years with near certainty (since 1/0.02 = 50). Therefore, this project would have a 50-year project lifetime (plus a 100-year verification period afterward). Because fuel treatments are estimated to last for 10 to 15 years, multiple fuel treatments must be implemented over the course of the project life to maintain fire suppression qualities.

The project would also need to account for all the relevant carbon pools (though soil carbon can justifiably be omitted for simplification) and for the emissions associated with any project activities such as fossil fuel combustions, the construction of any roads, etc.

5.2 Be additional

The project type would not currently meet OQI's regulatory requirement for additionality if it is performed on federal lands. If a project was conducted on private lands, it would need to demonstrate that there was a barrier (financial or otherwise) to fuel treatment implementation that the sale of carbon credits helped to overcome.

Since most projects would occur on federal lands, this project type is unlikely to meet the “Be additional” criterion until policymakers provide clarity as to the appropriate role for carbon market financing on public lands.

5.3 Be based on a realistic baseline

This project type can meet the “Be based on a realistic baseline” criterion if the project is properly designed utilizing a probabilistic modeling technique (similar to that used in the case study). However, it must accurately model pre- and post-fire carbon stocks over the entire project lifetime.

5.4 Be accurately quantified and monitored

This project type can meet the “Be accurately quantified and monitored” criterion if the project is properly designed to have a unique monitoring plan that accurately and conservatively quantifies carbon stocks.

The offsets from this project type can be quantified as the difference between baseline and project carbon stocks (plus any associated carbon stored as harvested wood product) by using a modeling technique similar to that used in the case study. As discussed in Chapter 2, the project’s crediting must be conservative to ensure quality offsets.

Fuel treatment projects need to be monitored over time against a clearly defined set of conditions or thresholds that indicate the avoidance of the problem wildfire on the treated landscape (e.g., average fire size, number of fires suppressed, etc). Any behavior on the landscape that exceeds these thresholds would trigger an on-site third party verification. If the verification indicates that carbon stocks have been reduced below a threshold level, then a reversal has occurred. Reversals are discussed further under permanence.

5.5 Be independently validated and verified

This project type can meet the “Be independently validated and verified” criterion if the project is properly designed so that the modeling technique would be validated by a transparent stakeholder process. In addition, the monitoring reports would need to be verified by qualified independent third parties and on-site verifications would be required on a regular basis and after any fire large enough to trigger verification requirements.

5.6 Be unambiguously owned

This project type can meet the “Be unambiguously owned” criterion if the project is properly designed to carefully document which participant claims ownership. All participants with a potential claim to ownership over the reduction (e.g., the entity performing the treatment, the landowners, or the entities utilizing any removed biomass) would need to agree to, and provide evidence of, clear and uncontested ownership over the offsets. All issued offsets need to correspond to a unique serial number that is stored on a public registry.

5.7 Address leakage

Leakage is not expected to be a concern with this project type. Any activity-shifting leakage concerns (i.e., that fewer fuel treatments are performed on other lands due to the project activity) would be addressed as part of concerns about additionality. Any market-shifting leakage (i.e., the additional harvested wood product or biomass brought to market) would be expected to increase carbon stores on the land of other entities, and therefore can be safely and conservatively excluded from analysis.

5.8 Address permanence

This project type can meet the "Address permanence" criterion if the project is properly designed to maintain the project case fire levels for 100 years past the project lifetime. For example, if the project lifetime is 75 years, the monitoring, verification, and fuel treatments would have to be conducted for a total of 175 years. This is due to the fact that without further treatment, the baseline landscape wildfire fuel loadings and other conditions will reset themselves and the expected wildfire severity will increase, emitting the carbon that was sequestered by the project activity. With this consideration, the offset project becomes a commitment to scheduling a series of repeated landscape fuel treatment projects over time so as to maintain the "with project" wildfire risk conditions that give rise to lower expected wildfire emissions.

In addition, fuel treatment projects would involve many of the permanence efforts that improved forest management projects do, including contractual requirements to maintain project activities over the project lifetime, buffer pool contributions to account for unintended reversals, and contractual obligations to reimburse credits in the case of an intended reversal. A reversal would occur if it is determined that a wildfire exceeds a given threshold size and severity.

5.9 Do no net harm

This project type can meet the "Do no net harm" criterion if the project is properly designed to adhere to all relevant state and federal forest practice regulations that protect water quality, endangered species, and biological diversity. The project must take place in a location that has been identified by an existing local and regional needs assessment that was transparently developed with stakeholder participation and explicitly addresses habitat impacts and the drought resistance of the forest in addition to wildfire risk.

5.10 Summary evaluation

It is theoretically possible to generate quality offsets if fuel treatment projects result in real emission reductions, are not located on federal land, and are properly designed. However, without emission reductions, there are no offsets to be generated. Further, quality forestry offsets cannot be located on federal lands until federal legislation or rule making clarifies the role of private financing of public management activities. If these two major hurdles can be overcome, it is recommended that the project be designed as outlined in this chapter, which is consistent with an improved forest management project.

CHAPTER 6: Lessons Learned

This report analyzes the viability of fuel treatment projects as a source of high quality carbon offsets. To make this determination, the report evaluated a fuel treatment case study to ascertain whether the assumed CO_2 benefit of the fuel treatment could be realized. Based on the case study, it was then determined what requirements the project type must meet to produce quality offsets. Following are the primary lessons learned from this analysis.

6.1 Fuel treatment projects: Evaluation as a carbon offset

While it is possible to design a quality fuel treatment offset project, it is unlikely that any projects of this type will be implemented for three primary reasons:

1. There are no indications that this project type actually results in emission reductions, so no offsets would be produced.

2. The activities necessary to ensure offset quality are likely to make this project type cost-prohibitive for some of the reasons cited below and detailed in Chapter 5:

    - The risk of reversal is high, which requires significant contributions of some of the offsets to buffer pools to insure against this risk.
    - The need to continue to implement fuel treatment practices periodically on the landscapes for an additional 100 years after a project is completed can be a disincentive when recruiting project participants.
    - The cost of third party verification will be high due to the need for verifiers to have specialized experience in wildfire ecology, forestry, and probabilistic simulation models.

3. The cost of monitoring and verification will be high due to the long span of time that both activities are periodically required to occur (project life plus 100 years).
4. The project potential is limited because the majority of potential projects would be on federal forestlands, which do not currently meet the “Be additional” criterion.

6.2 Fuel treatment projects: The opportunity

Regardless of their potential (or lack thereof) as a carbon offset project, fuel treatment projects remain necessary to provide clean water, fish, and wildlife habitat; make forests more resilient to wildfire (ideally, restoring fire’s ecological role in maintaining forest health and resilience), and protect communities from the risks associated with wildfires.

The need for conducting well planned and socially accepted fuel treatment projects will become even more important as a means to adapt western forests to climate change since most climate modeling scenarios predict that western forests will expand in area and increase in woody biomass. Climate-driven changes in wildfire regimes will likely be the dominant driver of change in western U.S. forests over the next century. For example, due to increased temperatures, reduced snowpack, and reduced summer precipitation, models predict an increase in the length of the fire season and in the likelihood of fires east of the Cascade Range. The frequency of wildfire is expected to increase along with severity and extent, and forests will experience unprecedented mortality and loss of productivity from insects and disease infestations.

6.3 Fuel treatment projects: Next steps

The following two areas warrant further investigation to conclusively determine if fuel treatments are a good source of offsets.

- If there is a federal decision that this project type can be implemented on federal lands, it would be prudent to definitively determine if there is a carbon benefit from this project type through further studies to attempt to receive offset funding.
- It may be possible to effectively use the removed biomass to create energy or biochar, both of which could benefit the climate and the rural economies. Further study is needed to properly define how the CO_2 emission benefits (or carbon neutrality or even a carbon cost) from the fuel treatment projects is linked with either of these project activities. It is the overall net reduction of CO_2 emissions to the atmosphere—both those accruing to the forestland as a result of treatment and those accruing to the power plant or other end use as a result of utilization—that will define the potential of the combined activity to provide a climate benefit. Projects will need to be carefully constructed so that the quality offset criteria are met.

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FINAL REPORT ON WESTCARB FUELS MANAGEMENT PILOT ACTIVITIES IN LAKE COUNTY, OREGON

Goslee, K., T. Pearson, S. Grimland, S. Petrova, J. Walls and S. Brown.

Winrock International

DOE Contract No.: DE-FC26-05NT42593

Contract Period: October 1, 2005 - May 11, 2011

Table of Contents

Abstract

This report summarizes work by Winrock International, Lake County Resources Initiative (LCRI), and other Lake County, Oregon partners to implement hazardous fuel reduction/biomass energy pilot activities in WESTCARB Phase II (2006-10). Wildfire is a significant source of GHG emissions in Oregon and throughout the WESTCARB region. WESTCARB developed methodologies to evaluate, validate and demonstrate the potential of reducing hazardous fuel for biomass energy to contribute to GHG mitigation and adaptation. The report describes hazardous fuel reduction pilot activities on Federal and private lands in Lake County; pre- and post-treatment measurements to quantify forest carbon impacted by treatment and/or fire; analysis of data from these pilots to determine the net GHG impact of the fuel reduction treatments; and related work by LCRI to facilitate continued hazardous fuels reduction efforts in Lake County.

Keywords: *Carbon, sequestration, hazardous fuel reduction, forest, Lake County*

Executive Summary

Introduction

The West Coast Regional Carbon Sequestration Partnership (WESTCARB), led by the California Energy Commission, is one of seven US Department of Energy regional partnerships working to evaluate, validate and demonstrate ways to sequester carbon dioxide and reduce emissions of greenhouse gases linked to global warming.

Earlier analyses by Winrock showed wildland fire to be a substantial source of greenhouse gas (GHG) emissions throughout the region. Actions to reduce hazardous fuel loads, so as to reduce the probability, areal extent, or severity of wildfires, could result in lower net GHG emissions when compared to a baseline scenario without such treatments. Fuel reduction may also contribute to carbon sequestration by enhancing forest health or growth rates in post-treatment stands. Finally, for treatments where fuel removal to a biomass energy facility is feasible, additional GHG benefits may be created by substituting the biomass for fossil fuel rather than leaving the biomass in the forest to decompose.

Hazardous fuel reduction/biomass energy pilot activities were implemented in the two WESTCARB terrestrial pilot locations, Shasta County, California and Lake County, Oregon. These projects provide real-world data on carbon impacts of treatments, costs, and project-specific inputs to a related WESTCARB task, in which Winrock International and the WESTCARB Fire Panel are working to investigate whether the development of a rigorous methodology to estimate GHG benefits of activities to reduce emissions from wildland fires is feasible.

Purpose

This report provides results from the WESTCARB Phase II hazardous fuel reduction pilot activities in Lake County, Oregon. In addition we report on the revised 2010 Long-range Strategy for the Lakeview Federal Stewardship Unit, a related activity done in conjunction with the WESTCARB research efforts.

Project Objectives

The overall goal of WESTCARB Phase II is to demonstrate the region's key carbon sequestration opportunities through pilot projects, methodology development, reporting, and market validation. WESTCARB research will inform policymakers, communities, and businesses on how to invest in carbon capture and storage technology development and deployment to achieve climate change mitigation objectives.

The specific objectives of the Phase II Lake County fuel reduction pilots are to investigate the feasibility of fuels-treatment-based terrestrial sequestration by conducting pilot projects in a representative West Coast forest; compile information on site conditions, fuel treatment prescriptions, and costs; and inform and field-test the WESTCARB fire GHG emissions methodology. Fuels treatments were implemented on two project areas: Bull Stewardship and Collins-Hot Rocks.

Methodology for measuring impacts of hazardous fuels treatments

Pre- and post-treatment measurements were made on two fuels treatment projects in Lake County, Oregon. These projects involved removal of non-commercial biomass and sawtimber with the overall objective of reducing fuel loading and risk of catastrophic wildfire. The actual fuels treatments were not initiated under WESTCARB support, but they provided an opportunity to conduct on-the-ground measurements of actual hazardous fuel reduction efforts.

The fuel reduction activities were located in the southwest corner of the county. One project area, Bull Stewardship, was on the Fremont-Winema National Forest, and the other, Collins-Hot Rocks, was on privately owned land.

A total of 38 plots were established in the Bull Stewardship and 22 in the Collins Companies Hot Rocks lands. Pre- and post-treatment measurements on these plots addressed live trees greater than 5 cm diameter at breast, canopy density, standing dead wood, understory vegetation, forest floor litter and duff, and lying dead wood. These represent the forest carbon pools that are likely to be affected by fire, treatment, or both, and so are critical to the accounting of hazardous fuel reduction treatment impacts and potential wildfire impacts on forest carbon.

These measurements were used to determine the carbon stocks before and after treatment and before and after a potential wildfire, for each project area. Growth modeling was conducted with the Forest Vegetation Simulator for both with and without treatment stands. Emissions from a potential fire were modeled in both with- and without-fuels treatment scenarios using both the Fuel Characteristic Classification System and the Forest Vegetation Simulator fire and Fuels Extension (FVS-FFE). FVS was also used to project growth on burned stands, incorporating the impacts of fire on the future stand.

Because it was not possible to send harvested biomass that did not go into sawtimber to a biomass energy plant and it was instead piled for burning, the CO_2, CH_4, and N_xO emissions from burning this biomass were calculated. Board feet of timber harvested was converted to metric tons of carbon, with retirement rates applied.

Project Outcomes

Bull Stewardship

Including carbon stored in long term wood products and emissions from pile burning, for treated stands without wildfire, a total of 73.2 tons of carbon per acre are stored, with 60.4 t C/ac still stored in the same stands following a wildfire.

Incorporating the risk of fire of 0.6% to calculate net emissions or removals (section 2.8), the fuels treatment on the Bull Stewardship project resulted in an effective immediate net emissions of 36.7 t CO_2-e/ac (10.0 tons of carbon per acre).

In the absence of a wildfire, the fuels treatments and commercial harvest result in short term emissions of 59.4 t CO_2/ac and emissions of 36.5 t CO_2/ac over 60 years (table A1).

Table A1: Net short and long term emissions from fuels treatment without fire on Bull Stewardship in tons of carbon dioxide per acre (+ = removals; - = emission)

	Short term 10 years	Long term 60 years
Harvested timber	**17.2**	**12.6**
Treatment emissions	**-68.2**	**-40.7**
Pile burning emissions (CO_2e)	**-8.4**	**-8.4**
NET	**-59.4**	**-36.5**

For the treatment to yield benefits to the atmosphere, the emissions from treatments will need to be offset by reductions in emissions from a potential wildfire hitting the area. In order for the treatment to have an impact, such a fire would have to occur before fuels have returned to hazardous conditions, at which point it will be necessary to re-treat the forest. According to the FVS-modeled results, if a wildfire were to occur in the year of treatment, after 10 years the net emissions from treatment would be 40.7 t CO_2/ac.

Collins-Hot Rocks

Including carbon stored in long term wood products and emissions from pile burning, for treated stands without wildfire, a total of 34.1 tons of carbon per acre are stored, with 25.1 t C/ac still stored in the same stands following a wildfire.

Incorporating the risk of fire of 0.6% to calculate net emissions or removals (section 2.8), the fuels treatment on the Collins-Hot Rocks project resulted in an effective immediate net carbon emission of 76.3 t CO_2-e/ac (20.8 tons of carbon per acre).

In the absence of a wildfire, the fuels treatments and commercial harvest result in short term emissions of 108 t CO_2/ac and emissions of 113 t CO $_2$/ac over 60 years (table A2).

Table A2: Net immediate and long term emissions from fuels treatment without fire on Collins-Hot Rocks in tons of carbon dioxide per acre (+ = removals; - = emission)

	Short term 10 years	Long term 60 years
Harvested timber	**8.8**	**6.2**
Treatment emissions	**-101.9**	**-104.9**
Pile burning emissions (CO_2e)	**-17.6**	**-17.6**
NET	**-110.7**	**-116.3**

For the treatment to yield benefits to the atmosphere, the emissions from treatments will need to be offset by reductions in emissions from a potential wildfire hitting the area. In order for the treatment to have an impact, such a fire would have to occur before fuels have returned to hazardous conditions, at which point it will be necessary to retreat the forest.

According to the FVS-modeled results, if a wildfire were to occur in the year of treatment, after 10 years the net emissions from treatment would be 81.1 t CO_2/ac.

Related Efforts

The Lakeview Stewardship Group developed the 2005 Long-Range Strategy for the Lakeview Federal Stewardship Unit (Lakeview Stewardship Group 2005; see http://www.lcri.org/unit/longrange.htm) and the revised 2010 Long-range Strategy for the Lakeview Federal Stewardship Unit. In conjunction with the WESTCARB research efforts, the work of the Lakeview Stewardship Group have recently borne fruit in six important developments.

- After lengthy negotiations, a 20-year Interagency Biomass Supply MOU was signed on November 1, 2007. The purpose of the MOU is to provide a framework for planning and implementing forest and rangeland restoration and fuels reduction projects that address identified resource needs while being supportive of the Lakeview Biomass Project.
- The efforts of Lake County Resources Initiative (LCRI) and its Lake County partners have resulted in a commitment to the first 10-year Stewardship Contract in the US Forest Service Pacific Northwest Region. The contract, considered a model for the region, provides long-term supply of material necessary for the recent investments in a biomass power plant and small-log mill described below.
- Oregon Governor Kulongoski's office and biomass plant developer DG Energy jointly announced in January 2007 that DG Energy will construct a 13 MW biomass plant in Lakeview. This represented the culmination of multi-year efforts by all the partners in the Lakeview Stewardship Group to reach agreement around sustainable harvest levels and long-term biomass supply mechanisms necessary for investment in new capacity. Since collecting all the data from the stewardship contracts and other significant information from private lands it has been determined that a 25 MW biomass plant is sustainable. Currently the project is scheduled for a final decision on construction during summer 2010 and breaking ground in September 2010 with an estimated completion date of December 2012.
- Oregon Governor Kulongoski in March 2007 announced that the Collins Companies will expand their Fremont Sawmill operation in Lakeview by building a new $6.8 million dollar small-log mill. The small-log mill is the direct result of the 20-year Interagency Biomass Supply MOU and 10-year Stewardship Contract efforts spearheaded by LCRI, and provides an added tool for improving management of forests and hazardous fuels in Lake County.
- Considerable changes have occurred on Fremont-Winema National Forest since the beginning of the WESTCARB project in 2006. The original Forest Service prescriptions for Bull Stewardship, Burnt Willow and Kava are for much lighter treatments than treatments currently being implemented by the Forest Service. One of the critical outcomes is that there is infrastructure in place to restore the Forest Service lands to healthy conditions that will be able to better adapt to climate change.
- The national office of the Forest Service announced in February 2010 that they are accepting proposals for the Collaborative Forest Landscape Restoration Program (CFLRP). Region 6, which includes Lake County, sent in five proposals with the Lakeview Stewardship Group, with

> Fremont-Winema proposal being the number one priority. Over 10 years this could mean an additional 20 million dollars above regular appropriations for fuels management and restoration in the 500,000 acre Lakeview Federal Stewardship Unit.

Conclusions and Recommendations

In both projects, the treatments resulted in overall carbon emissions. This result clearly has negative implications for the future potential of fuels treatments as a carbon projects offset category. Within the treated areas, both projects had significant net emissions when considering treatment and the risk of a potential wildfire. If a fire were to occur in the year of treatment, all projects would still experience net emissions, though the impact of treatment emissions would be slightly reduced.

Both pilots led to a projected decrease in crown fire potential, which decreases fire severity and size. While treatments lead to net carbon emissions in both the short and long term in all projects, there are, of course, additional benefits to fuels treatments, such as increased ability to successfully fight fires and decreased cost of fire fighting; reduced loss of life and property; and reduced potential damage to wildlife habitat.

The results from this study in combination with the paired study in Shasta County and the allied study in Mendocino National Forest underlie the unsuitability of fuels treatment as a potential greenhouse gas offset generating activity. Instead we argue the shift should be made to policies minimizing greenhouse gas emissions from wildfires and from fuel treatments while minimizing wildfire risks to lives, homes, wildlife habitat, and livelihoods in the WESTCARB region.

1.0 Introduction

1.1 Background and overview

The West Coast Regional Carbon Sequestration Partnership (WESTCARB), led by the California Energy Commission, is one of seven US Department of Energy regional partnerships working to evaluate, validate and demonstrate ways to sequester carbon dioxide and reduce emissions of greenhouse gases linked to global warming. Terrestrial (forestry and land use) sequestration options being investigated include afforestation, improved management of hazardous fuels to reduce GHG emissions from wildfires, biomass energy, and forest management. Shasta County, California and Lake County, Oregon were chosen for Phase II terrestrial sequestration pilot projects because of the diversity of land cover types present, opportunities to implement the most attractive terrestrial carbon activities identified in Phase I, and replication potential elsewhere in the WESTCARB region.

Earlier reports identified fire as a significant source of GHG emissions throughout the WESTCARB region. Average estimated emissions from fires for the 1990-96 analysis period were: 1.03 $MMTCO_2e$ for Oregon (Pearson et al 2007a); 1.83 $MMTCO_2e$ per year for California (Pearson et al 2009); 0.18 $MMTCO_2e$/yr for Washington (Pearson et al. 2007b); and 0.47 $MMTCO_2e$/yr for Arizona (Pearson et al. 2007c).

The estimated baseline GHG emissions helped focus attention in Phase II on the questions: can actions by landowners to manage forest fuel loads be shown to produce measurable GHG reductions by decreasing the risk, severity, or extent of catastrophic wildfires? If so, can scientifically rigorous methods for measuring, monitoring, and verifying these GHG reductions serve as the basis for new protocols and market transactions, ultimately allowing landowners who reduce hazardous fuels to receive "carbon credit" revenues and improving the cost-effectiveness of fuel reduction? To explore these questions, hazardous fuel reduction (and where possible, removal of fuel for biomass energy generation) was chosen as a WESTCARB Phase II pilot activity in Shasta and Lake counties, and the WESTCARB Fire Panel was formed to develop fire GHG methodologies and protocols as needed.

1.2 Project Objectives

The overall goal of WESTCARB Phase II is to validate and demonstrate the region's key carbon sequestration opportunities through pilot projects, methodology development, reporting, and market validation. WESTCARB research will inform policymakers, communities, and businesses on how to invest in carbon capture and storage technology development and deployment to achieve climate change mitigation objectives.

The specific objectives of the Phase II Lake County fuel reduction pilots are to:

- Verify the feasibility of fuels-treatment-based terrestrial sequestration by conducting pilot projects in a representative West Coast forest;
- Compile information on site conditions and fuel treatment prescriptions;
- Inform and field-test the WESTCARB fire GHG emissions methodology by:
  - Collecting measurements of real-world fuel treatments to quantify:
    - The carbon stocks available to be burned before and after treatment,
    - The direct impacts of fuel treatments on carbon stocks in different carbon pools (e.g. increases in dead wood, decreases in dense growth), and
    - The fuel removed from the forest for potential biomass energy applications;

    - Providing input data for fire models used to simulate fire behavior and emissions in the baseline (without-treatment) and with-treatment scenarios.
- Promote continued hazardous fuels reduction efforts on Lake County forests and support the location of a biomass power plant in Lakeview through the work of the Lake County Resources Initiative including:
    - Serving as a liaison to the Lakeview Stewardship Group to assist in identifying the sustainable scale for the biomass power plant in Lakeview.
    - Serving as a liaison to secure a Memoranda of Understanding with U.S. Forest Service, Bureau of Land Management, and Oregon Department of Forestry stating a commitment to supply the biomass power plant.

1.3 Report Organization

The report is organized in four sections: project approach, results, related work and conclusions/ recommendations. Section 2 summarizes the private- and federal-lands fuel treatments chosen for study as WESTCARB pilot activities, and methods used for pre- and post-treatment measurements and data analysis. Section 3 provides results of those measurements and analyses. Section 4 details related work undertaken by the Lake County Resources Initiative regarding continued hazardous fuels treatments in Lake County. Section 5 discusses the findings and provides recommendations based on this research.

2.0 Project Approach

2.1 Fuel reduction project locations and descriptions

Pre- and post-treatment measurements were made on two fuels treatment projects in Lake County, Oregon. These projects involved removal of non-commercial biomass and sawtimber with the overall objective of reducing fuel loading and risk of catastrophic wildfire. Treatments also included chipping and removal of biomass fuel to a biomass energy plant. The actual fuels treatments were not initiated under WESTCARB support, but they provided an opportunity to conduct on-the-ground measurements of actual hazardous fuel reduction efforts.

The fuel reduction projects were located in the North Warner Mountains, northeast of Lakeview, Oregon. Figure 1 shows Lake County land ownership and forest classes. The fuel reduction activities were located in the southwest corner of the county.

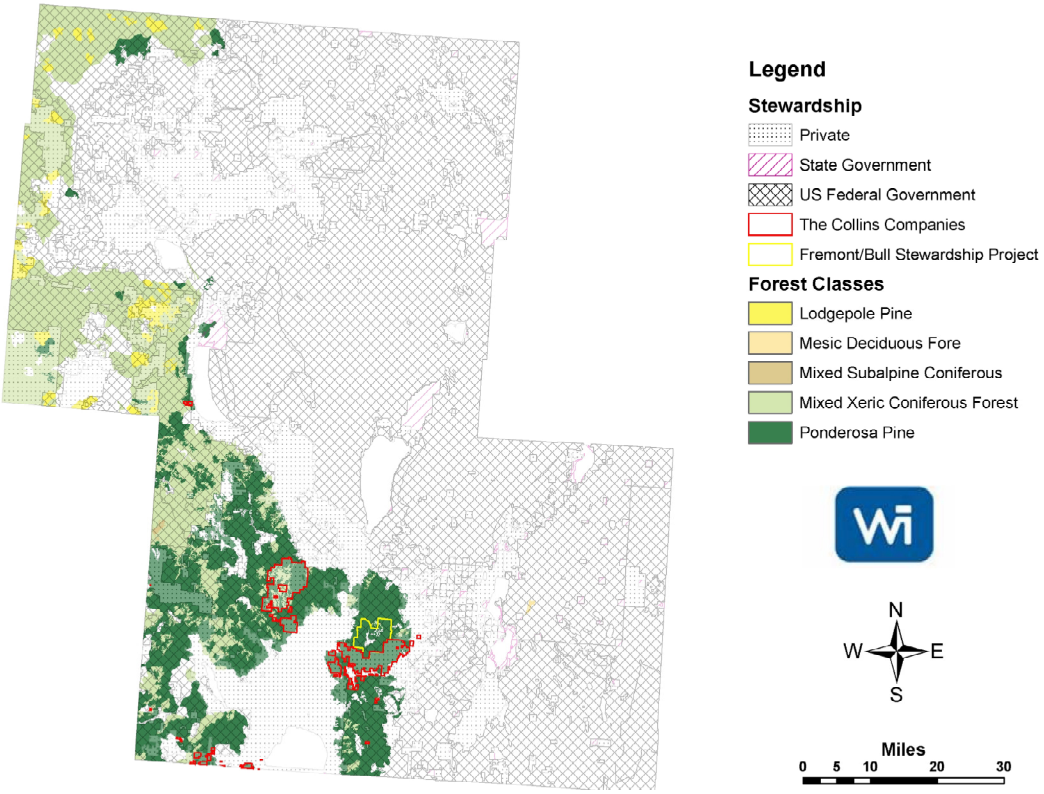

Figure 1. Lake County forest classes, Collins Companies lands (red) and Bull Stewardship Project boundary (yellow) adjacent to the eastern Collins Companies parcel.

The study on fuels treatments in Lake County was designed to examine the major ownership classes on forestlands in the county: Federal Government-owned National Forests and privately-owned industrial timberlands (Fig. 1 and 2):

- Federal lands - Fremont-Winema National Forest
- Private industrial timberlands – Collins Companies lands

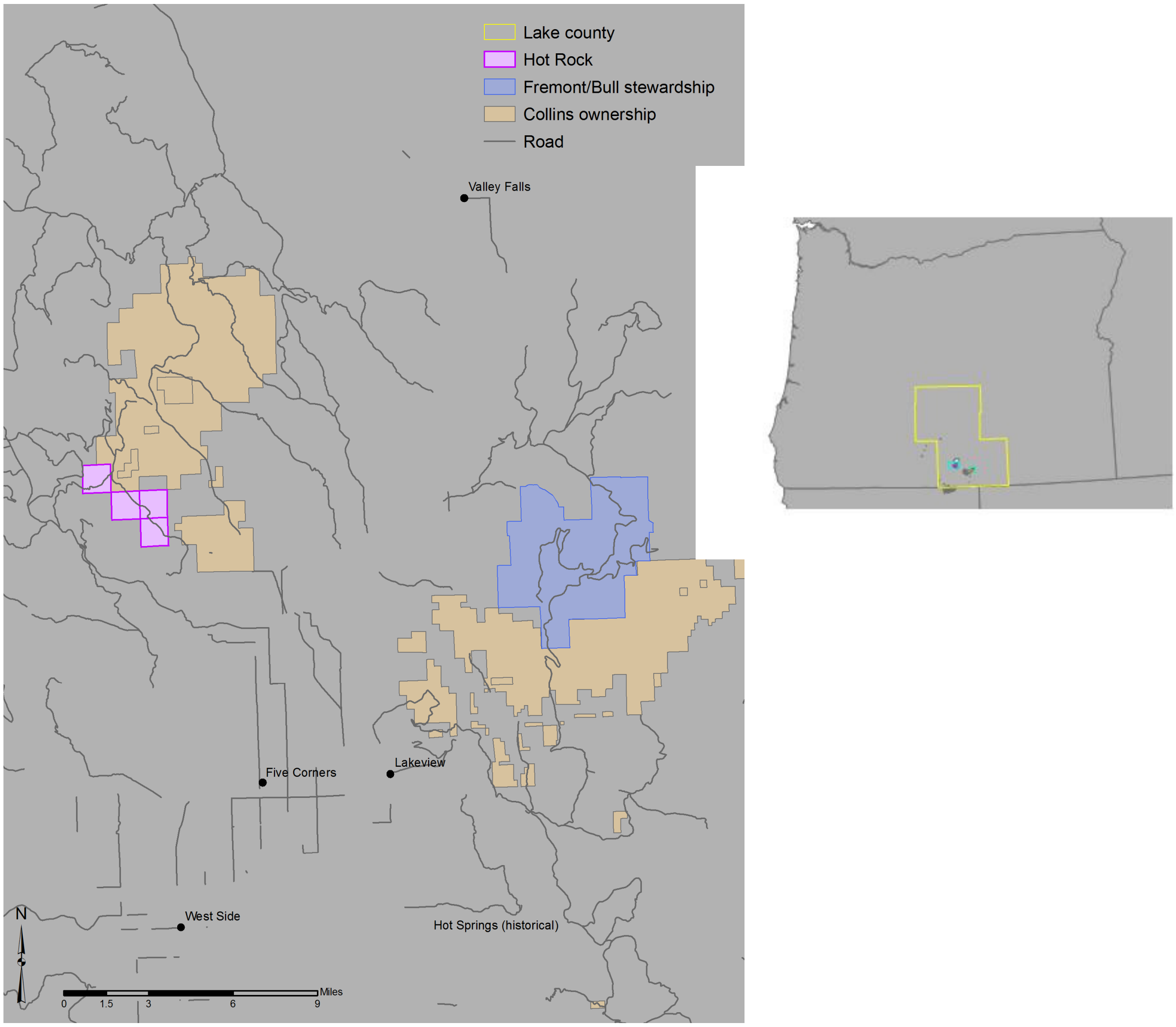

Figure 2. Lake County - US Forest Service Bull Stewardship Project (blue), and Collins Company Hot Rocks fuel treatments (pink).

2.1.1 Fuel reduction on Bull Stewardship Project lands

Location

The Bull Stewardship Project, on US Forest Service Fremont-Winema National Forest lands, was implemented by Collins Companies. The project is located approximately 9 miles northeast of the town of Lakeview, Oregon within the boundary of the Lakeview Federal Sustained Yield Unit in the Crooked Creek and Deep Creek Watersheds. The treatment area was 1,200 acres.

Treatment

Fuel reduction treatments began in July 2006, with pre-treatment measurements by Winrock/LCRI crews immediately preceding treatment. Treatments on Bull Stewardship were suspended in 2006 and began again in 2007. The treatments were ultimately completed in 2008. Stoppages were due to excessive fire risks.

The overall objective of the Bull Stewardship Project is forest health improvement and wildfire risk reduction, accomplished through a combination of commercial timber harvest and non-commercial biomass removals. Two types of treatment unit are included: timber harvest/stewardship and stocking level control. The treatment units within Bull Stewardship are shown in Figure 3.

On the timber harvest/stewardship units, the prescription calls for removal of commercial timber >9" diameter at breast height (DBH) (timber harvest component) and removal of non-merchantable material 7-8.9" DBH (stewardship component). The contractor has the option to remove non-merchantable material, including slash from commercial timber and whole non-commercial (<9") trees, for chipping and transport to a cogeneration facility.

On the stocking level control units, several different prescriptions exist, all requiring treatment of material 2 ft tall through 8.9" DBH inclusive. This material remains where it is cut, to reduce fuel loading (fuel ladders), but is not removed to a landing for further processing, and there is no commercial (>9") timber removal on these units. The objective is to favor Western White Pine and Ponderosa Pine. Specific prescriptions on the different stocking level control units include:

> Treatment 1: Cut all coniferous live trees that are 2 feet tall through 8.9" DBH inclusive. Inclusive trees shall be cut within two drip lines of all western white pine or ponderosa pine 18"DBH or greater.
>
> Treatment 2: Cut all coniferous live trees that are 2 feet tall through 8.9" DBH inclusive within two drip lines of all western white pine or ponderosa pine 11"DBH or greater.
>
> Treatment 3: Cut all coniferous live trees that are 2 feet tall through 8.9" DBH inclusive within two drip lines of all ponderosa pine 18"DBH or greater.
>
> Treatment 4: Cut all coniferous live trees that are 2 feet tall through 6.9"DBH inclusive. Inclusive trees and all white fir and lodgepole pine shall be cut within two drip lines of all western white pine or ponderosa pine 18"DBH or greater. Do not cut any western white pine or ponderosa pine within the two drip lines of another western white pine or ponderosa pine. Do not include white fir 18"DBH or greater in spacing calculations.

According to Forest Service records, 1.22 million cubic feet (1,002 cubic feet/acre) were harvested in the course of the treatment.

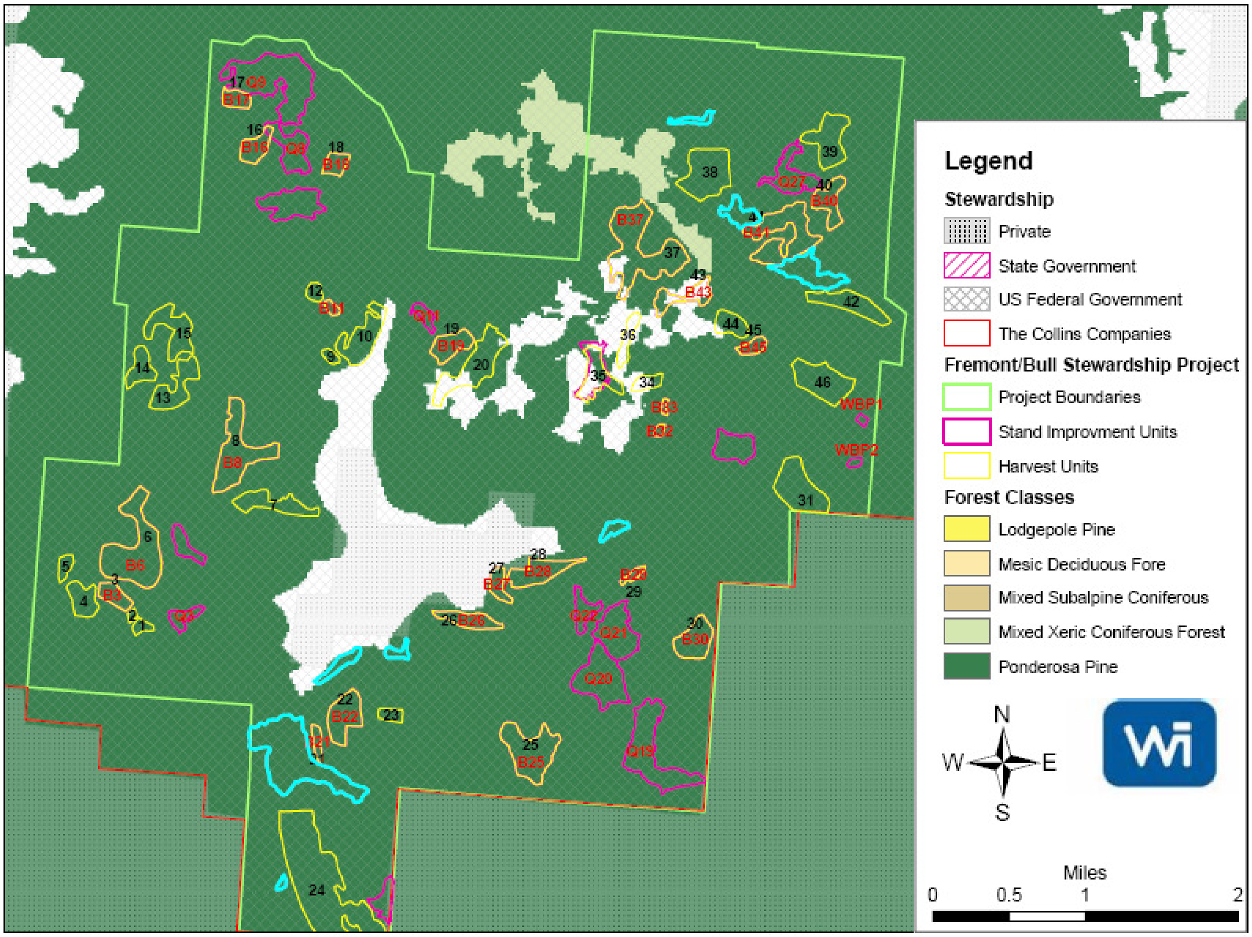

Figure 3. Treatment units on the Bull Stewardship Project. Treatments include commercial harvest units (yellow), stand improvement/stocking control units (pink), and combined timber harvest/stand improvement (blue).

2.1.2 Fuel reduction on Collins Companies lands

Location

Forest health/wildfire risk reduction projects on Collins Companies lands were included as WESTCARB pilots to evaluate approaches, costs and benefits of fuel reduction on private industrial timber lands. In 2007, Collins Companies began implementing fuels treatments on Collins lands in the Hot Rocks harvest units. See Figures 1 and 2 for overall Collins ownership boundaries in Lake County (red boundary), and Figure 4, showing the Hot Rocks harvest units. The total area treated was 288 acres.

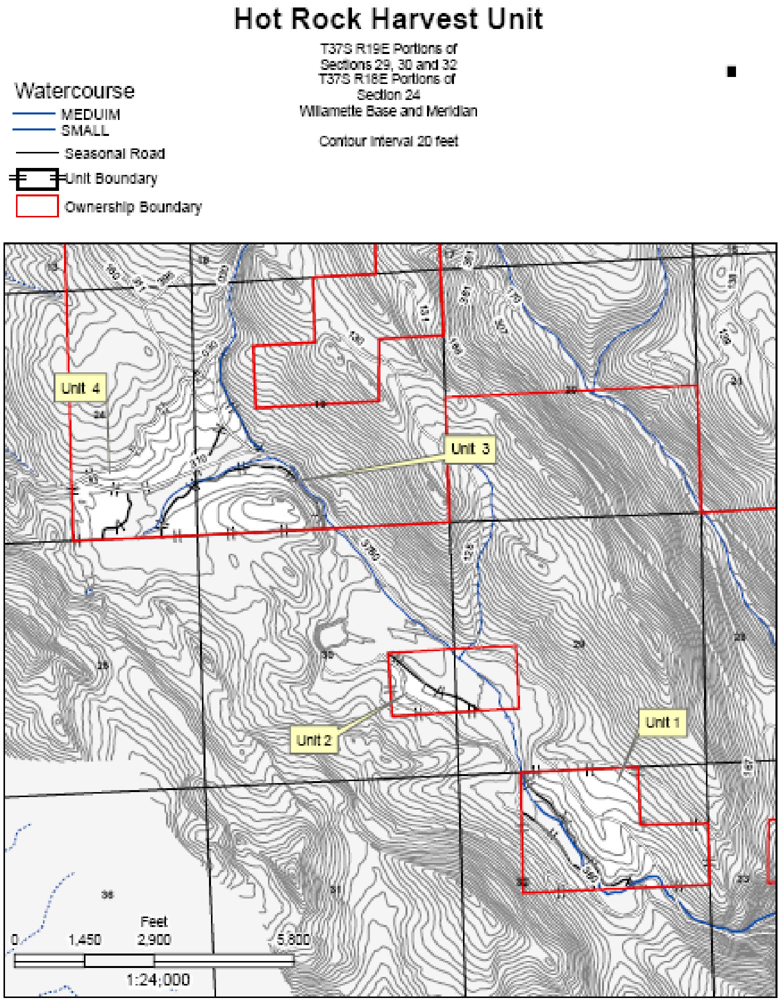

Figure 4. Hot Rocks harvest units, Collins Companies lands.

Treatment

Treatments were begun in June 2008 and completed in October 2008. The objectives of the Collins-Hot Rocks project was forest health improvement and wildfire risk reduction, accomplished through a combination of commercial timber harvest and non-commercial biomass removals. Treatments included selection harvest, commercial thinning, and variable retention harvest.

Selection harvest entails cutting trees greater than 8” dbh, with a post-harvest target of 80ft^2 basal area per acre and 160 trees per acre. Commercial thinning also targets a post-harvest basal area of 80ft^2/ac, but the minimum cutting diameter is 3”, and there are approximately 120 residual trees per acre. The variable retention post-harvest targets are 30 trees per acre and 20ft^2/acre. In all three harvest systems, the focus is on choosing retention trees which are defect and disease free, possess phenotype superiority and a live crown ratio[1] greater than 50%. Some wildlife trees are also retained based on nesting potential.

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[1] The ratio of tree crown length to total tree length.

The harvest removed 2,501 thousand board feet of sawtimber (8.7 thousand board feet /ac).

2.2 Pre- and post-treatment measurement methods

Field pre-treatment measurements[2] of Bull Stewardship and Collins-Hot Rocks fuels treatments were made in 2006 and 2007 and post-treatment measurement of both projects were made in 2008 and 2009.

2.2.1 Measurement Methods

The purpose of the measurements was to quantify the carbon stocks available to be burned before and after treatment, the direct impacts of fuel treatments on carbon stocks in different carbon pools (e.g. increases in dead wood, decreases in dense growth), and the fuel removed from the forest for biomass energy during treatment. Measurements also provided input data for fire models used to simulate fire behavior and emissions in the baseline (without-treatment) and with-treatment scenarios.

A total of 38 plots were established in the Bull Stewardship and 22 in the Collins Companies Hot Rocks lands.

Appropriate measurements of the following forest components were made at each plot:

- All trees >5 cm diameter at breast height, measured in nested plots and numbered for post-treatment measurements;
- Canopy density, measured at 36 points centered on the plot center;
- Standing dead wood;
- Understory vegetation, forest floor litter and duff, measured in clip plots and sub-sampled for dry weight determination;
- Lying dead wood, measured along transects, categorized by density class, and sub-sampled for density determination.

These represent the forest carbon pools that are likely to be affected by fire, treatment, or both, and so are critical to the accounting of hazardous fuel reduction treatment impacts and potential wildfire impacts on forest carbon. See Annex A for detailed Standard Operating Procedures followed in conducting pre- and post-treatment measurements of Lake County fuels treatments.

Plot locations were pre-assigned and random within units, taking into consideration elevation and species differences between units (higher elevation White Fir, higher elevation Lodgepole Pine, lower elevation White Fir/Ponderosa Pine). On navigation to each pre-assigned plot location, GPS coordinates were recorded and the plot center was marked using brightly painted rebar for ease of relocation post-treatment. Slope was noted for later analysis (plot-to-hectare expansion factor). All trees >5cm DBH were measured in a nested circular plot design, and numbered for post-treatment tally. Forest floor litter and duff was sampled in two 30 cm x 30 cm quadrats per measurement plot, and sub-samples collected for dry weight determination in a laboratory. The diameter of lying dead wood was measured along two 50 m line transects, categorized by density class, and sub-samples collected for density determination (dry weight per unit of green volume) and sent to a laboratory for drying. Post-treatment measurements were similar to pre-treatment as the objective is to examine the impact of treatments on

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[2] Field crews were made up of staff from Winrock and LCRI

forest carbon stocks. Trees were measured pre-treatment, and thus were only tallied to record removed/remaining post treatment. Forest floor litter and duff was re-measured in quadrats, and lying deadwood re-measured in line transects.

2.3 Fire modeling methods

Based on the field data disaggregated by carbon pool, emissions from a potential fire were modeled in both with- and without-fuels treatment scenarios. The modeling was conducted using two different approaches.

1. The FCCS program (**Fuel Characteristic Classification System**) was developed by the Pacific Northwest Research Station to capture the structural complexity and geographical diversity of fuel components across landscapes and to provide the ability to assess elements of human and natural change. FCCS is a software program that allows users to access a nation-wide library of fuelbeds or create customized fuelbeds. The fuelbeds are organized into six strata: canopy (trees), shrubs, nonwoody vegetation, woody fuels (lying deadwood and stumps), litter-lichen-moss, and ground fuels (duff and basal accumulations). FCCS calculates the relative fire hazard of each fuelbed, including crown fire, surface fire behavior, and available fuel potentials. It also reports carbon storage by fuelbed category and predicts the amount of combustible carbon in each category.[3]

2. In addition to the FCCS modeling, fire effects were modeling using the **Forest Vegetation Simulator Fire and Fuels Extension** (FVS-FFE). FVS provides different outputs to FCCS and FVS can be used to project growth, incorporating the impacts of fire on the future stand.

The two models produced slightly different results, as they use different modeling methodologies and different biomass equations. They also produce somewhat different output. Reported outputs from FCCS include flame length in feet; crown fire potential as a scaled index from 0-9; rate of spread in feet per minute; and carbon consumed for live canopy, dead wood, and total. Reported results from FVS-FFE include flame length in feet; the crowning index in miles/hour; and total carbon consumed. Results for both prescribed fire and wildfire are reported from FCCS, while only wildfire is reported from the FVS-FFE results.

Although FVS uses a somewhat simpler methodology than FCCS for projecting fire impacts, it is based on established fire models and allows for growth projections. In order to address growth over time, FVS projections are used throughout the results, but FCCS output is presented to demonstrate the range of potential fire emissions.

2.4 Fire risk

Annual burn probability is difficult to project accurately as it is a factor of the likelihood of ignition and the conditions on the ground at the time of ignition, including fuels, climate, temperature, and topography (see Finney, 2005). WESTCARB research conducted by the Oregon Department of Forestry and the USDA Forest Service shows that the average overall conditional burn probability (probability that wildfire reaches a stand given one ignition source) in southeastern Oregon is 2.2% for untreated landscapes and 1.7% for the treated landscape, a 22.6% reduction in burn probability as a result of

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[3] More information is available at the FCCS website: http://www.fs.fed.us/pnw/fera/fccs/. The modeling was conducted by Dr. David "Sam" Sandberg – Emeritus of the PNW Research Station Fire and Environmental Application Team.

treatment (Jim Cathcart, 2010, Oregon Department of Forestry, pers. comm.). This is an overestimate of annual burn probability as it does not include the probability of an ignition. The mean fire return interval from 2001 to 2008 for dry-mesic mixed conifer forests in Lake County is 153 years (Eric Waller, 2010, UCB CFRO, pers. comm.). The inverse of this provides an annual burn probability of 0.6%. It is important to note that this is a generalized probability and is not based specifically on pre- and post-treatment conditions for these projects, but rather for Lake County as a whole.

2.5 Growth modeling

Stand growth, both with- and without-treatment and considering all pools, was modeled with the US Forest Service's Forest Vegetation Simulator (FVS), using the Inland California and Southern Cascades variant. The standard allometric equations in the Fire and Fuels Extension (FFE) of FVS were used to produce biomass and carbon reports in conjunction with forest growth. Data from both the pre- and post-treatment inventories were used, with the pre-treatment inventory year counted as year zero to compare with and without treatment scenarios. Growth was projected over a 60 year period, and did not include any additional future treatments. To incorporate the effects of wildfire on growth, FVS-FFE was also used to model wildfire behavior.

2.6 Modeled scenarios

For both fire and growth, four different scenarios were modeled for both projects. Each scenario includes the following carbon pools: above-ground live, below-ground live, standing dead, and lying dead. For the treated scenarios, carbon stored in merchantable timber after 100 years is included. To simplify calculations, the emissions arising from wood product conversion and subsequent retirement are included at the beginning of the project.

	Untreated	Treated
No Wildfire	1.Untreated, no fire	3.Treated, no fire
Wildfire	2.Untreated, wildfire	4.Treated, wildfire

- *Scenario 1* gives the situation where there is no treatment or fire. At time zero it represents simply the carbon stocks (tons of carbon per acre) prior to treatment.
- *Scenario 2* is the carbon emissions and remaining stocks following a wildfire on untreated lands.
- *Scenario 3* is the carbon stocks remaining after the treatment, incorporating any emissions that were a result of treatment activities but in the absence of any fire.
- *Scenario 4* is the carbon emissions and remaining stocks following a wildfire on treated lands.

2.7 Harvested timber and biomass

Timber harvested is converted to metric tons of carbon according to Smith et al. (2006) that provides a factor of 7.48 thousand cubic feet and 0.44 thousand board feet per metric ton of carbon. The fraction of carbon in primary wood products remaining over time in end uses and stored in land fill, as described in Smith et al. (2006), are then applied: after 10 years, 48.9% of carbon will remain in use as long-term wood products, and 12.5% will be sequestered in landfills; after 60 years, 20% of carbon will remain in long-term wood products, and 25.1% in landfills; after 100 years, 13% will remain in wood products and 27.9% in landfills.

While the intention for this project was to use harvested biomass for energy production, there have been setbacks in the development of a biomass energy plant in the area and thus no demand for such a product(see section 4.2). As a result, the harvested biomass has been piled and burned or piled awaiting the completion of a biomass power plant. For this reason, all harvested biomass that did not go into sawtimber is considered an emission as it will most likely be burned prior to completion of the plant. There are many forested areas in need of hazardous fuels reduction without access to a biomass facility, and so this method of accounting, while it leads to increased emissions, will be broadly applicable.

The burning of these piles leads to emissions of methane and nitrous oxide as well as carbon dioxide. The following emissions factors are recommended by the US EPA (Battye and Battye 2002):

Assuming a smoldering fire: CH_4[4]: 0.21 t CO_2-e/t burned

NO_x[5]: 0.34 t Co_2-e/t burned

2.8 Net impact calculations

Net project benefits following a treatment must incorporate

- carbon stocks in the forest;
- carbon emissions in a wildfire, accounting for the probability of fire;
- growth;
- carbon stored as long-term wood products;
- emissions from biomass harvested but not removed from the forest.

The net emissions or removals in year one are calculated as

$$[(Ct + Cw + Ce - Cb) * (1 - risk)] + [(Ctf + Cw + Ce - Cbf) * (risk)]$$

Where

Ct	carbon stocks remaining in the forest after treatment and without a wildfire
Cw	carbon stored as wood products
Ce	reduced emissions from using biomass for energy generation
Cb	carbon stocks in the forest before treatment and without a wildfire
risk	probability of fire
Ctf	carbon stocks remaining in the forest after treatment and with a wildfire
Cbf	carbon stocks remaining in the forest before treatment and with a wildfire

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[4] Global warming potential of 21 used

[5] Global warming potential of 310 used

This equation states that the net emissions in year 1 are equal to:

The high probability that there will **be no fire** multiplied by the difference between stored carbon before and after treatment

Plus

The low probability that there will **be a fire** multiplied by the difference in total carbon storage after a fire in the treated stand and in the baseline stand.

3.0 Project Outcomes

3.1 Bull Stewardship

3.1.1 Field results

Prior to treatment, the Bull Stewardship project had 81.6 tons of carbon per acre across all pools. Following the treatment, the average carbon stock was 66.3 t C/ac. Treatment therefore resulted in a decrease in carbon stocks of 15.3 tons per acre, 19% of pretreatment stocks. The breakdown by pool is shown in Table 1, and the confidence limits at a 90% confidence interval for the aboveground live carbon pool are shown in Table 1a.

Table 1: Bull Stewardship carbon stocks (metric t C/ac) before and after fuels treatments

Carbon pool	Pre-treatment	Post-treatment	Difference
Trees	48.2	35.0	*-13.2*
Roots	13.8	9.7	*-4.1*
TOTAL TREES	62.0	44.7	*-17.3*
Standing dead	1.2	0.8	*-0.4*
Down dead wood	14.4	10.5	*-3.9*
TOTAL DEAD WOOD	15.6	11.3	*-3.7*
Forest Floor	3.6	9.8	*6.2*
Shrubs/herbaceous	0.5	0.6	*0.1*
TOTAL	81.6	66.3	*-15.3*

Table 1a. Upper and lower confidence limits at 90% CI for Bull Stewardship aboveground live carbon stocks (metric t C/ac) before and after fuels treatments

Aboveground live carbon	Pre-treatment	Post-treatment
LCL	43.5	30.3
mean	48.2	35.0
UCL	52.9	39.7
CI as a % of mean	9.7%	13.3 %

3.1.2 Potential fire emissions

Using FCCS-created fuel beds, a wildfire in the untreated stands would yield 52.8 tons of CO_2 per acre of emissions, while a wildfire in the treated stands would yield 42.0 t CO_2/ac (Table 2). Using the FVS Fire and Fuels Extension, a wildfire in the untreated stands would yield 42.7 t CO_2/ac of emissions, while a wildfire in the treated stands would yield 47.1 t CO_2/ac (table 3).

The potential flame length and rate of spread are essentially the same following the treatment as they are before treatment. The crown fire potential is lower in the treated stands.

Table 2: FCCS fire modeling results for Bull Stewardship

	Prescribed Fire		Wildfire	
	Pre-treatment	Post-treatment	Pre-treatment	Post-treatment
Flame Length (ft)	3.2	3.2	7.6	7.5
Crown Fire Potential (scaled index 0-9)	3.9	3.8	4.7	3.5
Rate of Spread (ft/min)	5.7	6.0	27.5	29.5
CO_2 emissions (t/ac)				
Canopy	-4.4	-5.1	-13.8	-15.4
Dead Wood	-28.2	-18.3	-36.3	-24.0
Litter	-2.4	-2.6	-2.8	-3.1
Total	-35.0	-26.0	-52.9	-42.5

Table 3: FVS fire modeling results for Bull Stewardship

	Wildfire	
	Pre-treatment	**Post-treatment**
Flame Length (ft)	6.6	6.7
Crowning index (miles/hr)[6]	14.5	24.7
CO_2 emissions (t/ac)	-42.7	-47.1
Total stand carbon remaining	69.5	53.5

3.1.3 Timber and biomass

The harvest on Bull Stewardship yielded 1,020 ft^3/ac. According to the conversion factor in Smith *et al.* (2006), this equals 7.6 t C/ac. Based on carbon disposition rates, a total of 4.7 t C/ac will remain stored in either long-term wood products or landfill after 10 years; 3.4 t C/ac will remain stored in either long-term wood products or landfill after 60 years; and 3.1 t C/ac will remain stored in either long-term wood products or landfill after 100 years.

Subtracting the removed sawtimber (7.6 t C/ac) from the total carbon removed in treatment (15.3 t C/ac), the remaining piled biomass represents 7.7 t C/ac or 15.4 tons of biomass per acre. This yields the following emissions (as described in section 2.7):

CH_4: 15.4 t burned * 0.21 t CO_2-e/t burned = 3.2 t CO_2e/ac

NO_x: 15.4 t burned * 0.34 t Co_2-e/t burned = 5.2 t CO_2e/ac.

The total CH_4 and NO_x emissions from pile burning are 8.4 t CO_2e/ac.

3.1.4 Growth modeling

Based on FVS modeling (Table 4), in the absence of fire, the treatment resulted in an initial decrease in carbon stocks of 15.3 t C/ac (compare columns 1 and 2), but the treated stands had slightly higher growth than untreated stands (4.2 t C/ac), for a total decrease in live stocks of 11.1 t C/ac over a 60 year period relative to no treatment.

In the event of a wildfire in year zero, the treated stands contain 16.2 t C/ac less than the untreated stands (difference between columns 3 and 4 in Table 4). Over 60 years, carbon stocks in both treated and untreated stands decreased, but the decrease was somewhat less for treated stands. There was a total decrease in live stocks for treated stands of 6.8 t C/ac relative to untreated stands after 60 years.

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[6] The 20-foot windspeed required to cause an active crown fire.

Table 4. Modeled total stand carbon pre and post treatment and with and without fire on the Bull Stewardship project. Modeling conducted using the Fuels and Fire Extension of FVS. Data in metric tons of carbon per acre

Year	Untreated, no fire (1)	Treated, no fire (2)	Untreated, wildfire (3)	Treated, wildfire (4)
0	81.6	66.3	69.7	53.5
10	84.9	66.3	60.0	46.5
20	86.1	68.7	52.2	41.6
30	86.6	70.5	47.5	38.4
40	86.6	72.6	44.5	36.4
50	86.5	74.3	42.3	35.1
60	86.5	75.4	40.9	34.1
Total change	*4.9*	*9.1*	*-28.8*	*-19.4*
Total % change	*106%*	*114%*	*59%*	*64%*

FVS growth modeling (Table 5) indicates that after 60 years in the absence of wildfire, treated stands continue to have fewer trees per acre, a lower basal area, lower quadratic mean diameter[7] (QMD), and fewer cubic feet and board feet than untreated stands. However treated stands with wildfire have proportionally more and larger trees, higher basal area, and more merchantable timber than the original stand after 60 yr.

Table 5. Projected Growth on Bull Stewardship project, modeled in FVS

	Untreated			Treated		
	Year 0	Year 60 – no fire	Year 60 - wildfire	0	Year 60 – no fire	Year 60 – wildfire
Trees per acre	271	90	31	145	87	23
Basal area	214	200	63	143	176	53
QMD	12.1	20.2	19.3	13.4	19.3	20.6
Cubic feet	5,915	6,106	1,833	4,304	5,415	1,595
Board feet	28,406	31,462	8,861	22,116	28,047	8,284

However, the rate of change (Table 6) is greater in the treated stands for all measurements except QMD. This indicates that while the treated stands did not catch up to the untreated stands in absolute numbers, they had a lower mortality rate and a higher per tree growth rate overall. In addition, the trees remaining in the treated stands remained larger, on average, than those in the untreated stands.

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[7] The diameter corresponding to the mean basal area of a stand.

In the event of a wildfire, treated stands have fewer trees per acre, and lower basal area, cubic feet and board feet after 60 years, but they have a higher rate of change in all categories except QMD than do untreated stands.

Table 6 Percent change after 60 years of growth on Bull Stewardship project

	Untreated		Treated	
	No fire	Wildfire	No fire	Wildfire
Trees per acre	33%	11%	60%	16%
Basal area	93%	29%	123%	37%
QMD	167%	160%	144%	154%
Cubic feet	104%	31%	126%	37%
Board feet	111%	31%	127%	37%

3.1.5 Net GHG emissions/sequestration

Including carbon stored in long term wood products and emissions from pile burning, for treated stands without wildfire, a total of 71.6 tons of carbon per acre are sequestered with 58.8 t C/ac still sequestered in the same stands following a wildfire. Figure 5 shows the tons of carbon per acre sequestered on Bull Stewardship in each of the four scenarios, the total carbon stored following treatment when wood products and biomass energy are included, and the percent change from untreated to treated and unburned to burned lands.

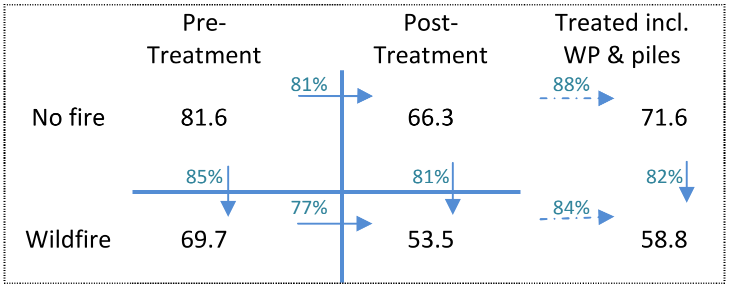

Figure 5: Tons of carbon per acre stored on Bull Stewardship project lands in each scenario, and including carbon stored in wood products and emissions from pile burning. Percentages show change from untreated lands to treated or from unburned to burned. WP = storage in long term wood products

Incorporating the risk of fire of 0.6%, and utilizing the equation described above for net emissions or sequestration (section 2.8), [(Ct+Cw +Ce-Cb)*(1-risk)]+[(Ctf+Cw+Ce-Cbf)*(risk)], the fuels treatment on the Bull Stewardship project resulted in an effective immediate net emissions of 36.7 t CO_2-e/ac (10.0 tons of carbon per acre).

In the absence of a wildfire, the fuels treatments and commercial harvest result in short term emissions of 59.4 t CO_2/ac and emissions of 36.5 t CO_2/ac over 60 years (table 7).

Table 7: Net short and long term emissions from fuels treatment, without fire, on Bull Stewardship in tons of carbon dioxide per acre (+ = removals; - = emission)

	Short term 10 years	Long term 60 years
Harvested timber	**17.2**	**12.6**
Treatment emissions	**-68.2**	**-40.7**
Pile burning emissions (CO_2e)	**-8.4**	**-8.4**
NET	**-59.4**	**-36.5**

For the treatment to yield benefits to the atmosphere, the emissions from treatments will need to be offset by reductions in emissions from a potential wildfire hitting the area. In order for the treatment to have an impact, such a fire would have to occur before fuels have returned to hazardous conditions, at which point it will be necessary to re-treat the forest. According to the FVS-modeled results, if a wildfire were to occur in the year of treatment, after 10 years the net emissions from treatment would be 40.7 t CO_2/ac. Therefore, the treatment leads to net emissions with or without fire, but total emissions are somewhat lower in the event of a wildfire.

3.2 Collins – Hot Rocks

3.2.1 Field results

Prior to treatment, the Collins-Hot Rocks project had 54.9 tons of carbon per acre across all pools. Following the treatment, the average carbon stock was 35.0 t C/ac. Treatment therefore resulted in a decrease in carbon stocks of 19.9 tons per acre, 36% of pretreatment stocks. The breakdown by pool is shown in Table 8 and the confidence limits at a 90% confidence interval for the aboveground live carbon pool are shown in Table 8a.

Table 8: Collins-Hot Rocks carbon stocks (metric t C/ac) before and after fuels treatments

Carbon pool	Pre-treatment	Post-treatment	Difference
Trees	35.4	13.9	*-21.5*
Roots	9.8	4.0	*-5.8*
TOTAL TREES	45.2	17.9	*-27.3*
Standing dead	1.1	0.5	*-0.6*
Down dead wood	3.2	12.1	*8.9*
TOTAL DEAD WOOD	4.3	12.6	*8.3*
Forest Floor	4.9	4.1	*0.5*
Shrubs/herbaceous	0.5	0.5	*0.0*
TOTAL	54.9	35.0	*-19.9*

Table 8a. Upper and lower confidence limits at 90% CI for Collins-Hot Rocks aboveground live carbon stocks (metric t C/ac) before and after fuels treatments

Aboveground live carbon	Pre-treatment	Post-treatment
LCL	27.4	10.9
mean	35.4	13.9
UCL	43.4	17.0
CI as a % of mean	22.6 %	22.1 %

3.2.2 Potential fire emissions

Using FCCS-created fuel beds, a wildfire in the untreated stands would yield 26.8 tons of CO_2 per acre of emissions, while a wildfire in the treated stands would yield 48.6 t CO_2/ac (Table 9). Using the FVS Fire and Fuels Extension, a wildfire in the untreated stands would yield 28.6 t CO_2/ac of emissions, while a wildfire in the treated stands would yield 33.1 t CO_2/ac (Table 10).

The potential flame length and rate of spread are substantially greater following the treatment that it is before treatment. The crown fire potential however is lower in the treated stands. This may indicate that the treatment increased deadwood, leading to a low and fast-moving fire, but reduced the potential for the fire to reach the crown.

Table 9: FCCS fire modeling results for Collins-Hot Rocks

	Prescribed Fire		Wildfire	
	Pre-treatment	Post-treatment	Pre-treatment	Post-treatment
Flame Length (ft)	2.0	3.6	4.5	8.5
Crown Fire Potential (scaled index 0-9)	3.3	2.1	4.0	3.2
Rate of Spread (ft/min)	3.1	4.8	13.3	24.0
CO_2 emissions (t/ac)				
Canopy	-3.5	-2.6	-10.8	-7.7
Dead Wood	-10.5	-30.4	-13.0	-38.5
Litter	-2.4	-1.3	-2.8	-1.7
Total	-16.4	-34.3	-26.6	-47.9

Table 10: FVS fire modeling results for Collins-Hot Rocks

	Wildfire	
	Pre-treatment	Post-treatment
Flame Length (ft)	3.8	8.2
Crowning index (miles/hr)[8]	11.6	20.6
CO_2 emissions (t/ac)	-28.6	-33.1
Total stand carbon remaining	46.7	26.0

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[8] The 20-foot windspeed required to cause an active crown fire.

3.2.3 Timber and biomass

The harvest on Hot Rocks yielded 8.7 mbf/ac[9]. According to the conversion factor in Smith et al. (2006), this equals 3.9 t C/ac. Based on carbon disposition rates, a total of 2.4 t C/ac will remain stored in either long-term wood products or landfill after 10 years; 1.7 t C/ac will remain stored in either long-term wood products or landfill after 60 years; and 1.6 t C/ac will remain stored in either long-term wood products or landfill after 100 years.

Subtracting the removed sawtimber (3.9 t C/ac) from the total carbon removed in treatment (19.9 t C/ac), the remaining piled biomass represents 16.0 t C/ac or 32.0 tons of biomass per acre. This yields the following emissions (as described in section 2.7):

CH_4: 32.0 t burned * 0.21 t CO_2-e/t burned = 6.7 t CO_2e/ac

NO_x: 32.0 t burned * 0.34 t Co_2-e/t burned = 10.9 t CO_2e/ac.

The total CH_4 and NO_x emissions from pile burning are 17.6 t CO_2e/ac.

3.2.4 Growth modeling

Based on FVS modeling (Table 11), in the absence of fire, the treatment resulted in an initial decrease in carbon stocks of 19.9 t C/ac (compare columns 1 and 2), and a reduced increase in carbon stocks of 8.7 t C/ac after 60 years, for a total decrease in live stocks of 28.6 t C/ac over a 60 year period relative to no treatment.

In the event of a wildfire in year zero, the treated stands contain 20.7 t C/ac less than the untreated stands (difference between columns 3 and 4). Over 60 years, carbon stocks in both treated and untreated stands decreased, but the decrease was slightly less for treated stands. There was a total decrease in live stocks for treated stands of 17.9 t C/ac relative to untreated stands after 60 years.

Table 11: Modeled total stand carbon pre and post treatment and with and without fire on the Collins-Hot Rocks project. Modeling used the Fuels and Fire Extension of FVS. Results in metric tons of carbon per acre

Year	Untreated, no fire (1)	Treated, no fire (2)	Untreated, wildfire (3)	Treated, wildfire (4)
0	54.9	35.0	46.7	26.0
10	61.7	33.9	39.9	20.9
20	69.0	37.3	36.0	18.6
30	73.4	41.3	34.6	17.8
40	76.8	45.6	34.6	17.8
50	79.5	49.5	35.6	18.4
60	81.8	53.2	37.1	19.2
Total change	*26.9*	*18.2*	*-9.6*	*-6.8*
Total % change	*149%*	*152%*	*79%*	*74%*

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[9] Harvest data was reported in cubic feet by the Forest Service for the Bull Stewardship project and in board feet by the Collins Company for the Hot Rocks project.

FVS growth modeling (Table 12) indicates that after 60 years in the absence of wildfire, treated stands continue to have fewer trees per acre, lower basal area, and fewer cubic feet and board feet than untreated stands while the QMD is greater in the treated stands.

Table 12 Projected Growth on Collins-Hot Rocks project, modeled in FVS

	Untreated			Treated		
	Year 0	Year 60 – no fire	Year 60 - wildfire	0	Year 60 – no fire	Year 60 – wildfire
Trees per acre	480	156	70	159	119	30
Basal area	198	210	87	77	158	43
QMD	8.7	15.7	15.1	9.4	15.6	16.2
Cubic feet	4,215	6,149	2,349	1,567	4,341	1,139
Board feet	13,887	28,639	10,139	5,168	19,151	5,135

However, the rate of change (Table 13) is greater in the treated stands for all measurements except QMD. This indicates that while the treated stands did not catch up to the untreated stands in absolute numbers, they had a lower mortality rate and a higher per tree growth rate overall. In addition, the trees remaining in the treated stands remained larger, on average, than those in the untreated stands.

Table 13 Percent change after 60 years of growth on Collins-Hot Rocks project

	Untreated		Treated	
	No fire	Wildfire	No fire	Wildfire
Trees per acre	33%	15%	75%	19%
Basal area	106%	44%	205%	56%
QMD	180%	174%	166%	172%
Cubic feet	146%	56%	277%	73%
Board feet	206%	73%	371%	99%

In the event of a wildfire, treated stands have fewer trees per acre, and lower basal area, cubic feet and board feet after 60 years, but they have a higher rate of change in all categories except QMD than do untreated stands.

3.2.5 Net GHG emissions/sequestration

Including carbon stored in long term wood products and emissions from pile burning, for treated stands without wildfire, a total of 34.1 tons of carbon per acre are sequestered with 25.1 t C/ac still sequestered in the same stands following a wildfire. Figure 6 shows the tons of carbon per acre sequestered on Bull Stewardship in each of the four scenarios, the total carbon stored following treatment when wood products and biomass energy are included, and the percent change from untreated to treated and unburned to burned lands.

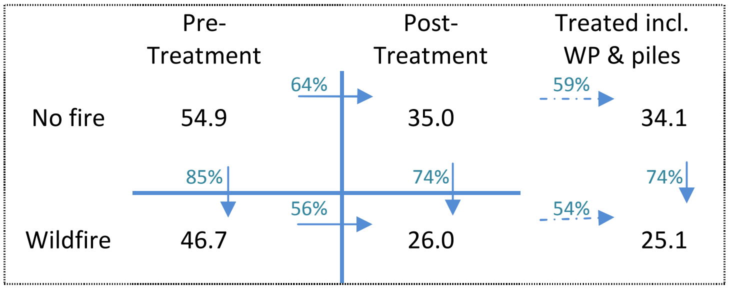

Figure 6: Tons of carbon per acre stored on Collins-Hot Rocks lands in each scenario, and including carbon stored in wood products and emissions from pile burning. Percentages show change from untreated lands to treated or from unburned to burned. WP = storage in long term wood products

Incorporating the risk of fire of 0.6%, and utilizing the equation described above for net emissions or sequestration (section 2.8), [(Ct+Cw +Ce-Cb)*(1-risk)]+[(Ctf+Cw+Ce-Cbf)*(risk)], the fuels treatment on the Collins-Hot Rocks project resulted in an effective immediate net carbon emission of 76.3 t CO_2-e/ac (20.8 tons of carbon per acre).

In the absence of a wildfire, the fuels treatments and commercial harvest result in short term emissions of 111 t CO_2/ac and emissions of 116 t CO_2/ac over 60 years (table 14).

Table 14: Net short and long term emissions from fuels treatment without fire on Collins-Hot Rocks in tons of carbon dioxide per acre (+ = removals; - = emission)

	Short term 10 years	**Long term 60 years**
Harvested timber	**8.8**	**6.2**
Treatment emissions	**-101.9**	**-104.9**
Pile burning emissions (CO_2e)	**-17.6**	**-17.6**
NET	**-110.7**	**-116.3**

For the treatment to yield benefits to the atmosphere, the emissions from treatments will need to be offset by reductions in emissions from a potential wildfire hitting the area. In order for the treatment to have an impact, such a fire would have to occur before fuels have returned to hazardous conditions, at which point it will be necessary to retreat the forest. According to the FVS-modeled results, if a wildfire were to occur in the year of treatment, after 10 years the net emissions from treatment would be 81.1 t

CO_2/ac. Therefore, the treatment leads to net emissions with or without fire, but total emissions are lower in the event of a wildfire.

4.0 Related efforts

4.1.1 Lakeview Stewardship Group

The Lakeview Stewardship Group was formed in 1998-99, involving LCRI, the Collins Companies, Concerned Friends of the Fremont/Winema, Defenders of Wildlife, USDA Forest Service Fremont-Winema National Forest, Lake County Chamber of Commerce, Lakeview High School, Lakeview Ranger District, Oregon Department of Economic and Community Development, Paisley Ranger District, Sustainable Northwest, The Threshold Foundation, The Wilderness Society, and local citizens. These partners have been engaged in a long-term, consensus-based effort to articulate a strategy for sustainable forest management of the 495,000-acre Lakeview Federal Stewardship Unit (LFSU) in the Fremont-Winema National Forest. In the context of dramatically reduced timber harvest offerings, mill closures, economic decline and sometimes acrimonious industry vs. environment debates, the LSG has been working to develop collaborative management goals balancing the full range of economic, social and ecosystem values provided by the forest. A key output of this process was the 2005 Long-Range Strategy for the Lakeview Federal Stewardship Unit (Lakeview Stewardship Group 2005; see http://www.lcri.org/unit/longrange.htm) and the revised 2010 Long-range Strategy for the Lakeview Federal Stewardship Unit (see Annex B).

The LFSU long-term objectives are to “sustain and restore a healthy, diverse, and resilient forest ecosystem that can accommodate human and natural disturbances; sustain and restore the land’s capacity to absorb, store, and distribute quality water; and provide opportunities for people to realize their material, spiritual, and recreational values and relationships with the forest.” Integral to sustaining and restoring a healthy, diverse, and resilient forest ecosystem that can accommodate human and natural disturbances is the effort to improve management of wildfire on National Forest lands. Partners have focused on reaching agreement and developing new tools to reduce hazardous fuel loading and improve forest health. In relation to WESTCARB goals, the most important of these tools are: stewardship contracts, Memoranda of Understanding and other mechanisms for long-term biomass supply as the basis for investments in new capacity; installing new biomass energy and small log processing facilities in Lakeview, to promote cost-effective utilization of the full range of material removed from the forest to meet stewardship and fuel reduction goals; and exploring new ways to manage forest carbon, including developing the science and policy basis for transacting carbon credits from fuel reduction.

LSG efforts have recently borne fruit in six important developments, summarized below.

4.1.2 Twenty-year biomass supply MOU

After lengthy negotiations, a 20-year Interagency Biomass Supply MOU was signed on November 1, 2007. The parties to the MOU include Lake County Resources Initiative, Lake County, Town of Lakeview, City of Paisley, DG Energy LLC, DG Investors LLC, The Collins Companies, Oregon Department of Forestry, USDA Forest Service Fremont-Winema National Forest, and Bureau of Land Management- Lakeview District. The purpose of the MOU is to provide a framework for planning and implementing forest and rangeland restoration and fuels reduction projects that address identified resource needs while being supportive of the Lakeview Biomass Project. In the MOU, each of the parties offers specific commitments relevant to fire risk reduction, forest health, biomass energy and a sustainable forest industry in the region. For the Forest Service, these include exploring new long-term supply mechanisms and offering at least 3,000 treatment acres per year within and another 3,000 acres per year outside the Lakeview Federal Stewardship Unit. BLM meanwhile commits to offer 2,000 treatment acres per year District-wide. LCRI's commitments include providing local coordination between the Collins Companies, Jeld-Wen and Forest Service on the WESTCARB project, with the goal of establishing a financing system for reducing uncharacteristically large fire events and provide additional revenues for restoration activities, and working with Iberdrola Renewables to support construction of an appropriately sized (25 MW) biomass plant in Lake County. The Oregon Department of Forestry's commitments include using SB1072 authorities to facilitate 10-year stewardship contracts, developing a cooperative state-wide MOU among state agencies, Forest Service and BLM bringing together elements of existing state programs under Energy, Economic and Community Development, Fish and Wildlife, and Forestry, and supporting the work of federal agencies to develop stewardship contracts and promote bioenergy.

The MOU was reviewed by Forest Service and BLM legal counsel and is in effect. The MOU signing was November 1, 2007, at a ceremony in Lakeview for the launch of the biomass plant and small-log sawmill. Undersecretary of Agriculture Mark Rey was in attendance along with many State dignitaries including two national environment group and two regional environmental groups. The text of the 20-year Interagency Biomass Supply MOU is included in Annex C.

4.1.3 Ten-year stewardship contract

The efforts of LCRI and its Lake County partners have resulted in a commitment to the first 10-year Stewardship Contract in the US Forest Service Pacific Northwest Region. The contract, considered a model for the region, provides long-term supply of material necessary for the recent investments in a biomass power plant and small log mill described below. The 10-year stewardship contract awarded to the Collins Companies on July 22, 2008 guarantees 3,000 acres of treatment per year and a total of $100,000 of work over the 10-year period. Specific treatment prescriptions are planned on a two year cycle. The MOU states in addition to the 10-year stewardship contract in the Unit there will be two additional 10-year contracts, one on Forest Service lands outside the Unit and one on BLM lands. There contracts have not been pursued because of the current economic downturn.

4.1.4 Biomass Power Plant

Oregon Governor Kulongoski's office and biomass plant developer DG Energy jointly announced in January 2007 that DG Energy will construct a 13 MW biomass plant in Lakeview. This represented the culmination of multi-year efforts by all the partners in the Lakeview Stewardship Group to reach agreement around sustainable harvest levels and long-term biomass supply mechanisms necessary for investment in new capacity. In their initial efforts to locate a biomass plant in Lake County, LCRI received volume estimates for slash piles that ranged from 1 to 11 bone dry tons (BDT). It is impossible to appropriately size a biomass plant with this range. Using what information was available and a Coordinated Resource Offering Protocol by Mater Engineering it was decided it could sustain a 15 MW biomass plant. Since collecting all the data from the stewardship contracts and other significant information from private lands it has been determined that a 25 MW biomass plant is sustainable.

Marubeni Sustainable Energy subsequently bought the development rights from DG Energy in 2007. In 2009 Iberdrola Renewables purchased the development rights from Marubeni. As a result of new supply information the plant size has gone from a net 13MW to a net 24.9 MW and the investment went from $20 million to over $70 million. Currently the project is scheduled for a final decision on construction this summer 2010 and breaking ground in September 2010 with an estimated completion date of December 2012. The project is designed to use biomass from overstocked forests, helping to reduce wildfires, improve forest health and create jobs. The Lakeview Biomass Project was designated an “Oregon Solutions” initiative by Governor Kulongoski, resulting in a collaborative process involving federal and state agencies, industry, and non-profit organizations to build consensus for the project and secure a sustainable supply of biomass.

The Governor’s press release is at http://governor.oregon.gov/Gov/P2007/press_011007b.shtml and is included in Annex D. The Oregon Solutions Declaration of Cooperation is included in Annex E and a 2010 support letter from the Governor is in Annex F.

4.1.5 New small log mill in Lakeview

Oregon Governor Kulongoski in March 2007 announced that the Collins Companies will expand their Fremont Sawmill operation in Lakeview by building a new $6.8 million dollar small log mill. The small log mill is the direct result of the 20-year Interagency Biomass Supply MOU and 10-year Stewardship Contract efforts spearheaded by LCRI, and provides an added tool for improving management of forests and hazardous fuels in Lake County. The combination of the existing Fremont Sawmill for processing larger logs, the new small-diameter log mill, and the new biomass energy plant will provide the tools necessary for cost-effective utilization of the full range of material removed from the forest to meet stewardship, forest health restoration, and wildfire risk reduction objectives. The biomass plant and small log mill, the result of an “Oregon Solutions” initiative involving nearly 70 public, private and community organizations, represent two sides of “an integrated solution to effective management of forest health and reducing fire danger in the Fremont National Forest. Both the biomass facility and the small log mill serve as models for collaboration between industry, conservationists and state government in enhancing forest health, developing renewable energy and creating jobs” (Governor Kulongoski’s press release, March 7, 2007). The full text of the press release is included in **Annex D**.

A November 1, 2007 ceremony in Lakeview served as the ribbon-cutting for the new small-diameter sawmill and initial kickoff for the biomass energy plant, as well as the signing ceremony for the 20-year biomass supply MOU and announcement of the first 10-year stewardship contract offer by the Forest Service - Pacific Northwest Region.

In addition to the ecological outcomes, the economic outcomes are significant for a rural community. The sawmill and biomass plants are making an $80 million dollar investment in a county that is 78% public ownership. These investments have resulted in retaining 85 sawmill jobs, and will create 18 jobs at the biomass plant and 50-75 jobs in the woods. An Oregon Business 2010 report estimates these investments will have an annual payroll of over $18 million and will pay over $1 million/year in income tax to the State of Oregon (see attached Business Oregon report, Annex G). South Central Oregon Economic Development District estimates that local taxing districts such as the Town of Lakeview, Lake County, Library, Hospital, cemetery, school district, etc. will receive an estimated $1.8 million yearly in taxes. Oregon has established what is called Empowerment Zones and companies locating in these zones can get up to 15 years property tax abatement. The Lakeview Biomass plant is in an Empowerment Zone where they will be paying a substantially less Community Service Fee in lieu of property tax for 15 years. The Biomass Impact

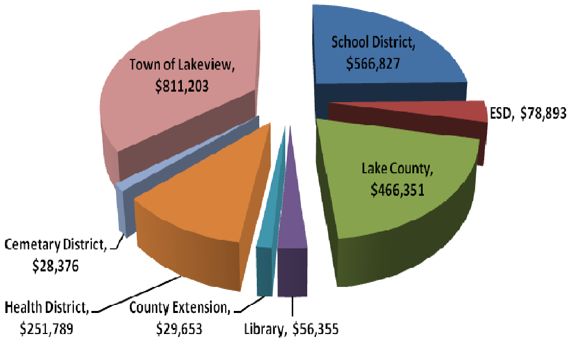

Figure 7: Distribution of increased tax revenue resulting from biomass facility in year 16 and beyond

to Taxing Districts graph (figure 7) is based on estimated taxes in year 16 and beyond.

4.1.6 Influence on hazardous fuels management

Considerable changes have occurred on Fremont-Winema National Forest since the beginning of this project in 2006. The original Forest Service prescriptions for Bull Stewardship, Burnt Willow and Kava were much lighter treatments than treatments currently being implemented by the Forest Service. In designing these projects, the Forest Service was cautious on their prescriptions as they were concerned about possible lawsuits. When the Lakeview Stewardship Group reviewed the completed treatments in these early stewardship projects they informed the Forest Service that treatments need to be heavier in order to reduce fuel loads enough to influence fire behavior and restore natural fire to the landscape. In addition, the Collins Companies invested in a new small diameter sawmill that took merchantable material from a 9” DBH to a 7” DDH, resulting in an increase in the volume of sawlogs taken off the forest. Another significant change that occurred during the project was the collapse of the economy in 2008 with lumber prices being so low that all sawmills were losing money. Because logging contractors can request an extension to carry out a prescription, this delayed the work until a time when the market returns to more favorable conditions.

The 20-year MOU and the Lakeview Stewardships Group’s *2005 Long-range Strategy for the Lakeview Federal Stewardship Unit* was significant enough that The Collins Companies invested $6.8 million in a new sawmill rather than closing down the sawmill. The other significant changes during this time were that the Lakeview Stewardship Group informed the Forest Service they wanted the Forest Service to concentrate on commercial logging operations, and eliminate fire salvage logging. The sawmills viability hinged on getting approximately 20MBF off the Lakeview Federal Stewardship Unit. As a result of the 10-year Stewardship Contract Collins was awarded in 2008, the goal of 20 MBF was exceeded as shown in Figure 8. World market conditions have reduced the amount since 2008, and it will likely climb again with better market return. One of the critical outcomes is that the infrastructure is in place to restore the Forest Service lands to healthy conditions that will be able to adapt to climate change.

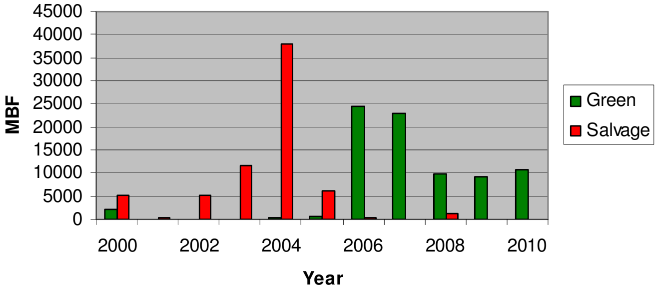

Figure 8: Board feet harvested in Lake County between 2000 and 2010 through either salvage logging or green harvests

4.1.7 Collaborative Forest Landscape Restoration Program (CFLRP)

The National office of the Forest Service announced in February 2010 that they are accepting proposals for the Collaborative Forest Landscape Restoration Program (CFLRP). Projects must be collaborative in nature, address at least a 30,000 acre landscape, and and include a strategic plan. The CFLRP stated that up to 10 projects could be chosen this fiscal year and no more than two from any one region would be funded. Region 6 sent in 5 proposals with the Lakeview Stewardship Group Fremont-Winema proposal being the number 1 priority. Over 10 years this could mean an additional 20 million dollars above regular appropriations for fuels management and restoration in the 500,000 acre Lakeview Federal Stewardship Unit. As part of the CFLRP proposal the Lakeview Stewardship group revised their 2005 Long-range Strategy for the Lakeview Federal Stewardship Unit, see Annex H. Final CFLRP awardees will be notified by late summer.

5.0 Conclusions and Recommendations

In both projects, the treatments resulted in significant net carbon emissions[10]. This result clearly has implications for the future potential of fuels treatments as a carbon projects offset category.

The reasons for the net emission from hazardous fuel reductions are multiple. In the case of the Collins-Hot Rocks project, deadwood stocks increased following the treatment. This may be due to an increase in the amount of limbs and branches left following the treatment. Because the projects included sawtimber removal, the live standing carbon removed was substantial. However, due to milling inefficiencies and the retirement of wood products over time, only a fraction of the carbon removed as sawtimber is stored in wood products over the long term. Had it been possible to utilize biomass for energy production, some of the emissions may have been offset, but there would still be net emissions as a result of treatment. As it was, the piling and burning of biomass further contributed to overall emissions.

While the Bull Stewardship treatment led to a slight decrease in fire intensity, the Collin-Hot Rocks treatment led to an increase in fire intensity, and both led to an increase in potential emissions from a fire. Both treatments led to a substantial increase in large woody fuel loads and subsequent biomass consumption. If the woody fuels that resulted from the treatments been removed from the site, there likely would have been a decrease both in surface fire behavior and potential carbon release. Both treatments produced an apparent decrease in crown fire potential from future fires, which reduces the severity and size of wildfires, and improves the ability to control a fire.

The rate of growth increased slightly following the treatments, but in the absence of a wildfire, total carbon stocks in the treated areas still had not surpassed those in untreated areas after 60 years. Following a wildfire, carbon stocks continued to decline for both the treated and the untreated stands.

Within the treated areas, both projects had significant net emissions when considering treatment and the risk of a potential wildfire. If a fire were to occur in the year of treatment, all projects would still experience net emissions, though the impact of treatment emissions would be slightly reduced.

One critical factor not addressed in this study is the impact of fuels treatment on fire intensity and emissions outside the treated area itself. In many cases, the reduced intensity of fire in a treated area decreases the intensity of fire in the surrounding untreated areas, increasing the beneficial aspects of the treatment without removing additional biomass. This is often referred to as a fire shadow. The size of a fire shadow along with the level of reduced emissions varies based on a number of factors, including topography, location of treatment, climatic conditions, and fire intensity. Incorporating the fire shadow

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[10] A complete accounting of emissions would have also incorporated equipment use. Though this project did not address equipment emissions, a similar project in Shasta County found emissions ranging from 0.8 to 1.8 tons CO_2/ac. While this is not an insignificant amount, it is a small fraction of the emissions which result from the removal of biomass from the forest.

in the overall emission calculations would decrease the net emissions in most cases, but given the extent of emissions for both projects, it is likely that inclusion of a fire shadow would yield lower emissions but significant emissions would still result from treatment.

Both pilots led to a decrease in crown fire potential, which decreases fire severity and size. While treatments lead to net carbon emissions in both the short and long term in both projects, there are, of course, additional benefits to fuels treatments, such as increased ability to successfully fight fires and decreased cost of fire fighting; reduced loss of life and property; and reduced potential damage to wildlife habitat.

These results are mirrored well in the results from the Alder Springs treatment in Mendocino National Forest conducted under funding from the US Forest Service. In Alder Springs, net emissions of 26.3 tons of carbon dioxide per acre were recorded immediately after treatment climbing to a total of 86.9 t CO_2-e/ac after 60 years.

The results from this study in combination with the paired study in Shasta County and the allied study in Mendocino National Forest underline the unsuitability of fuels treatment as a potential greenhouse gas offset generating activity. Instead we argue the shift should be made to policies minimizing greenhouse gas emissions from wildfires and from fuel treatments while minimizing wildfire risks to lives, homes and livelihoods in the WESTCARB region.

5.1 Benefits to California

The research questions being explored in Lake County, and the validation and demonstration of new climate change mitigation opportunities, are equally relevant to California's public and private forests. Debates around managing the multiple economic, social and ecosystem benefits of the State's forests, and the need for creative and aggressive approaches to managing catastrophic wildfire at California's wildland-urban interface, have risen to prominence in the media and public consciousness. Moreover wildfire conditions are projected to worsen with global warming (California Energy Commission 2006), making new strategies for managing the fire-prone forests an important climate adaptation as well as climate mitigation opportunity.

Results from the Lake County, Oregon and Shasta County, California[11] hazardous fuel reduction pilot activities indicate that hazardous fuels treatments do not represent potential carbon offset projects. A third WESTCARB report[12] discusses in more depth the reasons such projects do not lead to offsets and addresses shortcomings of similar research that has indicated otherwise.

Regardless of these findings, wildfire poses a significant threat to ecosystems, property, and people, and fighting wildfire represents a large investment of resources. Carefully planned and properly implemented hazardous fuels treatments are a critical means of ensuring the safety of nearby communities and the health of forests. In addition, fuels treatments can lead to increased timber

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[11] Goslee, K., T. Pearson, S. Grimland, S. Petrova, and S. Brown. 2010. *Final Report on WESTCARB Fuels Management Pilot Activities in Shasta County, California.* California Energy Commission, PIER. CEC-500-XXXX-XXX.

[12] Pearson, T., K. Goslee, and S. Brown. 2010. *Emissions and Potential Emission Reductions from Hazardous Fuel Treatments in the WESTCARB Region.* California Energy Commission, PIER. CEC-500-XXXX-XXX.

production and reduced costs of fighting fires. While there may not be an opportunity to reduce wildfire emissions on a project by project basis, it is imperative that sound wildfire preventative strategies continue to be employed in California forests.

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Western Climate Initiative. August 22, 2007. Statement of Regional Goal.

Annex A: Standard Operating Procedures for Fuels Measurements in 2007

See separate attachment.

Annex B: 2010 Long-range Strategy for the Lakeview Federal Stewardship Unit

See separate attachment.

Annex C: 20-year Interagency Biomass Supply MOU

See separate attachment.

Annex D: Governor’s press release on new biomass plant in Lakeview, OR

See separate attachment.

Annex E: Oregon Solutions Declaration of Cooperation

See separate attachment.

Annex F: Governor’s Letter of Support for new biomass plant in Lakeview, OR

See separate attachment.

Annex G: 2010 Oregon Business report

See separate attachment.

Annex H: Lakeview Stewardship Group CFLRP proposal

See separate attachment.

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SUMMARY OF THE RANGELANDS SUITABLE FOR TERRESTRIAL CARBON SEQUESTRATION IN SHASTA COUNTY

Martin, N., S. Petrova, S. Brown, T. Pearson, and J. Kadyszewski.

Winrock International

DOE Contract No.: DE-FC26-05NT42593

Contract Period: October 1, 2005 - May 11, 2011

CALIFORNIA
ENERGY
COMMISSION

SUMMARY OF THE RANGELANDS SUITABLE FOR TERRESTRIAL CARBON SEQUESTRATION IN SHASTA COUNTY

PIER COLLABORATIVE REPORT

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WEST COAST REGIONAL CARBON SEQUESTRATION PARTNERSHIP
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Winrock International

November 2007
CEC-500-2007-101

California Climate Change Center
Report Series Number 2007-026

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Commission Work Authorization MR-045

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DISCLAIMER

Acknowledgments

This research was supported by U.S. Department of Energy cooperative agreement DE-FC26-05NT42593.

Please cite this report as follows:

Martin, N., S. Petrova, S. Brown, T. Pearson, and J. Kadyszewski. 2007. *Summary of the Rangelands Suitable for Terrestrial Carbon Sequestration in Shasta County*. California Energy Commission, PIER. CEC-500-2007-101.

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California's electricity and natural gas ratepayers. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

In 2003, the California Energy Commission's Public Interest Energy Research (PIER) Program established the **California Climate Change Center** to document climate change research relevant to the states. This center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions. Priority research areas defined in PIER's five-year Climate Change Research Plan are: monitoring, analysis, and modeling of climate; analysis of options to reduce greenhouse gas emissions; assessment of physical impacts and of adaptation strategies; and analysis of the economic consequences of both climate change impacts and the efforts designed to reduce emissions.

The California Climate Change Center Report Series details ongoing center-sponsored research. As interim project results, the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the center seeks to inform the public and expand dissemination of climate change information, thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

Summary of the Rangelands Suitable for Terrestrial Carbon Sequestration in Shasta County is a report for the West Coast Regional Carbon Sequestration Partnership – Phase II (contract number 500-02-004, work authorization number MR-045), conducted by Winrock International. The information from this project contributes to PIER's Energy-Related Environmental Research program.

For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-5164.

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Abstract

Winrock International evaluated the potential for terrestrial carbon sequestration through afforestation in Shasta County, California. The report presents suitability of rangelands for afforestation, potential carbon accumulation, total costs, and potential carbon supply, and also includes spatially explicit analyses illustrating attractive regions for afforestation within the county and the range of afforestation costs. Researchers determined that afforestation of Shasta County rangelands could result in the sequestration of about 17.7 million tons of carbon (t C) after 20 years at a cost of less than \$20/t C (\$5.45/ton of carbon dioxide [t CO_2]) or about 57.6 million tons of carbon after 80 years at a cost of less than \$10/t C (\$2.7/t CO_2). This opportunity, which will be tested and validated through pilot projects in Shasta County under the U.S. Department of Energy-funded West Coast Regional Carbon Sequestration Partnership (WESTCARB)—Phase II, could be replicated elsewhere in California and the WESTCARB region. The report also provides a summary of initial outreach efforts to landowners interested in conducting afforestation for carbon. The authors also include recommendations for further characterization and stratification, landowner outreach, and considerations for incorporating such projects into evolving voluntary carbon markets and regulatory programs.

Keywords: Terrestrial carbon sequestration, afforestation, rangelands, Shasta County, West Coast Regional Carbon Sequestration Partnership, WESTCARB

Executive Summary

Introduction

The West Coast Regional Carbon Sequestration Partnership (WESTCARB), led by the California Energy Commission, is one of seven U.S. Department of Energy regional partnerships working to evaluate, validate, and demonstrate ways to sequester carbon dioxide (CO_2) and reduce emissions of greenhouse gases (GHGs) linked to global warming. Afforestation, or establishing forests on lands not currently forested, represents the largest single terrestrial carbon sequestration opportunity for California and the region. It is likewise a substantial opportunity for Shasta County and may offer landowners near-term opportunities to participate in rapidly evolving GHG markets and regulatory systems.

Purpose

This report sought to provide a concise summary of analyses to date on the opportunity to sequester carbon through afforestation of rangelands in Shasta County, including forest suitability, carbon potential, and cost considerations. The report also provides an interim summary of initial outreach efforts to Shasta County landowners.

Project Objectives

The overall goal of WESTCARB Phase II is to validate and demonstrate the region's key carbon sequestration opportunities through pilot projects, methodology development, reporting, and market validation. WESTCARB research will facilitate informed decisions by policy makers, communities, and businesses on how to invest in carbon capture and storage technology development and deployment to achieve climate change reduction objectives. The sequestration opportunity presented here is afforestation of rangelands.

Project Outcomes

Forest suitability modeling of Shasta County rangelands was conducted based on biophysical factors of soil water availability, mean annual air temperature, annual average precipitation, slope, and elevation. The results of suitability modeling—after excluding wooded rangelands with canopy cover greater than 40 percent and grassy rangelands dominated by wet meadows—indicate that about 600 thousand acres, or about 80 percent of Shasta County rangelands, would be potential candidates suitable for afforestation (Figure S-1).

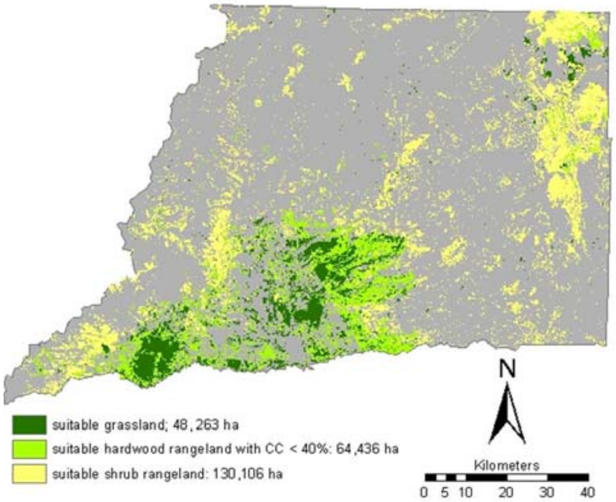

Figure S-1. Map of candidate rangelands for afforestation activities (suitable to support forest and meeting constraints)

Carbon sequestration potential varies by land type, with some lands favorable to mixed conifers that could sequester almost 200 tons of carbon per hectare (about 300 tons CO_2 per acre) over 40 years, and other lands more appropriate to oak restoration and other hardwood range types that would sequester less than 100 tons of carbon per hectare over the same project life. Figure S-2 shows the geographic distribution of sequestration potential.

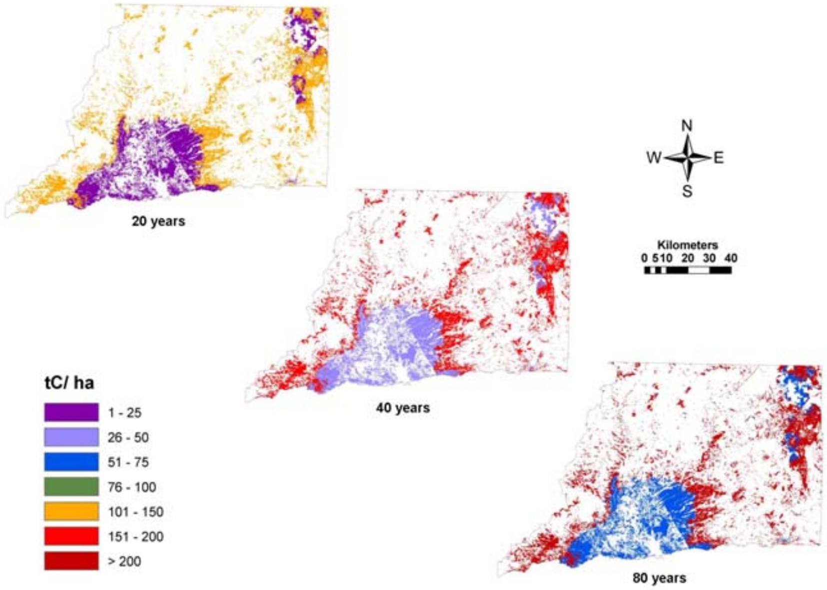

Figure S-2. Carbon sequestration potential on rangelands suitable for afforestation activities for 20, 40, and 80 years

Researchers analyzed the costs of sequestration through afforestation, including opportunity costs, conversion costs such as site preparation and planting, measuring and monitoring costs, and maintenance costs. The objective was to evaluate the net present value of total afforestation costs throughout the county, assuming that landowners would be willing to produce and sell carbon credits from afforestation if the price paid for these credits is greater than the present value of the stream of costs incurred in producing them. To detect variations in cost based on grazing conditions and topographic locations, researchers divided the rangelands suitable for afforestation into two main classes: (1) those that are likely grazed, and (2) those not grazed, with both classes subdivided into slope classes greater and less than 30 percent slope.

Depending on the forage productivity of rangeland suited for grazing, the net present value of the total costs of afforestation after 40 years was about \$500–\$900 per acre on slopes less than 30 percent and \$680–\$1050 per acre on slopes greater than 30 percent.

On rangelands not suited for grazing, where opportunity costs are assumed to be zero, the net present value of total costs after 40 years was about \$960/acre for lands with less than 30 percent slope and \$1160/acre for lands with greater than 30 percent slope, suggesting that high site preparation costs more than offset zero opportunity costs. Conducting cost analysis in a Geographic Information System (GIS) makes it possible to examine the range of costs throughout the county (Figure S-3).

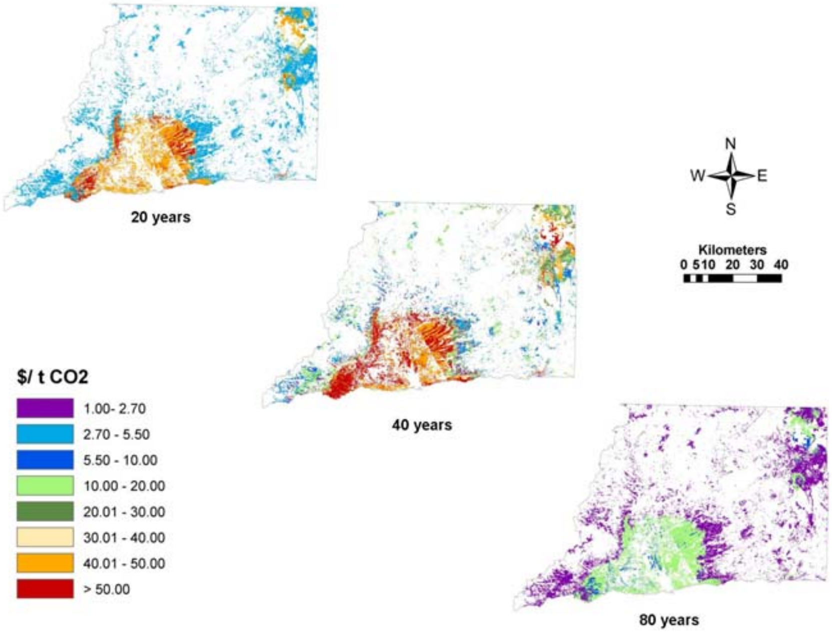

Figure S-3. Cost of CO$_2$ through afforestation of rangelands suitable for grazing in Shasta County

Outreach to Shasta County landowners and land managers began in October 2006 with an outreach meeting hosted by Western Shasta Resource Conservation District (RCD) and attended by a broad range of individual landowners, watershed group coordinators, state and federal agencies, private industries, and nonprofit organizations. The RCD has continued outreach through individual landowner meetings, watershed group meetings, and outreach via the Natural Resource Conservation Service. A landowner survey has been designed and will be implemented in 2007 to better understand landowner interests, required cost share levels for different project types, species preferences, and other requirements.

Conclusions

After 80 years, about 57.6 million tons of carbon (t C) could be sequestered on candidate rangelands in Shasta County at a cost of less than \$10/t C (\$2.7/t CO_2). In contrast, about 17.7 million tons of carbon could be sequestered after 20 years at a cost of less than \$20/t C (\$5.45/t CO_2). These quantities could be sequestered on about 57 percent of the rangeland suitable for afforestation.

Recommendations

More detailed land suitability analysis is needed before actual planting, including examining land capability classifications and soil series data and incorporating aspect into forest suitability modeling/afforestation planning. Landowner outreach efforts will continue, led by the RCD. Data should be collected from existing or planned afforestation efforts throughout the county, with which the project can collaborate to gather existing data or collect additional data; this will greatly expand the geographic and temporal scope of the research effort. Collaboration with other organizations is advised, particularly for implementing successful oak restoration projects. Agreements with participating landowners should be designed carefully, striking the appropriate balance between open participation to achieve research objectives and preparing landowners realistically for the requirements of future carbon markets.

Benefits to California

Results of WESTCARB afforestation pilot activities will inform both voluntary efforts, such as those by California Climate Action Registry members interested in offsetting GHG emissions through forestry, and regulatory developments, such as the process now underway by the California Air Resources Board (ARB) to design a GHG regulatory program under the California Global Warming Solutions Act of 2006 (also known as California Assembly Bill 32). Projects demonstrated to be cost-effective, verifiable, environmentally beneficial, and attractive to both regulated entities and landowners/carbon credit suppliers may become eligible for trading under the market-based compliance program ARB adopts.

1.0 Introduction

1.1 Background and Overview

The West Coast Regional Carbon Sequestration Partnership (WESTCARB), led by the California Energy Commission, is one of seven U.S. Department of Energy (USDOE) regional partnerships working to evaluate, validate, and demonstrate ways to sequester carbon dioxide (CO_2) and reduce emissions of greenhouse gases (GHGs) linked to global warming. Terrestrial (forestry and land use) sequestration options being investigated include afforestation[1] of marginal rangelands, improved management of hazardous fuels to reduce emissions from wildfires, biomass energy, and forest management. Shasta County, California, and Lake County, Oregon, were chosen for WESTCARB Phase II terrestrial sequestration pilot projects because of the diversity of land cover types present, opportunities to implement the most attractive terrestrial carbon activities identified in Phase I, and replication potential elsewhere in the WESTCARB region.

Afforestation of rangelands represents the largest terrestrial sequestration opportunity, both at the state level for California, Oregon, and Washington and within Shasta County (Brown et al. 2004; Dushku et al. 2007a, 2007b; Brown et al. 2007). For example, at the California level, it was found that at a price of < $5.5/ton of carbon dioxide (t CO_2) (< $20/ton of carbon [t C]), 345 million metric tons CO_2 could be sequestered on 2.7 million acres after 20 years and 3 billion metric tons CO_2 could be sequestered on 14.8 million acres after 40 years via afforestation using native species on existing rangelands suitable for forests (Brown et al. 2004).

Shasta County has large areas categorized as rangelands that were forested in the past and that according to forest suitability criteria would be capable of growing trees. Categories of lands in Shasta County classified as rangelands and currently in use as rangelands include open grasslands, irrigated and non-irrigated areas, riparian zones, and rangelands covered with oaks, foothill pines, and other hardwood species on which cattle may still be grazed for most of the year (Figure 1-1). Some of the lands classified as rangelands are covered by dense shrubs such as manzanita or are in a state of arrested succession to forest after fires. These rangelands are apparently not suitable for grazing, but also present an opportunity for afforestation projects.

All rangeland types could theoretically be converted back to forest through site preparation and planting with appropriate species. Afforestation of rangelands would provide a net carbon sequestration benefit equivalent to the per-unit area net change in carbon stocks of the planted forest at X age (with X representing the duration of the activity or of afforestation contracts), multiplied by the total area afforested.

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[1] Under the USDOE revised 1605(b) guidelines, afforestation is the establishment of new forests on lands that have not been recently forested, that is a land-use change; reforestation is the re-establishment of forest cover, naturally or artificially, on lands that have recently been harvested or otherwise cleared of trees. In contrast, the California Climate Action Registry does not use the term afforestation and instead defines reforestation as the establishment and subsequent maintenance of native tree cover on lands that were previously forested, but have had less than 10% tree canopy cover (essentially non-forested) for a minimum time of 10 years. This report uses the term afforestation as defined by USDOE.

Such project types are relatively straightforward to measure and monitor and are well accepted in existing carbon registries, reporting protocols, and voluntary carbon offset markets. Selling carbon credits from these projects would provide a new source of revenue for landowners, supplementing other income streams. It is assumed that landowners would be willing to produce and sell carbon from afforestation if the price paid for these credits is greater than the present value of the stream of costs incurred in producing them, including opportunity costs, conversion costs, maintenance costs, and measurement/monitoring/registration costs. This may be the case, particularly for marginally profitable grazing lands and/or grazing lands where afforestation does not require permanent removal of cattle.

From the perspective of carbon offset buyers, meanwhile, such projects could provide highly credible offsets at a reasonable cost. Interest in such projects is increasing, with a general growing awareness of global warming and increasing numbers of businesses, organizations, and even individuals taking voluntary actions to manage their GHG emissions. Afforestation, already recognized by the California Climate Action Registry (CCAR) as activity from which landowners may report and ultimately sell carbon credits to entities voluntarily offsetting their emissions, may also in the future become an activity eligible for market-based offset trading under the cap-and-trade regulatory program recently established by California Assembly Bill 32, the California Global Warming Solutions Act of 2006.[2]

Figure 1-1. Variety of rangelands in Shasta County, California. Clockwise from top left: rangelands with sparse conifers in the northeast corner of the county, hardwood rangelands near Shingletown, hardwood rangelands near Igo and Ono in the southwest, and open rangelands along State Route 44.

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[2] AB 32 (Nuñez), Chapter 488, Statutes of 2006.

1.2 Project Objectives

The overall goal of WESTCARB Phase II is to validate and demonstrate the region's key carbon sequestration opportunities through pilot projects, methodology development, reporting, and market validation. WESTCARB will produce methodologies, plans, data, technical papers, and reports that facilitate informed decisions by policymakers, communities, and businesses on how to invest in carbon capture and storage technology development and deployment to achieve climate change mitigation objectives.

This report focuses on one of those opportunities: afforestation of rangelands. The goal of the report is to summarize rangelands suitable for terrestrial carbon sequestration through afforestation in Shasta County, California. The report presents the results of research to date on afforestation potential in the county, provides a progress report on outreach to Shasta County landowners, and outlines next steps toward siting and implementing afforestation pilot activities during the remainder of WESTCARB Phase II.

1.3 Report Organization

The report is organized in methods, results, and conclusions/ recommendations. Section 2 presents methods for determining afforestation suitability, carbon potential and cost. The results of these analyses are summarized in Section 3. Section 2 also provides an overview of landowner outreach methods being employed in Phase II. Though landowner outreach remains in the early stages, Section 3 provides an interim report on these efforts. Section 4 provides recommendations for next steps in analysis and landowner outreach.

2.0 Project Approach

The approach used in this report generally follows that of previous work on the carbon supply from range and forest lands for the whole of California (Brown et al. 2004) and also uses information from analysis of baseline GHG emissions and removals for Shasta County (Pearson et al. 2006). The general approach was to:

- Identify the area and current use and cover of existing rangelands.
- Estimate the area and geographic location of existing rangelands that could be afforested and potential rates of carbon sequestration on these lands.
- Estimate the total cost of afforesting rangelands, including opportunity cost, conversion cost, maintenance cost, and measurement and monitoring cost.
- Determine the geographic distribution of available carbon credits at various prices.

Further detail on methods for calculating carbon supply from afforestation in Shasta County are available in Brown et al. (2007).

2.1 Identifying Rangelands for Terrestrial Carbon Sequestration

2.1.1 Forest Suitability of Rangelands

The total area of Shasta County is approximately 996 thousand hectares, of which 302 thousand (30%) are categorized as rangeland, 63% as forested land, and 6% in the non-forest/non-rangeland category comprised of barren, agriculture, urban, and water (Figure 2-1).

“Rangeland” includes not only open herbaceous and shrub lands (Wildlife Habitat Relationship [WHR] classes such as Annual Grass and Sagebrush), but also a variety of woodland classes (WHR classes such as Blue Oak Foothill Pine, Blue Oak Woodland, Chamise-Redshank Chaparral, Juniper, Mixed Chaparral, Montane Chaparral, Valley Oak Woodland, Wet Meadows).

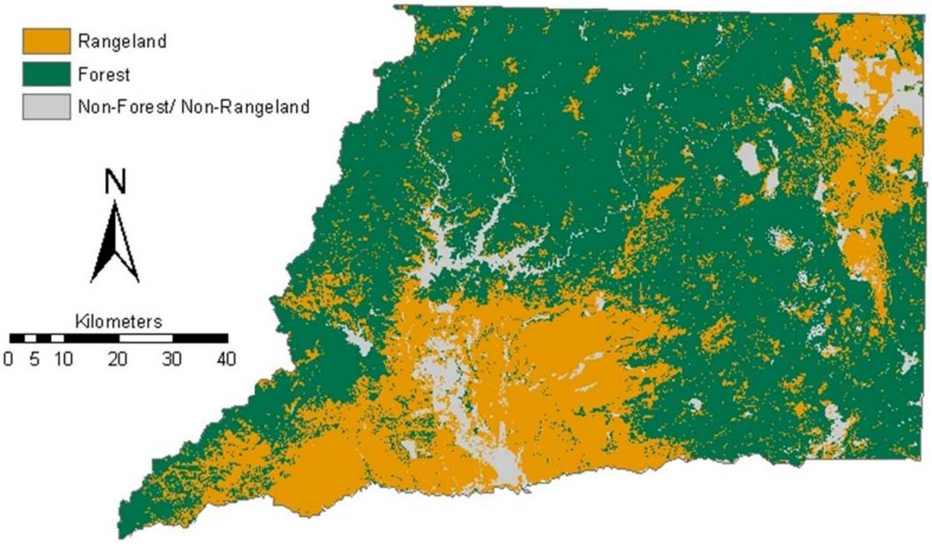

Figure 2-1. Landcover map for Shasta County identifying three land use categories: rangeland, forest, and non-forest/non-rangeland

A Geographic Information System (GIS)-based multi-factor forest suitability model was developed to identify those lands classified as rangeland but theoretically suitable to support forests. The model combined biophysical factor maps (including soil water availability, mean annual air temperature, annual average precipitation, slope, and elevation—calibrated using empirical locations of existing forests) to assign all rangelands a suitability value for forest growth, considering all five biophysical factors. To be considered suitable, a location needed to have high values across all the factor maps. Lands that fell into a category of any one of the factor maps where there were no existing forests were eliminated as candidate lands for afforestation.

A map of two landcover categories—forest and rangeland—was compared to the forest suitability map to show the range within the suitability scale where forests and rangelands currently exist, and where potential change of land use from rangeland to forestland should be explored. Forest suitability was then mapped throughout the county using the multi-factor modeling approach, showing the geographic distribution of the least to most suitable rangelands.

The next step was to identify, among the theoretically suitable rangelands, those that would be candidates for afforestation according to criteria that constitute candidate lands. From the rangelands shown in Figure 2-1, wooded rangelands with canopy cover > 40%, as well as grassy rangelands dominated by wet meadows, were assumed not to be suitable candidates for afforestation and were excluded from further analysis.

A further stratification of candidate lands was made after observation of certain areas mapped as rangeland but apparently unsuitable for grazing. These lands, classified as *chaparral* in the WHR map and falling within the perimeters of past wildfires, tend to be covered with dense shrubs such as manzanita and are generally impenetrable for livestock. They appear to represent a sort of arrested succession to forest. Intuitively it would be possible to convert these lands to forest for a net carbon gain. Because they are not suitable for grazing, opportunity costs might be small to nonexistent, making them attractive candidates for afforestation, but site preparation needed to allow forest to establish may be costly.

2.1.2 Carbon Sequestration Potential

To estimate the net carbon sequestration benefit of converting rangelands to forest, it is necessary to consider not only the change in area from one land use to another, but also the estimated difference in average carbon stocks between the two land uses. The net carbon benefit per unit area will be the difference in carbon stocks between the forest that is to be planted—at a given age such as 20, 40, or 80 years—and the baseline carbon stocks in the current land use. The total net carbon benefit will be the difference in carbon stocks multiplied by the area converted from rangeland to forest.

Estimates of carbon sequestration potential for forest planted on rangelands relied on Wildlife Habitat Relationship (WHR) forest classes aggregated into three larger classes hardwood, hardwood range, and mixed conifer that correspond to species groupings in the USDOE revised 1605(b) guidelines (USDOE 2006). This classification is shown in Table 2-1. By applying carbon values in t C/hectare (ha) to each simplified species group, based on USDOE 1605(b), U.S. Forest Service Forest Inventory and Analysis data (USDA Forest Service 2002), Winrock data from measurements in Shasta County forests, and other Winrock experience, it was possible to estimate potential carbon stocks from afforestation of suitable rangelands for each species class, as shown in Table 2-2.[3]

Table 2-1. Reclassification scheme of WHR classes according to USDOE (2006) classification

WHR	Birdsey (USDOE 2006) class
Montane Riparian	Hardwood
Montane Hardwood	Hardwood
Aspen	Hardwood
Blue Oak Woodland	Hardwood Range
Blue Oak Foothill Pine	Hardwood Range
Valley oak Woodland	Hardwood Range
Juniper	Hardwood Range
Subalpine Conifer	Mixed Conifer
Closed Cone Pine-Cypress	Mixed Conifer
Lodgepole Pine	Mixed Conifer
Sierran Mixed Conifer	Mixed Conifer
Eastside Pine	Mixed Conifer
Klamath mixed Conifer	Mixed Conifer
Jeffrey Pine	Mixed Conifer

Table 2-2. Estimates of the potential carbon stocks from afforestation of suitable rangeland areas

Forest class	Carbon stock at 20 yr (t C/ha)	Carbon stock at 40 yr (t C/ha)	Carbon stock at 80 yr (t C/ha)
Mixed conifer	132.4	170.3	411.1
Hardwood	24.8	77.4	217.5
Hardwood range	12	37	59

2.1.3 Afforestation Costs

Cost is a key factor affecting landowner interest in afforesting rangelands for carbon. The costs analyzed included opportunity costs, conversion costs such as site preparation and planting, measuring and monitoring (M&M) costs, and maintenance costs (Brown et al. 2007). Not included in the analysis were transaction costs—for example, costs to a potential buyer of seeking out willing landowners, costs to both buyer and landowner of concluding contracts, and potentially costs to one or both parties of registering and reporting projects. Total costs indicate a price at which landowners might be willing to change management of their lands, usually under a contract of some duration agreed between the landowner and a buyer of carbon credits.

To detect variations in cost based on grazing conditions and topographic locations, the rangelands suitable for afforestation were divided into two main classes: (1) those that are likely grazed, and (2) those not grazed, with both subdivided into two slope classes (greater than and less than 30% slope). Those with grazing would have an associated opportunity cost, whereas those not grazed

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[3] For further detail on the approach to estimating carbon accumulation potential for different species groups, see Brown et al. 2006.

would not. However, the shrub rangelands not suited for grazing have a high conversion cost of about \$900–\$1100/acre (\$2223–\$2717/ha) compared to \$450–\$600/acre (\$1112–\$1482/ha) for grassland and woody rangelands. Slope primarily affects conversion and maintenance costs.

2.1.4 Geographic Distribution of Costs

By dividing the present value of the total cost of afforestation (\$/ha) by the net potential carbon gain (t C/ha) at a given pixel on a map of candidate rangelands, it is possible to estimate the total cost of carbon (\$/t C or \$/t CO_2) for each pixel. This gives an indication of the least to most expensive areas within Shasta County for carbon sequestration through afforestation.

2.2 Methods for Landowner Outreach

Model-based analyses of rangeland forest suitability, carbon potential or cost only suggest which rangelands within Shasta County might successfully be converted for carbon purposes, or where within the county might be the most attractive regions to look for afforestation opportunities. Moving to actual afforestation pilot activities, it is necessary to identify specific landowners in the regions that appear attractive and assess their level of interest and potential concerns about planting forests on a portion of their lands and/or participating in carbon markets. Opportunities for landowners to participate in such activities in California are increasing; there is potential for landowners to secure additional income streams from carbon markets in the immediate, near and long-term as these markets and policy developments continue to evolve. The benefits are various and cannot be reduced to purely monetary considerations. However, participating in carbon sequestration activities also entails costs and constraints that landowners must consider.

2.2.1 Outreach/Stakeholders Meeting in Anderson

To begin this dialogue, Shasta County stakeholders—landowners, land managers, ranchers, foresters, and others—were invited to a WESTCARB Shasta County outreach/stakeholders meeting hosted by the Western Shasta Resource Conservation District (RCD) in Anderson, California, on October 26, 2006. Partner, landowner and stakeholder mailing lists were compiled and meeting invitations sent through flyers, e-mails, regular mail, and outreach via the RCD’s watershed groups throughout the county. A one-page summary of WESTCARB afforestation pilot activities planned for Shasta County was prepared for the meeting (see Appendix A).

At this meeting, the WESTCARB team reported on the results of research to date into forestry and land use opportunities that can sequester carbon and outlined opportunities for Shasta County landowners and land managers to participate in afforestation, fuel management, and forest management activities under WESTCARB. The objective of the meeting was to provide an overview of project opportunities, benefits and costs to landowners, evolving carbon credit markets, requirements for implementing, measuring and reporting projects, and related issues.

2.2.2 Ongoing Landowner Outreach

Following the October 26 meeting, Western Shasta RCD has continued to conduct in-person follow-up meetings with landowners. Outreach is also being coordinated via the watershed groups and partner agencies.

The RCD is currently contacting public and private interests to compile a list of restoration, planting and/or fuel management projects planned to be implemented in Shasta County between 2007 and 2009. In collaboration with the Natural Resource Conservation Service (NRCS), an information packet and landowner information release form was developed. This packet has been sent to NRCS clients identified as potential participants. Appointments have been made to meet with private land managers and agency representatives to obtain information on additional planned projects.

The RCD Watershed Coordinator met with the Shasta-Tehama Shedhead Watershed Coordinator Group and is in communication with the Sacramento River Area Conservation Forum regarding the Shasta County pilot project. The Watershed Coordinator is scheduling meetings with individuals to identify planned projects and possible collaboration opportunities.

3.0 Project Outcomes

Results of county-level analysis and outreach are presented here.

3.1 Identifying Rangelands for Terrestrial Carbon Sequestration

3.1.1 Forest Suitability of Rangelands

Historical evidence suggests that a large proportion of rangelands, in Shasta County and California as a whole, were once forested. Forest suitability analyses suggest that forests could successfully be established and maintained on many rangelands in Shasta County.

Figure 3-1 shows that there is a substantial overlap of forest classes in areas that exhibit the same biophysical characteristics as current rangelands from an approximate suitability score of 45 to 85. About 50% of the total rangeland area overlaps with scores that currently support forests.

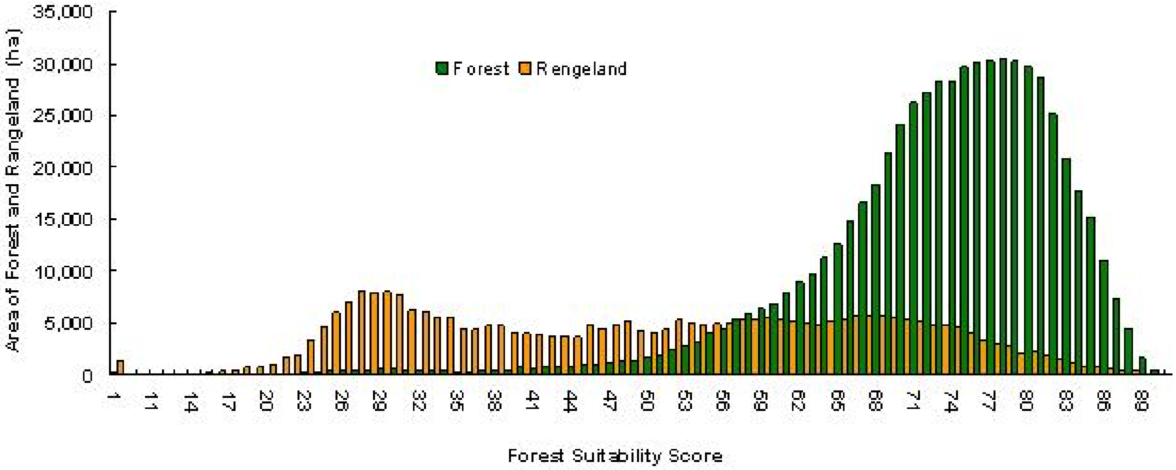

Figure 3-1. Distributions of areas of current rangeland and forest across forest suitability classes

Figure 3-2 shows the range in forest suitability across Shasta County rangelands according to the multi-factor modeling approach. Lands currently classified as *forestland* have been removed from this map, so the high suitability values on the map represent rangelands that may theoretically be converted to forest with a net carbon benefit due to the higher carbon stocks of forests compared with rangelands.

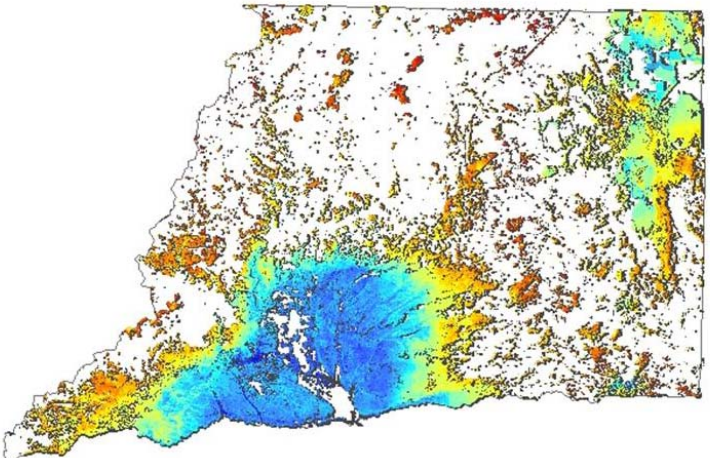

Figure 3-2. Suitability for forest growth on existing rangelands of Shasta County. The high values represent high suitability for rangelands to support forest

After exclusion of wooded rangelands with canopy cover > 40% and grassy rangelands dominated by wet meadows, the total remaining area of candidate rangelands is about 243 thousand ha, which represents about 80% of all rangelands in Shasta County, including 64,436 ha of woody rangelands with canopy cover < 40% suitable for afforestation (Figure 3-3).

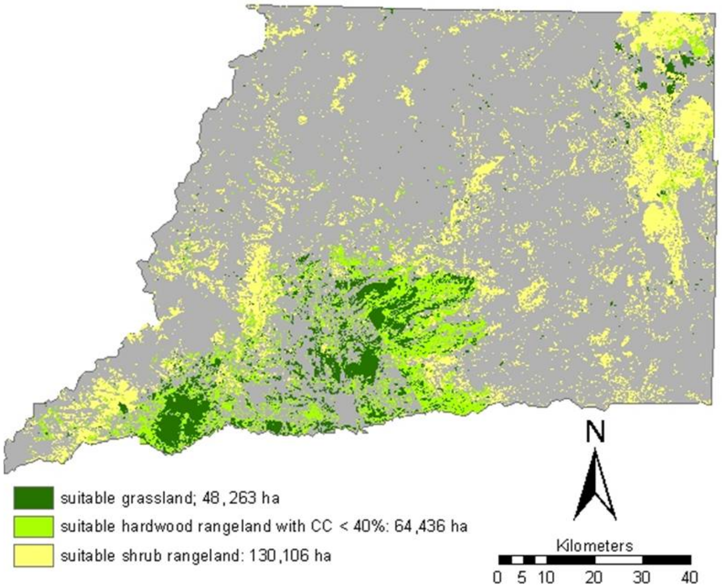

Figure 3-3. Map of candidate rangelands for afforestation activities (suitable to support forest and meeting constraints)

Finally, the results of further stratification of candidate lands into classified rangelands suitable and unsuitable for grazing is shown in Figure 3-4.

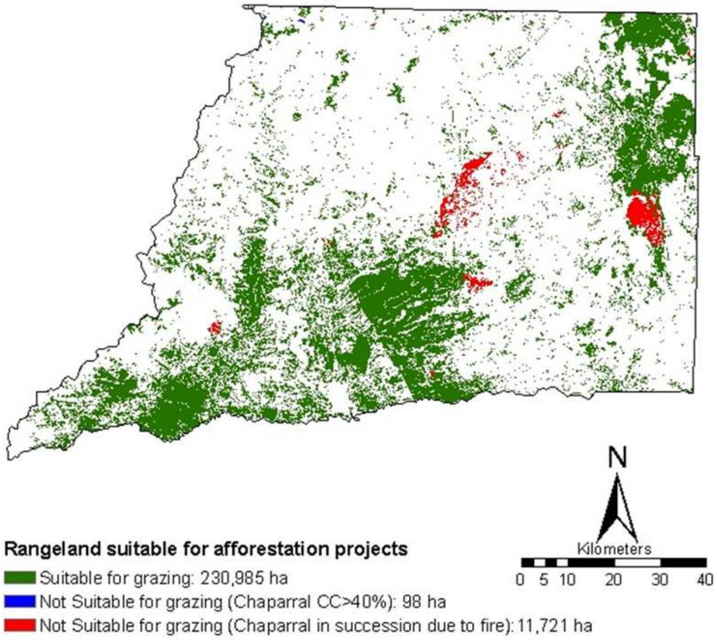

Figure 3-4. Distribution of rangeland suitable and not suitable for grazing. Rangelands not suitable for grazing represent chaparral areas in arrested succession due to past fires.

3.1.2 Carbon Sequestration Potential

Applying the carbon stock estimates in Section 2.1.2 to the map of rangelands suitable for afforestation results in a map of carbon sequestration potential throughout the county for 20-, 40-, and 80-year project durations (Figure 3-5).

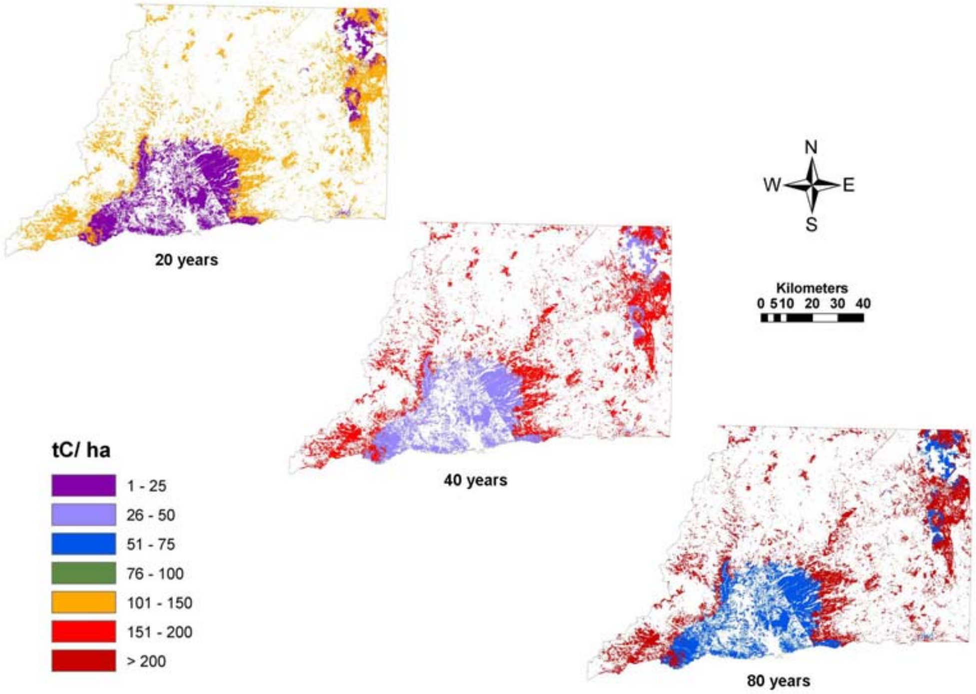

Figure 3-5. Carbon sequestration potential on rangelands suitable for afforestation activities for 20, 40, and 80 years.

Carbon sequestration analysis showed that carbon could be accumulated at faster rates, for all project durations, on rangelands in the southwestern and northeastern part of the county, east and north of Redding (Figure 3-5). These areas provide favorable conditions for planting fast-growing species that could accumulate carbon at rates above 100 tons per hectare in the first 20 years of afforestation projects and above 200 tons per hectare over 80 years.

3.1.3 Afforestation Costs

Depending on the forage productivity of rangeland suited for grazing, the net present value of the total costs of afforestation (opportunity, conversion, maintenance, and monitoring costs) after 20 years was about \$1300–\$1900/ha on slopes less than 30% and \$1700–\$2300/ha on slopes greater than 30%. On rangelands not suited for grazing, with no opportunity cost assigned, the net present value of total costs after 20 years was about \$2400/ha for lands with less than 30% slope and \$2900/ha for lands with greater than 30% slope—considerably higher than for lands suited for grazing—suggesting that high site preparation costs more than offset zero opportunity costs (Table 3-1). Whereas all costs appear relatively high, several points are important to note. First, Table 3-1 shows costs in \$/ha; to convert to \$/acre, divide by 2.47. Second, there is considerable variation, not only depending on forage production but by land type.

Finally, it should be emphasized that the important consideration for landowners is not so much the total cost per hectare, but rather how the net present value of a stream of costs compares to the net present value of the revenues available from sale of carbon credits. The total revenues to landowners will depend on the eventual price (\$/t CO_2) paid for carbon and the quantity sequestered (t CO_2), which varies throughout the county.

Table 3-1. Net present value of total costs, in $/ha over the time period, for afforesting rangelands in Shasta County for three time periods

Forage production Lbs/acre.yr	Total costs 20 year	40 year	80 year
Suitable for grazing with slopes <30%			
100	$1,298	$1,312	$1,317
500	$1,432	$1,507	$1,552
1000	$1,599	$1,751	$1,847
1500	$1,767	$1,995	$2,142
2000	$1,934	$2,239	$2,437
Suitable for grazing with slopes >30%			
100	$1,668	$1,682	$1,687
500	$1,802	$1,878	$1,923
1000	$1,970	$2,122	$2,218
1500	$2,137	$2,366	$2,513
2000	$2,305	$2,610	$2,807
Unsuitable for grazing with slopes <30%			
100	$2,376	$2,375	$2,369
500	$2,376	$2,375	$2,369
1000	$2,376	$2,375	$2,369
1500	$2,376	$2,375	$2,369
2000	$2,376	$2,375	$2,369
Unsuitable for grazing with slopes >30%			
100	$2,870	$2,869	$2,863
500	$2,870	$2,869	$2,863
1000	$2,870	$2,869	$2,863
1500	$2,870	$2,869	$2,863
2000	$2,870	$2,869	$2,863

3.1.4 Geographic Distribution of Costs

It is assumed that landowners would be willing to produce and sell carbon credits from afforestation if the price paid for these credits is greater than the present value of the stream of costs incurred in producing them. Generally, the cost per ton of carbon produced is greater for shorter time periods (20 years) and less for longer time periods (80 years), due to the effect of the economic discount rate in calculating the present value cost of carbon (the longer the time period the greater effect discounting has on the costs), and also rates of carbon accumulation over time (the longer the duration the greater the change in carbon stock). Figure 3-6 shows the range of costs on rangelands suitable for grazing and Figure 3-7 the range of costs on rangelands unsuitable for grazing.[4]

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[4] CO_2 is calculated by multiplying carbon stocks by 3.667.

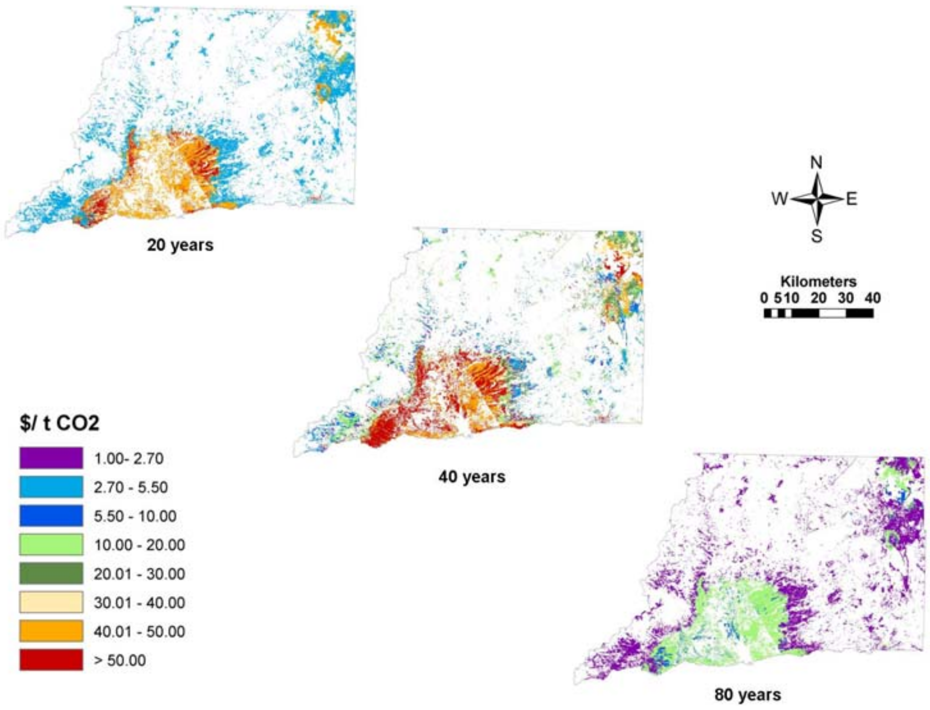

Figure 3-6. Cost of CO_2 through afforestation of rangelands suitable for grazing in Shasta County

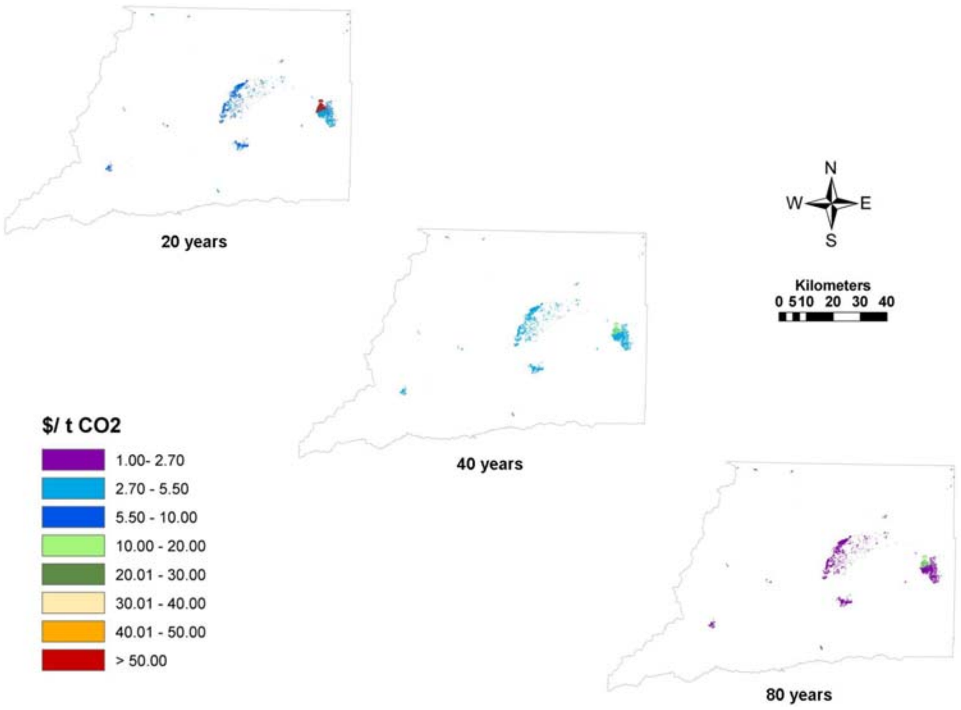

Figure 3-7. Cost of CO_2 through afforestation of rangelands unsuitable for grazing in Shasta County

The most expensive carbon on lands suited for grazing (> $40/t CO_2) is located in the south to southwest part of the county. The least expensive carbon over any of the three time intervals is located in the east and northeastern part of the county (Figure 3-6). These are the areas, not necessarily where the magnitude of carbon sequestration is greatest, but where carbon may be sequestered most cost-effectively through afforestation. The small amount of rangeland unsuited for grazing produces carbon at a mid-range of costs (Figure 3-7).

3.2 Landowner Outreach

Efforts by Western Shasta RCD, Winrock International, and other WESTCARB partners to conduct outreach to Shasta County landowners for afforestation projects are currently in the early stages. The October 26 outreach/stakeholders meeting in Anderson was attended by approximately 20 people, including several watershed group coordinators through whom the RCD expects to reach a large number of landowners. Attendees also included representatives from state and federal agencies, private industry, nonprofit organizations, and individuals. Dialogue at the meeting helped to highlight landowner interest, concerns, additional information needs, and further analysis tasks that are currently being undertaken by Winrock International, the RCD, and other WESTCARB partners.

The RCD District Manager, Winrock International, and WESTCARB representatives were interviewed by local television station KRCR Channel 7 which resulted in a story on the evening news.

A “Shasta County Landowner Willingness to Participate Survey” was developed to assist in further planning and siting of afforestation projects. The objectives of the survey are:

1. To understand the interest of Shasta County range landowners in planting forest plantations for the purposes of carbon sequestration.
2. To determine cost-share levels at which landowners will be willing to plant additional lands to forest plantation.
3. To assess the extent and type of land that individual landowners would be willing to plant if their expectations for cost-share support were met.
4. To evaluate species preferences for plantation on their lands.
5. To validate survey commitments by providing selected landowners with opportunities to plant their lands with pilot project funding.

This survey will be administered by the RCD beginning in late 2006/early 2007. The target sample size is at least 20 landowners in each of three landowner strata: multigenerational family landholdings; absentee owners with part-time interests in the lands and likely fewer financial investment constraints; and owner-occupants who are first-generation owners.

4.0 Conclusions and Recommendations

4.1 Conclusions

It is assumed that landowners would be willing to produce and sell carbon credits if the price paid for these credits is greater than the present value of the stream of costs incurred in producing them. Generally, the cost per ton of carbon produced is greater for shorter time periods (20 years) and less for longer time periods (80 years) (Figure 4-1).

After 80 years, about 57.6 million tons of carbon could be sequestered at a cost of less than \$10/t C (\$2.7/t CO_2). In contrast, about 17.7 million tons of carbon could be sequestered after 20 years at a cost of less than \$20/t C (\$5.45/t CO_2). These quantities could be sequestered on about 57% of the rangeland suitable for afforestation (Figure 4-2). The costs rise steeply with limited additional carbon on the remaining 44% of the rangelands suitable for afforestation because these tend to be on lands most suited for rangeland hardwoods with low rates of carbon sequestration.

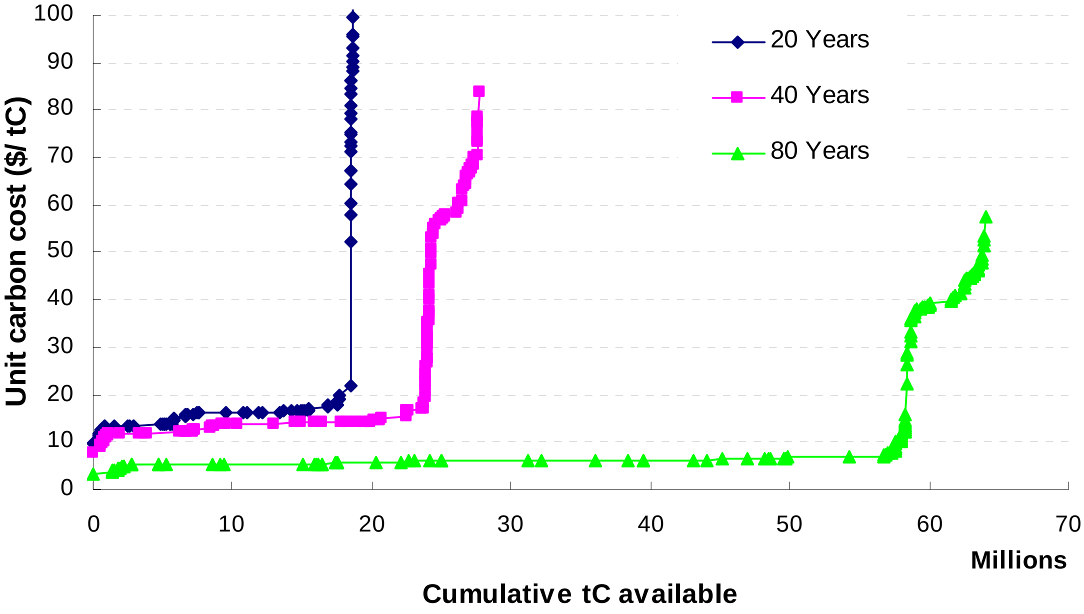

Figure 4-1. Carbon supply curves for afforestation activities on rangelands at 20, 40, and 80 years

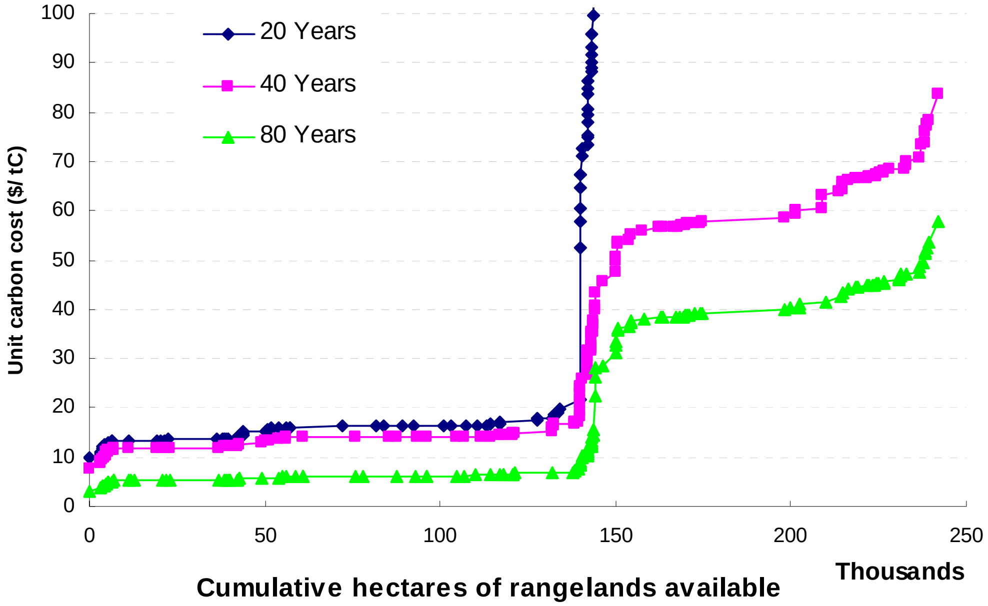

Figure 4-2. Land supply curves for afforestation activities on rangelands at 20, 40, and 80 years

4.2 Recommendations and Next Steps

The analysis presented above indicates regions within the county generally attractive for terrestrial carbon sequestration through afforestation. Though conducted at a finer level of resolution than similar state-level analyses, this model is not sufficient to conclude that a particular location (land parcel or pixel on the map) should be planted to trees, with X species at X cost yielding X tons of carbon. For this level of afforestation project planning, additional and more detailed land suitability analysis is needed prior to actual planting. This analysis is recommended to include further examination of land capability classifications and soil series data from the U.S. Department of Agriculture (USDA)-NRCS soil surveys for Shasta County and modeling growth of particular tree species based on site productivity.

In addition, it will be important to add the factor of aspect (direction lands face) to the five biophysical factors analyzed thus far. Trees planted on lands identical in slope, soil water availability, temperature, precipitation, and elevation—but different in aspect—may perform very differently in terms of growth and even survival.

Efforts are currently under way to procure seed and seedlings appropriate to the afforestation regions identified, even in advance of specific site selection, due to the long lead times for seedling procurement, seedling growing industries, site preparation, and planting. Use of improved seed stock wherever possible is recommended, including consideration of hardy or fast-growing hybrids.

Efforts are also under way by the RCD, Winrock, and WESTCARB partner W.M. Beaty & Associates to collect data on existing or planned afforestation efforts throughout the county, with which the project can collaborate to gather existing data and collect additional data, without necessarily funding afforestation directly. This will greatly expand the geographic and temporal scope of afforestation activities included in the research effort.

As afforestation site selection proceeds, it will be important to consider recent wildfire sites as afforestation opportunities. Site preparation costs in these locations may be greatly reduced, provided planting can be done relatively quickly, before competing vegetation reclaims the site.

For oak woodland restoration/afforestation efforts, collaboration with the University of California's Integrated Hardwood Range Management Program (IHRMP) is recommended. Initial contacts have been made. The IHRMP has ample experience in siting, seed considerations, and techniques for successful oak restoration, including techniques to protect seedlings from cattle so that afforestation may be done without foregoing grazing income.

An issue presently under consideration is whether landowners participating in WESTCARB afforestation activities should incur any short- or long-term obligations as a condition of cost sharing. The California Climate Action Registry requires, in order for forestry projects to be certified and reported, that project lands be placed under perpetual easement. This appears to be a barrier to participation for many landowners. WESTCARB afforestation projects will not have any such easement requirement, and need not necessarily stipulate any landowner obligations beyond those necessary for accomplishing research objectives—maintenance of the project and access for measurements through 2009. However it is possible that at least a short-term obligation could be useful; for example, WESTCARB could adopt the model of the California Forest Improvement Program, which requires in return for cost share funds that program participants not convert lands to uses incompatible with forest management for a minimum of 10 years. Other issues under consideration for possible landowner agreements include management/maintenance activities permitted, management/maintenance activities required, data sharing and access for ongoing measurements, notification in cases of disturbance or loss, and other issues. If WESTCARB concludes formal agreements with afforestation project participants, it will be important to consider these issues carefully and strike the appropriate balance between open participation in order to achieve research objectives and preparing landowners realistically for the requirements to participate in future carbon markets. Investigating landowner interest/uptake at different levels and lengths of obligation is in itself a useful research objective, as the State of California designs its policies for market-based carbon offset programs under current voluntary programs and future regulation.

4.3 Benefits to California

The State of California recently enacted the Global Warming Solutions Act of 2006, which directs the Air Resources Board (ARB) to develop GHG emission regulations to meet the state's target of statewide emissions at 1990 levels by 2020. Regulations will be developed over the next several years and take effect in 2012. By Executive Order on October 17, 2006, Governor Schwarzenegger directed the ARB to develop a comprehensive market-based compliance program as part of these regulations, which would allow the state to achieve the most cost-effective emission reductions and also permit trading with the European Union and the northeastern states' Regional Greenhouse Gas Initiative. One of ARB's tasks will be to decide what types of activities will be eligible for trading under the market-based compliance program, including what types of forestry activities and what specific protocols or requirements will need to be met in order for credits from such projects to be traded. Results from WESTCARB afforestation pilot projects in northern California will help to inform State policy developments and market eligibility questions, while also addressing issues of landowner uptake, project costs, measurement, monitoring, and verification.

In addition to informing regulatory developments, WESTCARB afforestation activities will provide valuable information to the increasing number of companies and organizations in the state taking voluntary actions to manage their GHG emissions. For example, CCAR members may undertake forestry projects for which CCAR has existing Forest Sector, Forest Project, and Forest Certification Protocols. These protocols will be “road-tested,” and new protocols developed, through WESTCARB. Pacific Gas & Electric Company has proposed a voluntary Climate Protection Tariff, offering its ratepayers the option to become “climate-neutral” by paying an additional monthly tariff; PG&E would then contract for carbon offset projects, initially forestry projects, for equivalent tons of CO_2. Afforestation activities in Shasta County would be eligible to supply credits into PG&E’s program, provided they meet the requirements of the relevant CCAR Forest Project Protocol. Thus WESTCARB afforestation activities will provide a near-term opportunity for landowners to sell carbon, while also informing PG&E, CCAR, and related state efforts about landowner concerns and constraints to broader participation in such programs. PG&E’s program has been tentatively approved by the California Public Utilities Commission, to begin in spring 2007, and other utilities in the state are considering developing similar programs.

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6.0 Glossary

ARB	California Air Resources Board
CCAR	California Climate Action Registry
CO_2	carbon dioxide
GHG	greenhouse gas
GIS	Geographic Information System
ha	hectare
IHRMP	Integrated Hardwood Range Management Program
M&M	measuring and monitoring
NRCS	Natural Resource Conservation Service
RCD	Western Shasta Resource Conservation District
USDA	United States Department of Agriculture
USDOE	U.S. Department of Energy
WESTCARB	West Coast Regional Carbon Sequestration Partnership
WHR	Wildlife Habitat Relationship

Appendix A

WESTCARB Afforestation Pilot Projects in Shasta County

This one-page outreach document was prepared for the October 26, 2006 landowner outreach/stakeholders meeting in Anderson, California.

WESTCARB Afforestation
Pilot Projects in Shasta County

Winrock International is working with the US Department of Energy, California Energy Commission, and Shasta County federal, state and private landowners to implement afforestation pilot projects under the West Coast Regional Carbon Sequestration Partnership WESTCARB. The goal of these projects is to demonstrate one of California's most promising climate change mitigation options: sequestering carbon by increasing forest cover on selected rangelands. Pilot projects in Shasta will provide on-the-ground experience in site preparation, planting and maintenance techniques for afforestation; help refine estimates of net carbon sequestration potential using field measurements and improved growth models; synthesize information on costs and benefits to landowners; and provide guidance to landowners considering undertaking afforestation to generate CO_2 credits for reporting to the California Climate Action Registry and/or for sale to carbon offset credit buyers.

Sites

Eligible lands for WESTCARB afforestation projects include federal, state and private land. Of Shasta County's approximately 746,000 acres of rangeland, initial analyses show 600,000 acres as suitable for afforestation, including grassland, hardwood rangeland, and shrub rangeland types. This includes both rangelands suitable for grazing (570,000 acres) and some densely vegetated sites, classified as rangeland but unsuitable for grazing and likely representing arrested succession to forest after fires. The most cost-effective regions for afforestation, in terms of cost per ton CO_2 sequestered, appear to be in areas to the southeast, southwest, and east and west of Redding, and in the northeast corner of Shasta County. Specific sites will be chosen in the remainder of 2006 and 2007, based on landowner interest, with site preparation and planting to take place in the 2007 and 2008 seasons.

Species

Three species groups are currently being considered for afforestation (though others may be added, in consultation with WESTCARB partners and landowners): mixed conifers for higher-elevation sites, including chaparral/arrested succession areas; mixed rangeland oaks for lower-elevation rangelands; and grey pine for lower elevation rangelands and transitional zones. These species all have excellent survival and performance in Shasta County, with seedlings available and experience among WESTCARB partners to ensure successful planting. Many of the highest-carbon, least-cost carbon sequestration opportunities are in the near term in mixed conifer areas; however, mixed conifers may be unable to grow successfully on many of the available sites. Grey pine, though of questionable value as a timber species, performs well across a broad range of sites and may also have value as fuel for biomass energy facilities.

Costs and Benefits to Landowners

Afforestation costs include opportunity costs (potential loss of rangeland forage production and thus profitability), conversion costs (for example fencing, site preparation, planting), measuring and monitoring costs, and maintenance costs. Lands classified as rangeland, but actually representing arrested succession to forest after fires, are unsuitable for grazing and may have zero opportunity cost, but high site preparation costs offset some of this advantage. Opportunity costs may be minimized by the fact that afforesting rangelands may not require foregoing grazing, perhaps only protecting seedlings or excluding cattle for a few years until seedlings are established. Costs in \$/acre and \$/ton CO_2 sequestered vary throughout the county. Landowners are expected to weigh potential revenues from carbon credits (t CO_2 sequestered over the life of a project, valued at current or projected prices per ton) against the present value of afforestation costs. Total costs could include the costs of reporting and certifying projects for the California Climate Action Registry in order to make these projects eligible for sale to carbon credit buyers requiring Registry participation. Demand for carbon credits, and the price offered per ton CO_2, are expected to increase as California moves toward mandatory regulation of greenhouse gas emissions, with the recent passage of the California Global Warming Solutions Act of 2006 (AB32) being a significant step in this direction.

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WESTCARB AFFORESTATION PILOT PROJECTS IN SHASTA COUNTY, CALIFORNIA

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Winrock International

DOE Contract No.: DE-FC26-05NT42593
Contract Period: October 1, 2005 - May 11, 2011

Arnold Schwarzenegger
Governor

WESTCARB AFFORESTATION PILOT PROJECTS IN SHASTA COUNTY, CALIFORNIA

Prepared For:

California Energy Commission
Public Interest Energy Research Program

Prepared By:

Winrock International

PIER PROJECT REPORT

September 2010
CEC-500-2010-XXX

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Commission Contract No. 500-02-004
Commission Work Authorization No. MR-045

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Please cite this report as follows:

Goslee, K., T. Pearson, S. Brown, B. Rynearson, L. Bryan, S. Petrova, and S. Grimland. 2010. *WESTCARB Afforestation Pilot Projects in Shasta County, California*. California Energy Commission, PIER. CEC-500-2010-XXX.

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission) conducts public interest research, development, and demonstration (RD&D) projects to benefit the electricity and natural gas ratepayers in California. The Energy Commission awards up to $62 million annually in electricity-related RD&D, and up to $12 million annually for natural gas RD&D.

The PIER program strives to conduct the most promising public interest energy research by partnering with RD&D organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally Preferred Advanced Generation
- Energy-Related Environmental Research

WESTCARB Afforestation Pilot Projects in Shasta County, California is a report for the West Coast Regional Carbon Sequestration Partnership – Phase II (contract number MR-06-03L, work authorization number MR-045), conducted by Winrock International. This report is submitted in fulfillment of deliverable #10, "Paper Summarizing Results from Shasta County Afforestation Pilot Activity." The information from this project contributes to PIER's Energy-Related Environmental Research program.

For more information on the PIER Program, please visit the Energy Commission's Web site at www.energy.ca.gov/pier or contact the Energy Commission at (916) 654-5164.

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Abstract

Afforestation was identified in Phase I of WESTCARB as a significant terrestrial carbon sequestration opportunity, both in Shasta County and at the state level for California, Oregon and Washington. This report summarizes work done under WESTCARB Phase II (2006-10) by Winrock International and its Shasta County partners, primarily the Western Shasta Resource Conservation District and WM Beaty and Associates, to implement afforestation pilot projects. Activities included refining land classification for afforestation potential; landowner outreach and formal surveys; setting criteria for selection and distribution of pilot plantings; developing site-specific planting and maintenance plans; negotiating landowner agreements; sourcing seed and growing seedlings in nurseries; taking baseline carbon stock measurements; collecting data on operational costs; conducting site preparation, planting and early maintenance; and modeling carbon accumulation. A total of twelve afforestation projects were implemented, totaling 476 acres. Initial survival rates were determined, and future growth and carbon stocks were modeled over a 100-year period.

Keywords: *Carbon, sequestration, afforestation, reforestation, forest, shrubland, rangeland, Shasta County*

Executive Summary

Introduction

The West Coast Regional Carbon Sequestration Partnership (WESTCARB), led by the California Energy Commission, is one of seven US Department of Energy regional partnerships working to evaluate, validate and demonstrate ways to sequester carbon dioxide and reduce emissions of greenhouse gases linked to global warming. Based on analyses conducted in WESTCARB Phase I and related work for the California Energy Commission, afforestation[1] represents the largest single terrestrial carbon sequestration opportunity for Shasta County, for California, and across the WESTCARB region. Protocols, policies and programs to encourage afforestation may make a substantial contribution toward the greenhouse gas (GHG) emission reduction goals of California and other Western states. Meanwhile, afforestation may offer landowners near-term opportunities to participate in rapidly evolving GHG reporting registries, offset markets and other carbon "credit" sale opportunities under voluntary and regulated markets. WESTCARB Phase II included pilot afforestation projects to evaluate the actual potential to implement these projects.

Purpose

The purpose of this report is to provide a final update on the WESTCARB Phase II afforestation pilot projects in Shasta County, California. The report summarizes pilot locations, site preparation and planting methods, species, post-planting maintenance, costs, landowner interests and concerns, carbon measurement and monitoring plans, projected tree growth and levels of carbon sequestration. WESTCARB conducted afforestation pilots through cost-shared agreements with private landowners.

Project Objectives

The overall goal of WESTCARB Phase II is to validate and demonstrate the region's key carbon sequestration opportunities through pilot projects, methodology development, reporting, and market validation. WESTCARB research will facilitate informed decisions by policymakers, communities, and businesses on how to invest in carbon capture and storage technology

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[1] The uses of the terms "afforestation" and "reforestation" differ across the US and internationally. In the US and under the USDOE revised 1605(b) guidelines for greenhouse gas reporting, "afforestation" is the establishment of new forests on lands that have not been forested for some considerable length of time, and is in essence a land-use change; "reforestation" is the re-establishment of forest cover, naturally or artificially, on lands that have recently been harvested or otherwise cleared of trees. In contrast, California state agencies and the California Climate Action Registry protocols generally use the term "reforestation" to mean the establishment of new forests on lands that have not been recently forested. Regardless of terminology, the practice being tested under WESTCARB is a land-use change activity that would qualify for carbon reporting in the State of California: *the establishment and subsequent maintenance of native tree cover on lands that were previously forested, but have had less than 10% tree canopy cover for a minimum time of ten years* (termed "reforestation" in California). In this report for consistency we use the term "afforestation."

development and deployment to achieve climate change mitigation objectives. The climate change mitigation opportunity presented here is afforestation.

The specific objectives of the Phase II Shasta County afforestation pilots are:

- Refine the Phase I economic analysis for afforestation with improved cost data;
- Gain on-the-ground experience to explore the feasibility, success and survival of afforestation projects;
- Refine carbon estimates for afforestation, using baseline measurements, proxy measurements in relevant species groups, and industry data;
- Gain experience with site preparation, seedling sourcing, planting techniques, post-planting maintenance treatments, and other considerations necessary to inform the efforts of land managers, landowners and businesses in replicating and expanding afforestation projects for climate change mitigation in California and the WESTCARB region;

Project Outcomes

Twelve landowner agreements for WESTCARB afforestation pilot projects were signed and implemented, totaling 476 acres (Table A). Projects range in size from 7 to 98 acres, and average 40 acres. Project baselines consisted of a variety of brush species, mostly in dense stands. Baseline carbon stocks ranged from zero, for a project that had recently burned in a wildfire, to 34 metric tons of carbon per acre, on a project with dense old-growth Manzanita. Projects were planted to ponderosa pine, mixed conifer stands, or native oaks. After 100 years, projections of net carbon stocks over 100 years on conifer plantings ranged from 53 t C/ac to 111 t C/ac. The native oak planting had projected net carbon stocks of 24 t C/ac after 100 years. Survival of planted conifer seedlings was high, despite limited rainfall in the year of planting. Project costs ranged from $354/ac to $1,880/ac.

Table A. WESTCARB Shasta County Afforestation Pilot Project Summaries

Project	Acres	Cost/ac	Baseline C stocks (t/ac)	Species	Trees/ac planted	Projected net project C stocks after 100 years (t/ac)
Red River Forests Partnership	98	$832	21	Ponderosa pine	300	73
Brooks Walker	7	$1,265	3	Ponderosa pine & red fir	300	100
Hendrix-Phillips Tree Farm	20	$1,223	24	Ponderosa pine	300	67
Goose Valley Ranch	60	$1,033	20	Ponderosa pine, Douglas fir, incense cedar	290	80
Lammers	50	$858	15	Ponderosa pine & Douglas fir	249	74
Frase	43	$600	0	Ponderosa pine	282	85
Kloeppel	51	$899	10	Ponderosa pine & Douglas fir	314	198
Sivadas	46	$778	44	Ponderosa pine	197	43
Eilers	20	$354	0	Ponderosa pine (18 acres)	208	64
				Ponderosa pine & blue oak (2 acres)	258	53
Wilson	14	$1,300	31	Ponderosa pine	274	60
Lakey	60	$482	0	Ponderosa pine	177	69
BLM	7	$1,880	0	Oak	143	24

Conclusions

Landowners have a strong interest in afforestation projects, and are willing to provide cost-share for projects intended to increase carbon sequestration. There is a wide range of project costs and projected net project carbon stocks, depending on the baseline condition of the land, the accessibility of the project, the quality of the site, and the resulting tree growth. Projects with high carbon stocks in the baseline do not result in positive net carbon stocks for 30 to 40 years after planting, and therefore may not be feasible on a strictly financial basis. However, sites with low carbon stocks in the baseline result in net positive results within the first 10 years, and sequester large amounts of carbon over the project lifetime. Those areas with high site quality result in large net increases in carbon stocks, although even in areas with poor site quality and limited rainfall, seedling survival was high, and projected carbon stocks can be significant.

Recommendations

WESTCARB states should continue to support efforts to explore the potential of afforestation to contribute to state GHG reduction goals. Many different afforestation project designs are conceivable, and can be replicated broadly elsewhere in California and the WESTCARB region. Afforestation can make a significant contribution to carbon sequestration, climate change mitigation and adaptation, and should be considered as part of the broad portfolio of strategies under consideration by the State of California (Climate Action Team and AB32) and analogous policy processes in other WESTCARB states.

Ongoing outreach and education is necessary to keep landowners informed about the opportunities to conduct afforestation for carbon sequestration, evolving carbon markets and climate change policies, and requirements for participation.

Benefits to California

Findings from the WESTCARB afforestation pilots have informed both voluntary efforts, such as those by Climate Action Reserve members interested in offsetting GHG emissions through forestry, and regulatory developments, such as the process now underway by the California Air Resources Board to design a GHG regulatory program under the California Global Warming Solutions Act of 2006 (AB32). The AB32 Market Advisory Committee, charged by Executive Order S-20-06 with advising the Air Resources Board on the design of a market-based compliance program under AB32, has recommended that such a program include offset projects provided such projects meet a series of stringent criteria ("real, additional, independently verifiable, permanent, enforceable, predictable, and transparent"), as well as meeting standards for rigorous accounting methods and environmental integrity (Market Advisory Committee 2007). Although debate remains over the role of offsets in GHG emission reduction programs, what sort of offset project types should be eligible, and the role of forestry within offset programs, afforestation projects like those being demonstrated under WESTCARB are perhaps the most likely to meet the Market Advisory Committee's quality criteria. Projects demonstrated to meet these criteria are likely to be attractive to landowners/carbon credit suppliers, to entities (companies, individuals, financial sector investors) purchasing offsets on the voluntary market, and to regulated entities seeking flexible compliance mechanisms to achieve GHG reductions.

1.0 Introduction

1.1 Background and overview

The West Coast Regional Carbon Sequestration Partnership (WESTCARB), led by the California Energy Commission, is one of seven US Department of Energy regional partnerships working to evaluate, validate and demonstrate ways to sequester carbon dioxide and reduce emissions of greenhouse gases linked to global warming. Terrestrial (forestry and land use) sequestration options being investigated include afforestation[2], improved management of hazardous fuels to reduce emissions from wildfires, biomass energy, and forest management. Shasta County, California and Lake County, Oregon were chosen for Phase II terrestrial sequestration pilot projects because of the diversity of land cover types present, opportunities to implement the most attractive terrestrial carbon activities identified in Phase I, and replication potential elsewhere in the WESTCARB region.

Earlier reports (Brown et al 2004; Brown et al 2007; Martin et al 2007a, 2007b; Martin *et al*. 2006) have presented the results of Winrock analyses of afforestation potential for California and for Shasta County. These analyses included suitability of lands classified as rangelands for afforestation, carbon sequestration potential, cost analyses (opportunity, conversion, measuring and monitoring, and maintenance costs), and carbon supply curves summarizing the area of land that might be afforested and resulting carbon sequestration at a range of prices for CO_2. Winrock concluded that afforestation represents the single largest terrestrial sequestration opportunity at the state level for California, Oregon and Washington (Brown et al 2004; Dushku et al 2005a, b; Brown et al 2006). For example, for California, it was found that at a price of <\$5.50t CO_2, 345 million metric tons CO_2 could be sequestered on 2.7 million acres after 20 years and 3 billion metric tons CO_2 on 14.8 million acres after 40 years via afforestation of rangelands with native species (Brown et al 2004). Afforestation was also the single largest opportunity for Shasta County; at the same price, afforestation could sequester 65 million metric tons CO_2 on 331 thousand acres after 20 years and 87 million metric tons CO_2 on 346 thousand acres after 40 years (Brown et al 2007).

Moving beyond these initial analyses, in Phase II Winrock has worked with Shasta County landowners to implement afforestation pilot projects. The purpose of pilot projects was to validate and demonstrate Phase I findings, refine earlier analyses with more specific cost and

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[2] The uses of the terms "afforestation" and "reforestation" differ across the US and internationally. In the US and under the USDOE revised 1605(b) guidelines for greenhouse gas reporting, "afforestation" is the establishment of new forests on lands that have not been forested for some considerable length of time, and is in essence a land-use change; "reforestation" is the re-establishment of forest cover, naturally or artificially, on lands that have recently been harvested or otherwise cleared of trees. In contrast, California state agencies and the California Climate Action Registry protocols generally use the term "reforestation" to mean the establishment of new forests on lands that have not been recently forested. Regardless of terminology, the practice being tested under WESTCARB is a land-use change activity that would qualify for carbon reporting in the State of California: *the establishment and subsequent maintenance of native tree cover on lands that were previously forested, but have had less than 10% tree canopy cover for a minimum time of ten years* (termed "reforestation" in California). In this report for consistency we use the term "afforestation."

carbon data and explore the interests and concerns of landowners in conducting afforestation for carbon sequestration.

1.2 Project Objectives

The overall goal of WESTCARB Phase II was to validate and demonstrate the region's key carbon sequestration opportunities through pilot projects, methodology development, reporting, and market validation. Results from WESTCARB research will be able to facilitate informed decisions by policymakers, communities, and businesses on how to invest in carbon capture and storage technology development and deployment to achieve climate change mitigation objectives.

The specific objectives of the Phase II Shasta County afforestation pilots were to:

- Refine the Phase I economic analysis for afforestation with improved cost data;
- Gain on-the-ground experience to explore the feasibility, success and survival of afforestation projects;
- Refine carbon estimates for afforestation, using baseline measurements, proxy measurements in relevant species groups, and industry data;
- Gain experience with site preparation, seedling sourcing, planting techniques, post-planting maintenance treatments, and other considerations necessary to inform the efforts of land managers, landowners and businesses in replicating and expanding afforestation projects for climate change mitigation in California and the WESTCARB region.

1.3 Report Organization

The report is organized into six sections. Section 2 summarizes methods for compiling information on planting in Shasta County, CA and identifying plantings sites for the afforestation pilots. Section 3 provides information on the planting methods used for the pilots. Section 4 details and Section 5 summarizes the planting sites. Section 6 summarizes findings and recommendations.

2.0 Identification of Planting Sites

2.1 Compile data on existing plantings

Public and private interests were contacted to compile a list of reforestation projects planned in Shasta County between 2007 and 2009. The objective was to further our understanding of afforestation activities already underway in California. Other projects currently underway or planned, such as projects under the EQIP and CFIP programs, are not explicitly designed for carbon sequestration purposes but involve similar activities and potentially data for analysis. Information collected included: project status, county, ownership size, project size, legal location, responsible RPF, land use prior to project, elevation, slope, aspect, soil, vegetation prior to planting, project description, maintenance methods, planting density, costs, projected volume accumulation if available, and seedling survival/growth rates if known.

2.2 Set criteria for WESTCARB pilot projects

Winrock, Western Shasta RCD, and WM Beaty & Associates established the following general criteria for selecting landowners to proceed to site-specific afforestation plans and landowner agreements:

- The practice supported by WESTCARB funding should be eligible for carbon registries, reporting and markets, should landowners choose to do so. The eligibility criteria for the practice must fit within "reforestation" as defined by the Climate Action Reserve, and described as "the establishment and subsequent maintenance of native tree cover on lands that were previously forested, but have had less than 10% tree canopy cover for a minimum time of ten years[3]." Proposed sites must therefore have had less than 10% tree canopy cover for at least ten years at the start of the project.
- Participation in a WESTCARB afforestation pilot would not, however, be contingent on landowners' willingness to report the activity to the Registry or sell credits. Some requirements of the Registry protocols current at the time posed challenges to landowners. Notably, acceptance of a perpetual conservation easement was not made a pre-condition of participating in a WESTCARB afforestation pilot, and this requirement was eliminated in subsequent versions of the protocols. The decision whether or not to report afforestation projects to the Registry, and/or sell carbon credits, entails specific requirements and costs that were left to individual landowner decisions. Landowners would be educated and even encouraged to consider this process, but WESTCARB research results could be secured whether or not participating landowners choose to do so.
- Lands where afforestation was required under existing forest practice rules and regulations (e.g. re-stocking requirements) were not eligible. Such lands would not meet the regulatory additionality test of carbon markets/reporting systems. Lands that currently have a stocking violation under California PRC 4561 were also ineligible.
- Landowners had to be willing to allow periodic access by field teams to the afforested portion of their lands for measurement and monitoring.
- Landowners were asked to complete a brief annual survey and provide photo documentation as a means of documenting survival and performance of the afforestation pilot, for 10 years beginning with the year of planting.
- Landowners must have been willing to share costs of afforestation, in recognition of mutual benefits and to create a vested interest in maintenance of the projects. A general cost-sharing guideline of 75% WESTCARB /25% landowner was adopted, applied to

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[3] The WESTCARB Shasta Afforestation pilot projects were chosen and initiated according to version 1.0 of the California Climate Action Registry (CCAR) Forest Project Protocols (FPP). The current version of the FPP is 3.2, which is administered by the Climate Action Reserve (CAR) and differs from version 1.0 in numerous areas. More information is available on the CAR website: http://www.climateactionreserve.org/how/protocols/adopted/forest/development/.

operational costs (site preparation, brush disposal, seed and seedlings, planting, seedling protection, and early maintenance treatments). Actual cost-sharing levels differed from 25% for various reasons, but 25% was to be the starting point for negotiations.

- WESTCARB funded 100% of other costs to secure research results and help build capacity of landowners. These costs included the initial analysis, landowner outreach, surveys, project plans etc. summarized here; Registered Professional Forester (RPF) supervision of the afforestation process; baseline carbon stock measurements and carbon accumulation modeling. Costs of reporting and certifying afforestation projects on carbon registries, and/or entering into market transactions, were at landowners' discretion and so 100% borne by landowners.
- A minimum size (acreage) for afforestation pilot projects was considered. A general guideline of at least 20 acres was adopted, for reasons of cost-effectiveness considering economies of scale in site preparation and planting. However this was applied as a flexible guideline. Smaller projects offering unique benefits were considered and accepted, particularly if near to a larger project so that equipment move-in/move-out costs could be reduced.
- The eventual "portfolio" of WESTCARB afforestation pilot projects was intended to include a diversity of land types and project types, and as broad a geographic distribution across the county as possible. Thus, an effort was made to include lands at low, medium and high elevations, lands suitable for oak, oak/conifer, and conifer afforestation projects, and representatives of the diversity of site conditions created by the elevation, slope, climatic, vegetation and other gradients within Shasta County. However, because a core WESTCARB objective is demonstration of projects with relevance to the county, state, and region as a whole, project selection considered not only uniqueness but also replication potential.

2.3 Landowner outreach and education

Model-based analyses of site suitability for growing trees, carbon potential or cost indicate only which rangelands within Shasta County might successfully be converted for carbon purposes, or where within the county the most attractive regions for afforestation opportunities might be located. Moving to actual afforestation pilot activities, it was necessary to identify specific landowners and assess their level of interest and potential concerns about planting forests on a portion of their lands. Landowners must weigh the benefits of planting forests and/or participating in evolving carbon markets against the costs and resulting obligations.

To begin this dialogue, Winrock worked with the Western Shasta Resource Conservation District (RCD) to host a Shasta County Landowner Outreach & Stakeholders Meeting in Anderson, CA, October 26, 2006. Invitations to this meeting were sent to landowners, land managers, ranchers, foresters and other Shasta County stakeholders through flyers, e-mails, regular mail, and outreach via the RCD's watershed groups throughout the county. The meeting invitation and agenda are included in **Annex A**.

Following the October 26 meeting, Western Shasta RCD conducted follow-up meetings with landowners, and coordinated outreach via the RCD's watershed groups and partner agencies. RCD staff met with the Shasta-Tehama Shedhead Watershed Coordinator Group, Sacramento River Area Conservation Forum, and individual landowners to discuss afforestation opportunities. To collect additional data and identify specific candidate landowners, a relatively simple but formal landowner survey was developed. The survey format is shown in **Annex B**. Over 400 letters were mailed to Shasta County landowners inquiring about interest in participating in afforestation, and 44 landowners participated in the formal survey.

Landowners indicated a considerable uncertainty and lack of information about evolving climate change policy, carbon markets, and income potential from these projects. To respond to this need, Winrock prepared a document "Talking Points for Shasta County Landowner Survey: Carbon Credit Revenue Potential from Afforestation" for the RCD's use in conversations with landowners. The intent was to provide landowners some sense of the magnitude of carbon sequestration (tons CO_2 or "credits") that afforestation on their lands could generate over time, the range of possible prices, and how carbon markets and policy are currently evolving. The "talking points" emphasized that it is not possible to predict with confidence the evolution of markets, future prices, or even future performance of an afforestation project on any given piece of land, and that actual revenues available from afforestation, along with timing of such revenues, will be the result of bilateral negotiations between offset buyers and sellers.

Following landowner survey results and desk review of potential projects, Beaty and Associates and the RCD met with 20 landowners on their property to assess the sites, discuss landowner goals and pilot project objectives, and determine if a project was feasible. These meetings were vital in not only determining project feasibility, but also to begin forming understanding and trust between landowner and those implementing projects.

2.4 Identified planting sites

Table 1 and Figure 1 show the size and location of the pilot projects, along with the species composition that was planted.

Table 1. WESTCARB afforestation pilot projects

Project	Acres	Species Planted
Red River Forests Partnership	98	Ponderosa pine
Brooks Walker	7	Ponderosa pine & red fir
Hendrix-Phillips Tree Farm	20	Ponderosa pine
Goose Valley Ranch	60	Ponderosa pine, Douglas fir, incense cedar
Lammers	50	Ponderosa pine & Douglas fir
Frase	43	Ponderosa pine
Kloeppel	51	Ponderosa pine & Douglas fir
Sividas	46	Ponderosa pine
Eilers	20	Ponderosa pine & blue oak
Wilson	14	Ponderosa pine
Lakey	60	Ponderosa pine
BLM	7	Oak

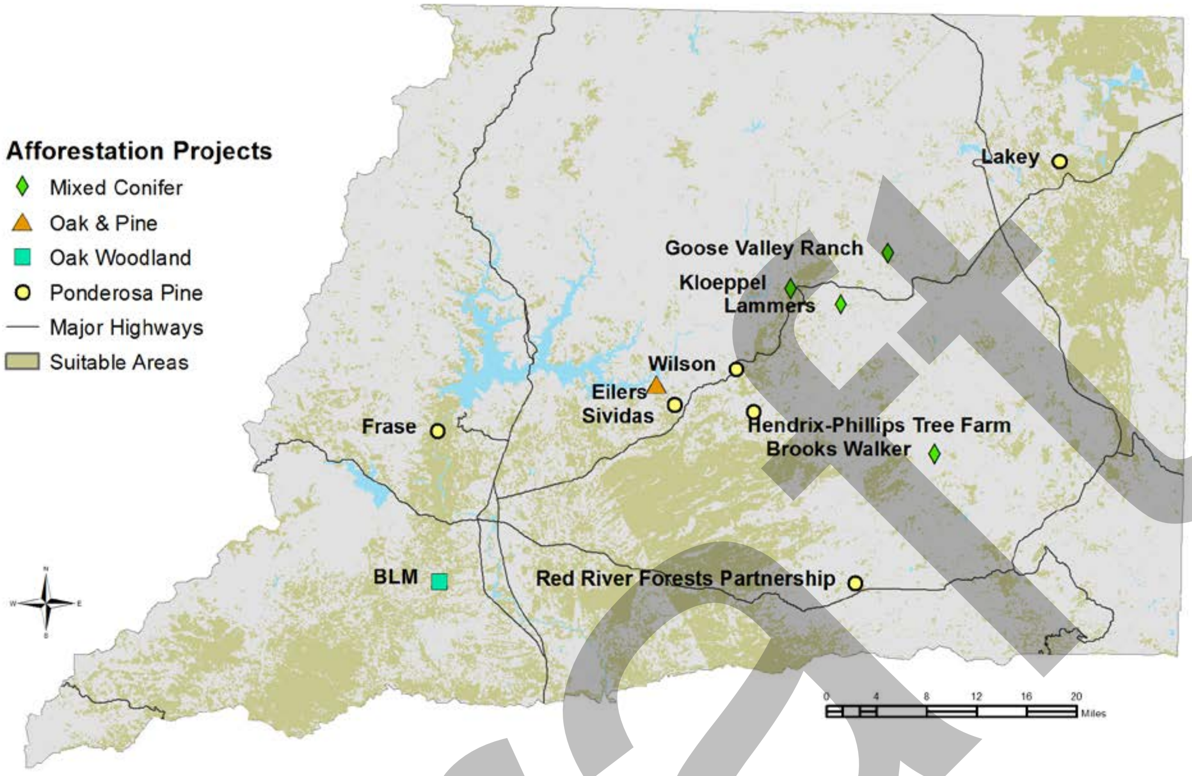

Figure 1. WESTCARB afforestation projects

3.0 Tree Planting Methods

3.1 Contract seed and seedlings

Generally, seedlings for conifer afforestation must be grown for at least a year prior to planting. Seed is purchased or collected, specific to the Seed Zone of the site to be planted, and delivered to a nursery for stratification[4], sowing, and growing under contract for a year or more. For example, for planting in spring 2008, seed and seedling arrangements with nurseries would need to be made in late fall 2006. This posed a significant implementation challenge. Due to contractual delays at the start of WESTCARB, the process of conducting landowner outreach and surveys, identifying specific sites, negotiating landowner agreements and drafting site-specific plans was only beginning in late 2006, at the same time seedlings should be planted in nurseries for successful spring 2008 planting. Because of the relatively long time required for site selection, landowner outreach and negotiation, specific afforestation pilot sites would be known and agreements signed by mid-2007 – at that point, too late to begin growing seedlings for spring 2008 planting (or, if seedlings were not specifically grown under contract for WESTCARB, to be guaranteed of adequate seedlings from nursery overstock).

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[4] Stratification is the exposure of a seed to a cold, moist treatment to overcome dormancy and promote germination.

Under these circumstances, Winrock made arrangements in fall 2006 with a nursery to grow seedlings using seed from a Seed Zone covering the areas of Shasta County where it was reasonably likely willing landowners could be identified. This decision necessarily limited the geographic and elevation range of sites that could be considered for spring 2008 planting to those appropriate to the Seed Zone chosen. Arrangements were made with the California Department of Forestry & Fire Protection for improved ponderosa pine seed from Seed Zone 522, NSTIA lot 1N, and with Cal-Forest Nursery in Etna, California to grow 40,000 Ponderosa pine seedlings in Styro 6 blocks. Western Shasta RCD and WM Beaty & Associates, Inc. were ultimately able to identify willing landowners matching the Seed Zone and number of seedlings being grown for 2008 planting.

A second round of afforestation sites for 2009 planting had considerably more flexibility because the entire process of site identification, site-specific planning, and negotiation with landowners took place in 2007 prior to the time (late fall 2007) when appropriate seed had to be delivered to nurseries to begin growing for spring 2009 planting. These "Round Two" afforestation sites were more broadly distributed, in geographic location and elevation, representing a broader range of Seed Zones and site conditions.

Oak afforestation projects do not necessarily require this long lead-time because oaks can be successfully direct-seeded from acorns collected the previous fall, though not every season produces a viable acorn crop. There were two projects that included oak planting, both of which were initially planted in early 2009.

3.2 Planning for tree planting

3.2.1 Site-specific plans

Site-specific afforestation planting and maintenance plans have been developed by a Registered Professional Forester (WM Beaty & Associates) for each of the candidate afforestation sites. These site-specific plans include details of location, acres available and suitable for afforestation, road access, any easements, utilities or sensitive areas, soil types, precipitation, seed zone, slope, aspect, site class, current vegetation conditions, a step-by-step plan for site preparation, planting, chemical and mechanical treatments, and estimated costs.

Development of such a plan involves a substantial time investment including site visits by the RPF. However, without a site-specific plan and cost estimates, it is difficult to enter into specific negotiations on a landowner agreement. Therefore of the landowners initially contacted and the subset (44) who had active enough interest to participate in the formal survey, a further subset were chosen, based on the criteria above and their demonstrated willingness to consider a cost-shared afforestation agreement, to receive site-specific plans. These plans were then incorporated into landowner agreements described below. All the site-specific afforestation planting and maintenance plans developed are included in **Annex C**.

3.2.2 Prepare NEPA documentation

The WESTCARB Phase II terrestrial pilot activities in Shasta and Lake Counties in December 2006 received a determination by the US Department of Energy NEPA Examiner that "the proposed action falls under one or more of the categorical exclusions listed in Appendix A or B of Subpart D of the DOE NEPA Implementing Procedures" (10 CFR Part 1021). However, the Shasta County afforestation pilot projects were excluded from this determination because at the time, specific sites had not been identified and it was not possible to make a determination on potential environmental impacts. Instead, USDOE requested to receive site-specific information on each afforestation pilot site as these were identified, in the format of the original USDOE Environmental Questionnaire provided for the project as a whole.

Winrock therefore, with assistance from Western Shasta RCD, prepared site-specific Environmental Questionnaires for each of the proposed afforestation pilot sites. These questionnaires describe the proposed project and any environmental impacts including land use, construction activities and/or operation, geological/soil conditions, vegetation and wildlife resources, socioeconomic and infrastructure conditions, historical/cultural resources, visual resources, atmospheric conditions/air quality, hydrologic conditions/water quality, soil and hazardous wastes, health/safety factors, and environmental restoration and/or waste management. In general, afforestation has minimal or positive environmental impacts; any significant impacts on soil conditions, vegetation and wildlife resources, or historical/cultural resources can be avoided and/or mitigated by simply flagging and avoiding sensitive areas, shifting project boundaries, or if necessary dropping the proposed afforestation pilot site in favor of another site without such potential impacts.

3.2.3 Draft and negotiate landowner agreements

Through the process of landowner outreach (>400 landowners) and formal surveys (44 landowners), a smaller number of landowners were identified who met the selection criteria described in section 2.2, were willing to share costs, and demonstrated continued commitment through multiple conversations and site visits, suggesting a high probability that they would be willing to commit to hosting a WESTCARB afforestation pilot project. For these landowners, site-specific afforestation planting and maintenance plans and cost estimates were incorporated into draft agreements provided to landowners for review and signing.

3.3 Baseline carbon stocks

Field crews composed of Winrock and Western Shasta RCD personnel implemented baseline carbon stock measurements on all WESTCARB afforestation pilots, prior to the removal of existing vegetation for site preparation. All of the sites which were cleared in summer/fall 2007 for spring 2008 planting were initially in various types of brush. Field crews visited each afforestation unit and established between five and eleven measurement plots at random distances and bearing from a starting point. Measurement plots were either of radius 2 m for very dense brush or 4 m for less dense brush. At each plot location, for each shrub originating within the plot radius, crews recorded number of stems, stem basal diameter, height, two crown diameters (N-S and E-W), and species.

A literature search revealed that no appropriate allometric equations exist to determine shrub biomass. It was concluded that conducting destructive sampling in the specific areas of the pilot project would yield the most accurate estimates of shrub carbon. In the field, individual shrubs were randomly selected and the number of stems was counted and the basal diameter recorded for each stem, along with height, and canopy diameter in two directions. Approximate canopy volume was calculated using the volume formula for a cone and the height and average canopy diameter. The shrub was then cut at the base and the wet weight of the entire shrub was recorded. A representative subsample of each plant was bagged, weighed, and shipped to a laboratory for dry weight. Using the data gathered from this destructive sampling across a number of the pilot sites in Shasta County, regression equations for Manzanita shrubs and non Manzanita shrubs were developed using as predictors average basal area and canopy volume.

The regression equation for aboveground biomass of Manzanita ($r^2 = 0.91$, n=47) is:

$$y = 3.96 + 0.06(ABA) + 1.09(CV)$$

Where
Y = biomass in kilograms,
ABA = Average Basal Area, and
CV = Canopy Volume.

For non Manzanita shrubs – primarily Buckbrush, Whitethorn, and Deerbrush – the regression equation for aboveground biomass ($r^2=0.65$, n=53) is:

$$y = 5.52 + 0.60(CV)$$

Where
Y = biomass in kilograms, and
CV = Canopy Volume.

Because time constraints allowed relatively few measurement plots, the baseline carbon estimates have a high uncertainty. Based on the variability in the plots, in all cases additional measurement plots would have been required to attain a 90% confidence interval within 10% of the mean. While some projects may have required as few as 15 baseline plots, others would have required as many as 72, with most projects requiring more than 30. This number of plots would not have been cost-effective, or feasible without delaying site preparation, and this is likely to true of many shrublands. Based on the number of plots measured per site, the 90% confidence interval ranged from 14% of the mean to 26% of the mean. Because of this level of uncertainty, the upper bound of the 90% confidence interval was used as the estimate of baseline carbon stocks. This yields a conservative estimate of net carbon sequestration through afforestation, since it would tend to overestimate baseline carbon stocks.

3.4 Site preparation, planting, and early maintenance

The site-specific planting and maintenance plans for each WESTCARB afforestation pilot project included a series of steps spanning two years or more. Plans varied slightly by project, but in general involved:

- Purchase of seed from CAL FIRE or private inventories of Sierra Pacific Industries and W.M. Beaty & Associates, Inc. if CAL FIRE inventory did not include seed suitable for a particular zone, elevation, and species.
- Contract with nursery to stratify and sow seed and grow conifer seedlings.
- Mechanical site preparation to masticate or remove or reduce existing vegetation that would prevent establishment of trees due to physical access for planters as well as moisture, light or nutrient competition;
- Disposal of brush through pile-burning, or alternately grinding and removal to a biomass energy facility (see Section 3.5);
- Chemical site preparation either immediately before or immediately after planting;
- Lifting of seedlings at the nursery and cold storage until planting;
- Planting at 150 to 300 trees per acre;
- Where needed, installation of seedling protectors or netting;
- Where needed and feasible within the term of WESTCARB, post-planting follow-up chemical applications to control competing vegetation and promote seedling survival.

The 20-acre Eilers pilot involved afforestation with a mixture of conifer and oak species and the 7-acre BLM project involved strictly afforestation with oak species.

3.5 Biomass energy

Two different approaches to disposal of the existing brush were explored under the WESTCARB afforestation pilot projects:

1. Brush piling and burning. This is the conventional and often the only feasible approach for brush disposal in "brush-conversion" afforestation projects. In the context of a carbon sequestration project where the intent is to monitor and implicitly maximize GHG benefits, this approach basically emits immediately to the atmosphere all the carbon stocks of the baseline vegetation.

2. Grinding and removal to a biomass energy facility of the brush that is removed prior to planting. This alternative would still emit as CO_2 the carbon contained in the brush (simply at a different location, at the biomass plant rather than at the afforestation site), but would have a better overall GHG balance. Efficient and complete combustion at the biomass plant would likely release less non-CO_2 GHGs than pile-burning; and electricity generated from biomass would offset generation of electricity using fossil fuels reducing the net emission The choice of the baseload power alternative, and the assumed GHG intensity of that alternative, would affect the net GHG benefits of removing brush for biopower generation instead of the more conventional pile-burning.[5]

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[5] For example, 1,100 pounds CO_2e per megawatt-hour, for a relatively efficient combined cycle natural gas turbine plant, per the California Public Utilities Commission's Interim Greenhouse Gas Emissions Performance Standard (SB1368; see http://www.cpuc.ca.gov/static/energy/electric/climate+change/070411_ghgeph.htm); or a higher GHG

Under the afforestation pilot, both alternatives were explored. Grinding and removal for biomass energy production is unfortunately significantly more complex and costly than conventional pile-burning. The following represents the requirements for consideration of a site for biomass extraction:

A. There must be a sufficiently large project area, type and quantity (tons per acre) of brush to justify the move-in/out costs of additional equipment (excavator, tub grinder, chip van(s), and water truck).

B. The site must be close enough to a biomass energy facility to make removal cost-effective considering transport costs and the price of diesel fuel, and have suitable road access to and within the afforestation unit to allow chip vans and other equipment that may not be able to negotiate sharp turns or rough roads.

C. Because of additional temporary roads and landings required for the grinder and chip vans, the approach requires mitigation (post-grinding sub-soiling of temporary roads) and management of environmental impacts, which are easier if site topography is relatively flat.

D. Finally, the technique used for clearing, piling, and grinding must produce piles significantly freer of soil and debris than if the plan is pile-burning. Piles with a substantial amount of soil created through mechanical site preparation can be burned, effectively and in compliance with all necessary permits and air-quality regulations, but the same pile put into a grinder and transported to a biomass energy plant may cause problems for the life of the grinding equipment, combustion at the plant, or fugitive emissions at the plant. This problem can be partially mitigated by having a water truck (at added cost) to control fugitive emissions from roads and grinding at the project site, and from unloading at the biomass plant, but a pile with too much soil will still cause problems for fuel handling and combustion.

Because the approach is unconventional, unfortunately there are relatively few contractors with the equipment and expertise necessary to control all these variables, producing a clean afforestation site ready for planting, and clean fuel delivered to the plant, at reasonable cost. However, where possible the approach was considered in each of the pilot projects.

3.6 Planting data collection

3.5.1 Data on costs

Phase I economic analyses of afforestation relied on very general conversion cost estimates. These cost estimates were refined in Phase II by gathering information on real-world and site-specific estimates of conversion costs from each of the pilot projects (mechanical and chemical site preparation, brush disposal, seedling growing, planting, seedling protection, and post-planting early maintenance). Cost estimates for each of these steps in the process were prepared

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intensity if one assumes that megawatt-hours not available from biopower would have to be replaced by increased imports of coal-fired electricity.

by an RPF, including consulting California Forest Improvement Program (CFIP) cost guidelines for reforestation and estimating site-specific costs for each proposed site. These cost estimates were the basis for negotiating prices with the afforestation subcontractor. The final actual costs of implementing each project were used to develop a range of costs for afforestation projects in Shasta County.

3.5.2 Modeling carbon accumulation

Earlier Winrock analyses have suggested that afforestation with mixed conifer may be able to accumulate around 170 t C/ha (252 t CO_2/acre) over 40 years, while lower-elevation Shasta County rangelands suitable for afforestation primarily with oaks and foothill pine might produce carbon at 40 years in the range of 26-50 t C/ha (39-74 t CO_2/acre) (Brown et al 2007).

Clearly WESTCARB Phase II, lasting only through fall 2010, does not provide sufficient time for direct monitoring of carbon accumulation in the afforestation pilots. Only the initial success of the pilots, in terms of establishment and early survival, can be monitored directly. Therefore for each of the WESTCARB afforestation pilots, quantities of carbon accumulation into the future were projected using a growth model with data specific to that pilot site.

Growth of conifers and/or hardwoods on the pilot projects was modeled using the US Forest Service Forest Vegetation Simulator (FVS). FVS is an individual-tree, distance-independent growth and yield model (Dixon 2002). It has numerous geographic variants and allows the user to project growth using Jenkins equations (Jenkins *et al.*, 2003) or localized Forest Service equations. The Fire and Fuels Extensions (FFE) of FVS can be used to determine forest biomass and the tons of CO_2 sequestered in the forest over a project lifetime. Growth for each pilot project was modeled for a 100-year period, using the Inland California and Southern Cascades variant and Jenkins equations[6], and future carbon stores were determined using FFE.

3.5.3 Evaluation of early performance of afforestation pilots

WESTCARB Phase II allowed 2.5 years' monitoring (for afforestation projects planted in spring 2008) or 0.5 years (for spring 2010 plantings). For the 2008 plantings, this time frame made it possible to observe how projects fared over two winters and most of three growing seasons, including the ability to monitor the need for post-planting chemical weed control in 2009 and 2010. For the 2009 plantings, Phase II allowed observation of one winter and most of two growing seasons, while for the 2010 planting, only one growing season passed prior to project end. Based on information received from landowners and periodic assessment of the project areas, additional maintenance was conducted where funding was available. In the late summer of 2010, WM Beaty and Associates conducted surveys of survivorship on all of the pilot projects.

To extend the availability of monitoring data somewhat, WESTCARB landowner agreements request that all participating landowners complete annual surveys and photo documentation

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[6] Specific carbon registries may have different requirements for which allometric biomass equations are allowed, but the Jenkins equations are commonly accepted as predictors of tree biomass (the Climate Action Reserve Protocols, v.3.2 do not allow the use of Jenkins equations, but the protocol version that was available at the initiation of these pilot projects (v.1.0) did allow their use).

for 10 years from the date of planting. These data will be compiled and archived at Western Shasta RCD, for analysis by WESTCARB partners or others pending availability of funding. The format of this annual survey is included in **Annex D**.

4.0 Details of Afforestation Pilots

4.1 Red River Forests Partnership

The Red River Forests Partnership WESTCARB Project is a 98-acre ponderosa pine afforestation project on lands owned by the Red River Forests Partnership and managed by WM Beaty & Associates, Inc. The site is at 3,880′ elevation, east of Shingletown, Shasta County, California (T31N, R01E, Section 24) (**Figure 2**). The lands to be afforested were occupied by brush, mostly greenleaf manzanita with some *Prunus* (**Figure 3**). The site can support vigorous ponderosa pine growth provided brush, which competes aggressively for limited summer soil moisture and light, is controlled during establishment and early growth phase. Access is excellent via paved county road to unit (less than one mile from State Hwy 44). Soils at this site consist of Windy and McCarthy Stony Sandy Loam, depth 40-60″; well drained, moderate to high permeability. Site class is estimated III Dunning.

Figure 2. Aerial photo of the 98-acre Red River Forests Partnership afforestation site, with blue outline

Site preparation by mechanical clearing of brush was completed in July through September 2007 (**Figure 3**). In March-April 2008, ponderosa pine seedlings grown by Cal-Forest Nursery were planted at 300 trees per acre. In spring-summer 2009, the project was treated with a follow-up directed foliar release (weed control) spray by handcrews.

Figure 3. Baseline conditions at Red River Forests Partnership site (top) and site preparation in August 2007.

Brush removal

Two different approaches to disposal of the existing brush were explored at the Red River Forests Partnership project. In the original plan, brush was to be piled and burned in fall 2007. However, the Red River project met each of the criteria outlined in Section 3.5 for consideration of removal of brush for biomass energy generation.

The Red River Forests Partnership project represented a relatively large project, very heavy and decadent manzanita brush (1 or more chip van loads per acre), flat terrain, excellent access via paved roads directly to the unit, about 30 miles total distance to the Wheelabrator Shasta biomass energy plant, a land manager willing to experiment with the process as long as the site was left ready for planting and any temporary roads or landings mitigated, a grinding contractor willing to grind and transport brush piles to Wheelabrator for the price Wheelabrator would pay for the fuel, and most significantly, the willingness of afforestation contractor Total Forestry to take on the added cost and risk of piloting this procedure.

Figure 4. Grinding and removal of brush from Red River Forests Partnership site to Wheelabrator Shasta biopower plant

Grinding and removal was ultimately only partially successful at this site. Brush was piled in windrows for the grinding contractor to remove with a tub grinder pulled along the pile or the pile brought to the grinder. Fugitive emissions during this process were controlled by a water truck. The grinder was able to produce clean fuel from the top of these windrows, but the lower part of the windrows was found to have too much soil for successful grinding or for fuel acceptable to Wheelabrator. Grinding production rates suffered when water needed to control dust from roads was not available to control dust emissions from grinding of piles, leading to a lower production rate and less cost-effective operation for the grinding contractor. As a result some fuel was produced and delivered to Wheelabrator, but the remaining brush had to be pile-burned in the conventional manner to leave the site ready for planting.

This was a learning process for Total Forestry, Winrock, Wheelabrator and the land manager WM Beaty & Associates. Grinding and removal could still be considered for future afforestation projects where the criteria suggested above are met. The option of brush grinding and removal was considered on a case-by-case basis for the other pilot projects, and was implemented on one other project, but at such high cost that replication potential is questionable.

Even if only partially successful, the exercise at Red River Forests Partnership provided valuable information from a research perspective on technical feasibility, site conditions, costs, and approach. To the extent afforestation of brush fields, demonstrated through research funds under WESTCARB, is taken up by landowners as a carbon offset or climate mitigation opportunity, it is important to demonstrate techniques and constraints on this activity. If afforestation for carbon becomes a significant opportunity adopted by a large number of landowners, this may promote additional investment in grinding and removal equipment by businesses developing expertise in these techniques, leading ultimately to improved results and lower costs.

Survival Monitoring

The project area was surveyed on August 30, 2010 with 50 1/100th acre plots. The survey found 328 ponderosa pine seedlings per acre. A possible reason for more trees per acre in 2010 than were planted in 2008 is likely that net acres are actually less than 98 acres due to small rocky areas, unburned brush piles and roads used for biomass operations that did not get planted but were not counted as plots when they were encountered in the survey.

Costs

The total cost of afforestation at this site was $81,532 or $832/acre. This cost includes mechanical site preparation ($503/acre); seedlings ($61/acre); planting costs ($101/ac); and post-treatment spraying ($167/ac).

The grinding and removal approach to brush disposal involved added costs, for a water truck and post-project removal (sub-soiling) of temporary roads and landings. This increased the combined cost of mechanical site preparation and brush disposal (pile burning / grinding and removal).

Baseline carbon stocks

Based on data from 8 measurement plots installed prior to clearing manzanita brush at the Red River Forests Partnership site, baseline carbon stocks in brush are estimated at a mean 42.6 t C/ha (63.3 t CO_2/ac) with a standard error of 3.8 t C/ha and a 90% confidence interval of 17% of the mean. The variability in this data indicates that 23 plots would be needed to attain a 90% confidence interval of 10% of the mean. The upper bounds of the 90% confidence interval is 51.5 t C/ha (31 t C/ac).

Projected growth and carbon benefits

Growth was modeled in FVS over 100 years, based on the survival count done in August 2010, with 300 ponderosa pine trees per acre planted in 2008, a 99% survival rate, and 30 ponderosa pine trees per acre naturally regenerated. Table 2 shows growth and carbon stocks for a 100 year period, starting in year 10.

Table 2. 100-year growth projections on Red River Forest Partnership 2008 planting

Year	Trees per acre	Board feet/ac	Total C stocks/ac	Net C stored/ac	CO_2 stored/ac	Total CO_2
2018	328	0	5	-16	-59	-5,739
2028	322	0	11	-10	-37	-3,626
2038	316	2,434	26	5	18	1,734
2048	316	6,465	41	21	75	7,369
2058	278	11,344	55	34	126	12,366
2068	246	15,649	68	47	172	16,883
2078	218	18,624	77	56	205	20,092
2088	179	21,350	84	63	232	22,739
2098	149	23,769	90	69	253	24,759
2108	126	25,936	94	73	268	26,296

Grinding and removal of brush, in place of pile burning, would displace some fossil fuel emissions from electricity generation and produce a small added benefit. If this were successfully implemented on the project as a whole, brush of about 10 bone dry tons (BDT) per acre on 98 acres might yield 980 MWh of electricity at a biopower plant. Assuming this quantity of electricity would otherwise come from fossil fuel alternatives and assigning it a GHG intensity of 1,100 pounds CO_2e per MWh, the project would deliver an additional 489 tCO_2e from fossil fuel emissions displacement. This benefit would accrue in the initial year of site preparation and brush removal, whereas the much larger carbon sequestration benefits accrue over 40 years.

4.2 Brooks Walker Jr, et al

The Brooks Walker, Jr. et al WESTCARB project is a 7-acre mixed conifer afforestation project on lands owned by Brooks Walker, Jr. et al and related trustees, and managed by WM Beaty & Associates, Inc. The afforestation site, called the Table Mountain brushfield, is at 5,440′ elevation in eastern Shasta County, California (T33N, R02E, Section 36 south ½) (**Figure 5**). The lands to be afforested are currently dominated by brush, mostly greenleaf manzanita with some snowbrush and Fremont silktassle. The site can support ponderosa pine, red fir and Douglas fir growth provided brush, which is competing aggressively for limited summer soil moisture and light, is controlled during establishment and early growth phase (**Figure 6**). Access is via seasonal dirt logging roads, ¼ mile from site. Soils at this site consist of Nanny Gravelly Sandy Loam & Windy & McCarthy very stony sandy loam. Site class is estimated III Dunning.

Figure 5. Aerial photo of the 7-acre Brooks Walker afforestation project, with white outline

Site preparation by mechanical clearing of brush began in September 2007. Brush disposal at this site was by conventional pile-burning, in fall 2007, as the site is too distant and access too difficult to permit consideration of removing brush to a biomass energy facility. In fall 2007, crews conducted an initial hand application of pre-emergent Velpar DF spray to keep brush, forb and grass seeds from germinating and competing with seedlings. In April-May 2008, ponderosa pine and red fir seedlings were planted at approximately 300 trees per acre. In spring-summer 2009, the project was treated with a follow-up directed foliar release (weed control) spray by handcrews.

Survival Monitoring

The Brooks Walker project was surveyed for survival on August 30, 2010 with 21 1/100th acre plots. The survey found 225 ponderosa pine trees per acre and 40 red fir trees per acre, for an 88% survival rate. In addition, there were 5 Jeffrey pine tree per acre, which had seeded in naturally.

Costs

The total cost of afforestation at this site was $8,854 or $1,265/acre. This cost includes site preparation, including slash disposal and spraying ($1,115/ac); seedlings ($71/ac); and planting ($79/ac). The project is relatively expensive compared to other WESTCARB afforestation pilots, due to the remote location and small project size. Unlike the larger projects, it provided an opportunity to test afforestation at relatively high (for Shasta County) elevation.

Baseline carbon stocks

Based on data from 5 measurement plots installed prior to site preparation at the Brooks Walker project site, baseline carbon stocks in brush are estimated at a mean 5.8 t C/ha (8.6 t CO_2/ac), with a standard error of 0.6 t C/ha and a 90% confidence interval of 23% of the mean. The variability in this data indicates that 27 plots would be needed to attain a 90% confidence interval of 10% of the mean. The upper bounds of the 90% confidence interval is 7.4 t C/ha (3 t C/ac).

Figure 6. Baseline conditions on the Brooks Walker project. Note heavy brush in foreground, timber in background, indicating growth potential.

Projected growth and carbon benefits

Growth was modeled in FVS over 100 years, based on the survival count done in August 2010, with 180 ponderosa pine (100% survival) and 120 red fir (33% survival) planted per acre in 2008, and 45 ponderosa pine and 5 Jeffrey pine trees per acre naturally regenerated. Table 3 shows growth and carbon stocks for a 100 year period, starting in year 10.

Table 3. 100-year growth projections on the Brooks Walker 2008 planting

Year	Trees per acre	Board feet/ac	Total C stocks/ac	Net C stored/ac	CO_2 stored/ac	Total CO_2
2018	270	0	5	2	7	47
2028	264	0	9	6	22	154
2038	259	2,290	24	21	77	539
2048	251	6,088	40	37	136	950
2058	217	11,260	55	52	191	1,340
2068	197	15,888	68	65	238	1,663
2078	179	20,471	79	76	279	1,951
2088	151	23,540	89	86	315	2,208
2098	130	26,410	97	94	345	2,413
2108	114	29,013	103	100	367	2,567

4.3 Hendrix-Phillips Tree Farm

The Hendrix-Phillips Tree Farm WESTCARB project is a 20-acre ponderosa pine afforestation project on lands owned by the First Descendants of the Phillips Family Trust. The afforestation site is at 2,200′ elevation near Oak Run in Shasta County, California (T33N, R1W, Section 16 southwest ¼) (**Figure 7**). Current vegetation is scattered trees (black oak, grey pine & ponderosa pine), brush (primarily whiteleaf manzanita with some greenleaf manzanita, buckbrush, buckeye and poison oak), and some forbs and grasses. The area can support good ponderosa pine growth provided brush, which is competing aggressively for limited summer soil moisture and light, is controlled during establishment and early growth phase. Access is via seasonal dirt road into unit, a few miles from a paved county road. Soil types include Aiken Stony Loam: loam, deep (60″+) well drained, rocky; Aiken Loam: loam, deep well drained, not rocky; Cohasset Stony Loam: 48″-60″ deep, well drained; Supan very Stony Loam: 24-40″ deep, very stony. Site class is II to IV Dunning.

Site preparation by mechanical clearing of brush began in October 2007. Brush disposal by grinding and removal to a biomass energy facility was considered at this site, but ultimately not considered cost-effective due to quoted prices of $700-800/acre for mechanical site preparation and brush removal. Therefore brush disposal was by pile-burning in fall 2007. Prior to planting, crews broadcast by hand pre-emergent Velpar DF spray to keep brush, forb and grass seeds from germinating and competing with seedlings. In late February 2009, crews planted 6,000 containerized ponderosa pine seedlings, at 300 trees per acre, and installed mesh netting to protect seedlings. In spring 2009, crews sprayed re-sprouting poison oak that otherwise would have overtopped the conifer seedlings.

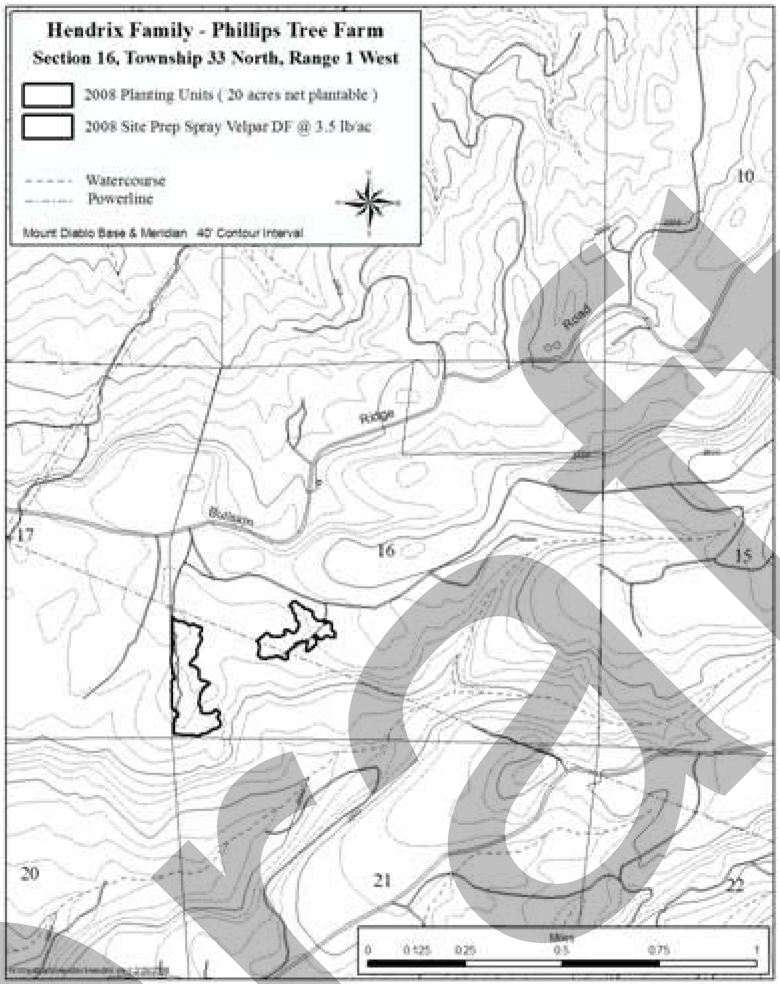

Figure 7. Map of the 20-acre Hendrix-Phillips Tree Farm WESTCARB afforestation pilot project

Perpetual conservation easement

One of the unique features of this WESTCARB afforestation pilot is that the landowner has for some time managed the entire ownership (approximately 1,000 acres, including the 20-acre afforestation site) under a perpetual conservation easement managed by the Pacific Forest Trust. Unlike many private landowners for whom the Climate Action Reserve's (California Climate Action Registry's) previous forest protocol requirement of a perpetual easement presented a significant barrier to participation, the Phillips Family Trust had the ability to proceed through the entire process of entity- and project-level reporting to the Registry, third-party certification, and even selling carbon "credits" produced by their afforestation activity to a willing buyer. The 20 acre brushfield, which is now a plantation/forest, was included in a CAR Conservation Forestry Project (called Improved Forest Management or IFM by the current protocols). Cost for registering and certifying just the 20 acres for an afforestation project would have cost more than revenue generated, so they likely would not have proceeded with a reforestation project on that 20 acres alone even though they met the conservation easement requirement.

Survival Monitoring

On August 12, 2010, twenty 1/100th acre plots were sampled with the following results: 280 ponderosa pine trees per acre are very well distributed throughout the project area (Survival after two years = 90%). All of 20 plots were stocked with at least one ponderosa pine. Most of the mortality occurred in the first growing season (summer of 2009) and most of the surviving trees are very healthy and vigorous (e.g. good stem caliper, buds and needle color and length for two year old seedlings). The high survival rate occurred despite precipitation levels at 14% of normal during the first year of seedling establishment. Scattered throughout the entire project area are one and two year old ponderosa pines that seeded in as a result of the project activities (clearing and competing vegetation control). In the eastern unit one & two year-old gray pine seedlings also seeded in (~150 trees per acre) as a result of project activities. Most of the project area is also occupied by grasses, forbs and 6 month old whiteleaf manzanita that germinated in 2010. Some poison oak has re-sprouted and is scattered throughout the project area. There a few small areas that have been invaded by yellowstar thistle.

Suggested potential future activities

To prevent the growth of brushy fuel loads and to maintain conifer vigor and health, a directed foliar spray application on the seedling whiteleaf manzanita should be conducted in the spring of 2011 or spring of 2012, prior to conifer bud elongation. Manzanita can be controlled with 2% LV4 (ester formulation of 2,4D) or with 5% glyphosate product (e.g. Razor) plus 3% to 5% methylated seed oil surfactant. In conjunction with this treatment yellowstar thistle could be treated with a low rate of Transline in the mix (¼%). In the summer of 2011 or 2012 re-sprouting poison oak should be treated with 3% to 5% glyphosate product plus 1% surfactant. During any of these treatments spray contact on the ponderosa pine seedlings must be avoided. In approximately 6 to 8 years (2016-2018) a pre-commercial thinning treatment will likely be needed to reduce stocking levels to approximately 170 trees per acre, leaving the most vigorous ponderosa pine at 16 foot by 16 foot spacing. Please note that these are suggested possible future treatments, and it is necessary to obtain a specific recommendation for spraying from a licensed Pest Control Advisor prior to any treatment. Also to prior to pre-commercial thinning a registered professional forester (RPF) should be consulted.

Costs

The total cost of afforestation at this site was $24,453 or $1,223/acre. This cost includes site preparation including brush disposal ($560/ac); seedlings ($60/ac); planting costs including first follow-up chemical application (385/ac); and additional follow-up spraying ($218/ac). The project is relatively expensive compared to other WESTCARB afforestation pilots, due to the location and relatively small size.

Pursuing brush grinding and removal on this project would have increased the cost of mechanical site preparation and brush disposal by at least $235/acre, and increased the total project cost to $30,158.

Baseline carbon stocks

Based on data from 10 measurement plots installed prior to site preparation at the Hendrix-Phillips project site, baseline carbon stocks in brush are estimated at a mean 49.4 t C/ha (73.3 t CO_2/ac), with standard error of 4.5 t C/ha and a 90% confidence interval of 17% of the mean. The variability in this data indicates that 28 plots would have been needed to attain a 90% confidence interval of 10% of the mean. The upper bounds of the 90% confidence interval is 59.4 t C/ha (24 t C/ac).

Projected growth and carbon benefits

Growth was modeled in FVS over 100 years, based on the survival count done in August 2010, with 300 ponderosa pine planted per acre in 2008, and a 93% survival rate. Table 4 shows growth and carbon stocks for a 100 year period, starting in year 10.

Table 4. 100-year growth projections on the Hendrix Phillips Tree Farm 2008 planting

Year	Trees per acre	Board feet/ac	Total C stocks/ac	Net C stored/ac	CO_2 stored/ac	Total CO_2
2018	279	0	5	-19	-70	-1,408
2028	274	0	10	-14	-51	-1,029
2038	269	2,452	24	0	0	-2
2048	250	6,310	39	15	55	1,098
2058	220	10,883	52	28	103	2,051
2068	201	14,998	64	40	147	2,931
2078	176	18,618	73	49	180	3,591
2088	146	21,607	81	57	209	4,178
2098	126	23,525	87	63	231	4,618
2108	110	25,814	91	67	246	4,911

4.4 Goose Valley Ranch

The Goose Valley Ranch WESTCARB project is a 60-acre mixed conifer afforestation project on lands owned by the Denny Land & Cattle Company – Goose Valley Ranch, LLC. The afforestation site is at 3,680′ to 3,900′ elevation, north and west of Lake Margaret, approximately 5 miles west of Burney, Shasta County, California (T35N R2E Section 8 - NE½ of NE¼; NE¼ of NW¼; SE¼ of NW¼; NE¼ of SW¼) (**Figure 8**).

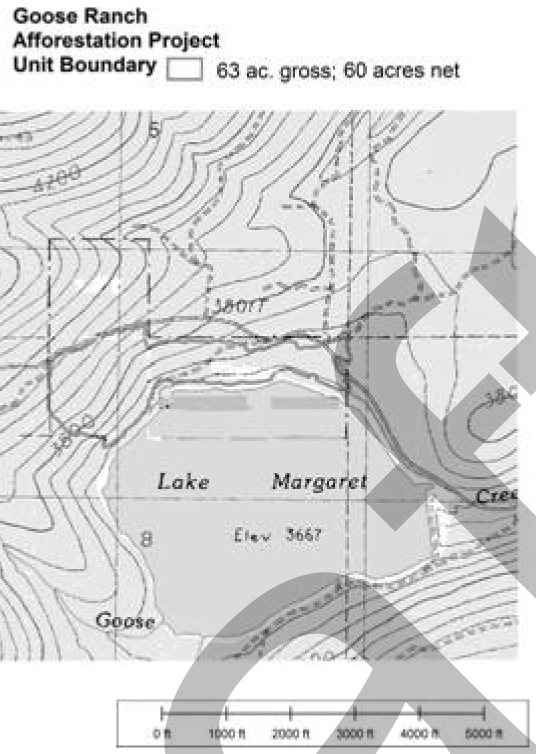

Figure 8. Map of the 60-acre Goose Valley Ranch afforestation project

The site was dominated by thick brush, primarily *Ceanothus cordulatus* (whitethorn), approximately 5’ high, 15+ years old, with some bracken fern, manzanita, squaw carpet, gooseberry, and some grasses and forbs (**Figure 9**). There was an estimated 2-10% cover of scattered black oak and willow trees. Soils include Depner Gravelly Sandy Loam (on approximately 30 acres) and Wyntoon Sandy Loam (on approximately 30 acres in N½ of NE¼). Site class is Dunning site II / CACTOS site index 74. Afforestation in ponderosa pine, Douglas fir and incense cedar should be successful, considering the soils, site class and performance of these species on adjacent parcels, provided that brush that is competing aggressively for limited summer soil moisture and light is controlled during the establishment and early growth phase.

Figure 9. Baseline conditions at Goose Valley Ranch site (left) and ponderosa pine and incense cedar 30 months after planting and control of competing vegetation (right)

Site preparation by mechanical clearing of brush began in October 2007. Brush disposal by grinding and removal to a biomass energy facility was considered at this site, but ultimately not pursued, due to a combination of cost (quoted prices of over $650/acre for mechanical site preparation and brush removal) and potential ground impacts on slopes near Lake Margaret. Therefore brush disposal was by pile-burning. In March 2008, the 60-acre site was planted at 290 trees per acre with 13,000 ponderosa pine, 2,200 Douglas fir, and 2,200 incense cedar seedlings grown at the Cal-Forest Nursery. Planting was followed in spring 2008 by a directed foliar spray application by hand crews to control competing vegetation and allow seedlings to become established. Following the planting, the project area was sprayed with Round-Up, based on the landowner's desire to avoid use of a heavier herbicide. However, there was significant return of understory brush vegetation, which required application of stronger herbicides in the summer of 2009 in order to ensure survival of the tree seedlings.

Afforestation on past fire sites

One of the unique features of the Goose Valley Ranch pilot is the opportunity to conduct afforestation on sites that have burned in past wildfires and returned to persistent brush rather than forest. This is known as the "brush-and-burn" cycle in Shasta County; unless salvage logging and reforestation is conducted immediately after a severe fire, as is often done by the forest industry, burned lands tend to be occupied by brush, which excludes the natural regeneration of conifers. Once established, the brush vegetation state endures for many years or decades, and/or because brush also poses a very high fire risk, may burn again before conifers are able to re-colonize the site and eventually grow through and out-compete the brush. The same phenomenon was noted in earlier Winrock analyses, where areas classified as rangeland but surrounded by classified forest land were shown to match precisely with past fire perimeters (Brown et al 2007). These lands are likely misclassified as rangelands, since they are not suitable for any sort of grazing, and may instead represent the sort of arrested succession to forest implied in the "brush-and-burn" cycle. Winrock analyses identified these lands as a special sort of afforestation opportunity, where opportunity costs to landowners might be low or zero (no foregone forage production), but assumed high conversion costs might more than overwhelm this advantage.

Several WESTCARB afforestation pilots present an opportunity to afforest such lands. In the case of Goose Valley Ranch, the project site is a brushfield burned in the 1992 Fountain Fire. Immediately adjacent lands owned by Sierra Pacific Industries were reforested following the fire, but smaller private landowners generally lack the resources for reforestation. The neighboring SPI lands however illustrate what afforestation on this site (similar conditions and soils) could produce over 15 years (**Figure 10**).

Figure 10. Sierra Pacific Industries lands neighboring the Goose Valley Ranch site, illustrating potential conifer growth on these lands over 10-15 years.

A potential added GHG benefit is that WESTCARB/landowner-funded actions to convert brush back to forest will have the effect of reducing fuel loads and thus future fire danger at this location. Thus afforestation poses the possibility of interrupting the brush-and-burn cycle, with the direct GHG benefit of the carbon sequestered in conifers net of baseline carbon stocks in brush, and the added indirect GHG benefit of possibly reducing emissions from future fires. This is an important co-benefit and one that has received little attention; WESTCARB efforts to create a methodology for quantifying reduced GHG emissions from wildfires have primarily focused on fuel reduction/biomass energy activities that involve thinning of understory fuels in forest lands rather than conversion of brush to forest.

Survival Monitoring

On August 24, 2010, sixty four 1/100th acre plots were sampled with the following results: 242 trees per acre including 211 ponderosa pine + 17 Douglas fir + 14 incense cedar per acre (survival after two years ~ 100% PP, 39% DF & 37% IC). Almost all of the mortality occurred in the first growing season (summer of 2009) and most of the surviving trees are healthy and vigorous (e.g. good stem caliper, buds and needle color and length). Conifer seedlings are well distributed throughout the project area. Stocking on ~ 8 acres in the most eastern portion of the project area is less than the remainder of the project, but still adequate. Control of competing vegetation is generally good, but there are enough whitethorn re-sprouts and some bearclover to warrant monitoring for possible treatment in a few years. There are many residual large conifers and black oaks scattered throughout the project area.

Suggested potential future activities

To minimize future hazardous brushy fuel loads and to maintain conifer vigor and health, brush density and growth should be monitored and treated if needed within the next few years. In 5 or 6 years (~2016) a pre-commercial thinning treatment will likely be needed on all but the eastern most 8 acres to reduce stocking levels to approximately 170 trees per acre, leaving the conifers at 16 foot by 16 foot spacing. Prior to pre-commercial thinning a registered professional forester (RPF) should be consulted.

Costs

The total cost of afforestation at this site was $61,958 or $1,033/acre. This cost includes site preparation including brush disposal ($438/ac); seedlings ($61/ac); planting costs ($106/ac); and follow-up spray ($428/ac).

Pursuing brush grinding and removal on this project would have increased the cost of mechanical site preparation and brush disposal by least $260/acre, and increased the total project cost to $78,163.

Baseline carbon stocks

Based on data from 10 measurement plots installed prior to site preparation at the Goose Valley Ranch project site, baseline carbon stocks in brush are estimated at a mean 41.7 t C/ha (61.8 t CO_2/ac) with a standard error of 3.3 t C/ha and a 90% confidence interval of 15% of the mean. The variability in this data indicates that 21 plots would be needed to attain a 90% confidence interval of 10% of the mean. The upper bounds of the 90% confidence interval is 49.1 t C/ha (20 t C/ac).

Projected growth and carbon benefits

Growth was modeled in FVS over 100 years, based on the survival count completed in August 2010, with 208 ponderosa pine (100% survival), 43 Douglas fir (39% survival), and 39 incense cedar (37% survival) planted per acre in 2008, and 2 ponderosa pine trees per acre naturally regenerated. Table 5 shows growth and carbon stocks for a 100 year period, starting in year 10.

Table 5. 100-year growth projections on the Goose Valley Ranch 2008 planting

Year	Trees per acre	Board feet/ac	Total C stocks/ac	Net C stored/ac	CO_2 stored/ac	Total CO_2
2018	241	0	5	-15	-55	-3,307
2028	236	0	11	-9	-32	-1,949
2038	231	2,821	25	5	19	1,131
2048	220	6,652	42	22	81	4,871
2058	190	12,378	57	37	136	8,171
2068	171	17,002	71	51	188	11,251
2078	143	21,122	81	61	224	13,451
2088	119	24,063	89	69	254	15,211
2098	102	26,290	95	75	276	16,531
2108	90	29,285	100	80	294	17,631

4.5 Lammers Properties

The Robert Lammers WESTCARB project is a 50-acre mixed conifer afforestation project on lands owned by Robert Lammers. The afforestation site is at approximately 3,900′ elevation, south of Highway 299E and west of Burney, Shasta County, California (T35N R1E, S ½ of NE ¼ of Section 34) (**Figure 11**).

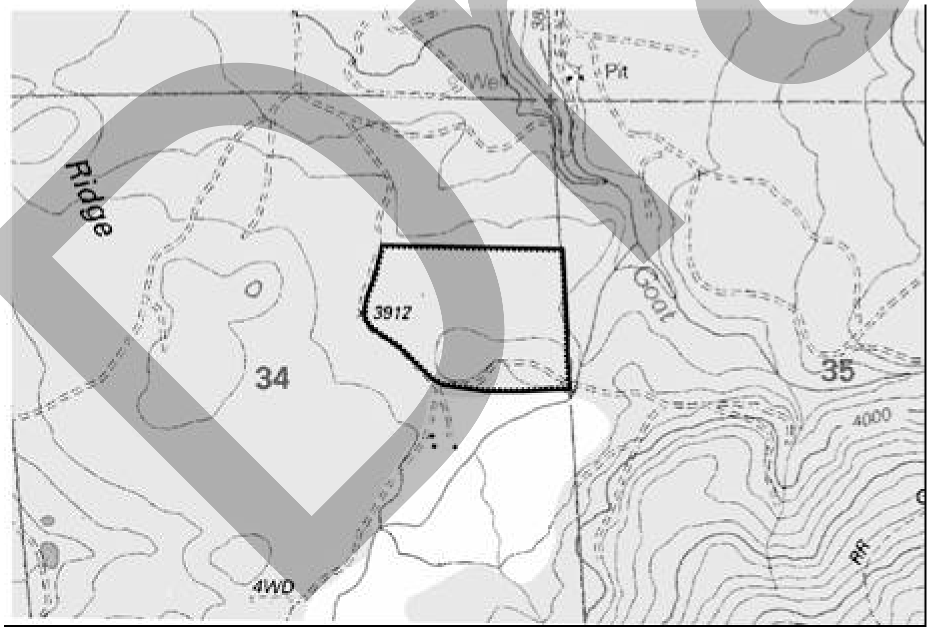

Figure 11. Map of the 50-acre Lammers afforestation project

Prior to the 1992 Fountain Fire the vegetation at this site was Sierra Mixed Conifer forest. After the 1992 Fountain Fire, mixed conifer forest was replaced by brush, mostly greenleaf manzanita

(*Arctostaphylos patula*) with very minor amounts of whitethorn (*Ceanothus cordulatus*) and deerbrush (*Ceanothus integerrimus*), and less than 5% cover of re-sprouted black oak trees (*Quercus kelloggii*) interspersed in the brush, primarily in the southern portion of the project area. Soils are Windy & McCarthy stony sandy loams; well drained; moderately deep (48" to 52" depth to bedrock); rapid permeability; slightly to moderately acid. Site Class is estimated Dunning III. Afforestation in a mix of ponderosa pine and Douglas fir would be well suited to these soils and site conditions. This is a suitable site for "High" NSTIA ponderosa pine orchard seed which should provide at least 10% or greater volume growth than seed collected in the wild from unknown pollen sources.

Site preparation by mechanical clearing of brush was conducted in summer 2008. Brush disposal was accomplished by grinding and removal to a biomass energy facility; Burney Mountain Power received the brush for biomass energy feedstock. However, though haul distance, good road access and flat topography are all conducive to brush grinding and removal, the costs of removing brush for biomass from this project turned out to be prohibitive on a commercial scale (see additional cost details below). In late fall 2008, crews sprayed 3 lbs. Velpar DF per acre to control competing vegetation prior to planting. In March 2009, the 50-acre site was planted at 249 trees per acre with 8,180 one-year old containerized ponderosa pine seedlings and 4,275 one-year old containerized Douglas fir seedlings.

Afforestation on past fire sites

The comments above for Goose Valley Ranch also apply to the Lammers property, which is located in the middle of the 1992 Fountain Fire. The Lammers property was not reforested, and therefore returned to brush after this fire, but is surrounded by industry (Roseburg Resources) lands that were immediately salvaged and reforested. The Roseburg lands provide a clear illustration both of the suitability of this site to support afforestation in pine or mixed conifers, and potential growth of such trees over the next 15 years (**Figure 12**). As described above, returning this brushfield to mixed conifer forest is likely also to reduce future risk of fire and associated GHG emissions.

Figure 12. Baseline conditions at Lammers WESTCARB afforestation pilot site. Note the brushfield to be afforested on the right, compared to similar lands on the left owned by Roseburg Resources and forested in the years following the 1992 Fountain Fire.

Survival monitoring

On August 12, 2010, fifty 1/100th acre plots were sampled with the following results: 159 ponderosa pine + 14.3 Douglas fir trees per net acre are very well distributed throughout the project area (Survival after two years ~ 97% for PP & 17% for DF; **Figure 13**). The poor survival of the Douglas fir is likely due to the sandy soil type (Windy-McArthy), which is deep but has very low available water holding capacity, in combination with the relatively dry spring & summer of 2009. Although initial survival and establishment of planted Douglas fir seedlings on this soil type and dry summer climate is difficult, those that did survive are now well established and should grow well on this site. Almost all of the mortality for both species occurred in the first growing season (summer of 2009) and most of the surviving trees are healthy and vigorous (e.g. good stem caliper, buds and needle color and length for two year old seedlings). Portions of the project area are occupied with re-sprouting whitethorn, Prunus spp. and black oaks. Throughout most of the project area, 4 month old greenleaf manzanita seedlings seeded in during 2010 but appear to be suffering the effects of residual Velpar DF uptake. In late August 2010 the landowner contracted with a licensed Pest Control Operator to treat the resprouting whitethorn, Prunus spp. and black oaks that would otherwise have severely impacted the health and vigor of the young conifer seedlings.

Figure 13. Douglas fir and ponderosa pine seedlings 18 months after planting on the Lammers project

Suggested potential future activities

In order to minimize the growth of brushy hazardous fuels and to maintain conifer vigor and health, the landowner should monitor the greenleaf manzanita seedlings over the next few years and treat if needed. This treatment would likely involve a directed foliar application in the spring of 2012, prior to conifer bud elongation, using 2% LV4 (ester formulation of 2,4D) or 5% glyphosate product (e.g. Razor) plus 3% to 5% methylated seed oil surfactant. The treatment should avoid spray contact on the conifer seedlings. Current stocking of 173 trees per acre is the ideal stocking level for post pre-commercial thinning stocking level at plantation age 7 to 10 after pre-commercial thinning typically occurs. Since most mortality occurs within 2 years after planting no further planting or pre-commercial thinning treatments should be needed, provided that the manzanita brush is controlled for the next few years. Unless an unusual and significant die off of the ponderosa pine occurs in the next few years interplanting is not necessary and unless natural seeding of conifers significantly increases the number of conifer trees per acre in the next few years a pre-commercial thinning treatment is not likely to be needed. Please note that these are suggested possible future treatments, and it is necessary to obtain a specific recommendation for spraying from a licensed Pest Control Advisor prior to any treatment. Also to prior to pre-commercial thinning a registered professional forester (RPF) should be consulted.

Costs

The total price of afforestation at this site was $42,885 or $857/acre. This includes site preparation ($687/ac); seedlings ($67/ac); and planting costs ($104/ac). However, the contractor who completed the chipping and removal of brush to a biomass facility significantly underbid the job and found that it was a far more costly process than anticipated. The full cost for chipping and removal, after subtracting income from the sale of chips, was $1,565.50. This increased the actual costs of the project to $87,675 ($1,753.50/ac).

Baseline carbon stocks

Based on data from 7 measurement plots installed prior to site preparation at the Lammers project site, baseline carbon stocks in brush are estimated at a mean 29.8 t C/ha (44.3 t CO_2/ac) with a standard error of 3.4 t C/ha and a 90% confidence interval of 22% of the mean. The variability in this data indicates that 34 plots would be needed to attain a 90% confidence interval of 10% of the mean. The upper bounds of the 90% confidence interval is 37.9 t C/ha (15 t C/ac).

Projected growth and carbon benefits

Growth was modeled in FVS over 100 years, based on the survival count done in August 2010, with 164 ponderosa pine (97% survival) and 86 Douglas fir (16% survival) planted per acre in 2009. Table 6 shows growth and carbon stocks for a 100 year period, starting in year 10.

Table 6. 100-year growth projections on the Lammers 2009 planting

Year	Trees per acre	Board feet/ac	Total C stocks/ac	Net C stored/ac	CO_2 stored/ac	Total CO_2
2019	173	0	4	-11	-42	-2,079
2029	169	0	7	-8	-31	-1,529
2039	166	1,634	17	2	6	304
2049	163	4,402	29	14	50	2,504
2059	159	9,303	42	27	98	4,888
2069	147	13,343	54	39	142	7,088
2079	134	17,804	65	50	182	9,104
2089	124	22,167	75	60	219	10,938
2099	115	25,567	83	68	248	12,404
2109	102	28,321	89	74	270	13,504

4.6 Frase property

This 43-acre ponderosa pine afforestation project is located at T33N R5W Section 29 (S½), northwest of Redding at low elevation (800′) and with site conditions distinct from any other WESTCARB afforestation pilot (**Figure 14**). Soils in the area, according to NRCS mapping, are "Goulding very rocky loam, 30 to 50 percent slopes, eroded" which is described as a shallow (16" to 20") soil. Seed zone is 521 (southwest portion of zone). Site class is Dunning IV on slopes and low III on flatter areas. Mechanical site preparation, through mastication of previously existing heavy manzanita brush, had already been conducted by the landowner. Current vegetation is small manzanita seedlings, toyon, coffee berry, poison oak, blackberry, and scattered black and live oak and ponderosa pine, gray pine and knobcone pine from seedling size to 80′ tall. Site preparation was done in fall 2008 and involved only chemical treatment to control competing vegetation (since mechanical site preparation by mastication had been done by the landowner prior to this pilot project). In February 2009, 12,140 ponderosa pine seedlings were planted at 282 trees per acre.

The unique feature of this pilot is a site typical of tens of thousands of acres below 2,000' elevation where fumes from copper smelting circa 1910 killed all the vegetation from Kennett south to Red Bluff, along the west side of the Sacramento River. Prior to the ponderosa pine die-off from smelting, some of the forest in this general area was probably harvested in the very late 1800s and/or very early 1900's for fuel and mine timbers. Most of the ponderosa pine that has regenerated in the vicinity of the project area was planted by the Civilian Conservation Corps in the 1930s. Survival was spotty but where seedlings survived the trees have grown fairly tall, even on steep slopes that were heavily impacted by gully erosion. Most of the area, however, is occupied by decadent brush that periodically burns. Soil erosion subsequent to the smelting-caused vegetation die-off has likely degraded site productivity, more so on the steeper slopes in the general vicinity. As there are still several thousand acres of this former ponderosa pine habitat now occupied mostly by brush, this project made an excellent afforestation pilot project for potential replication throughout the area.

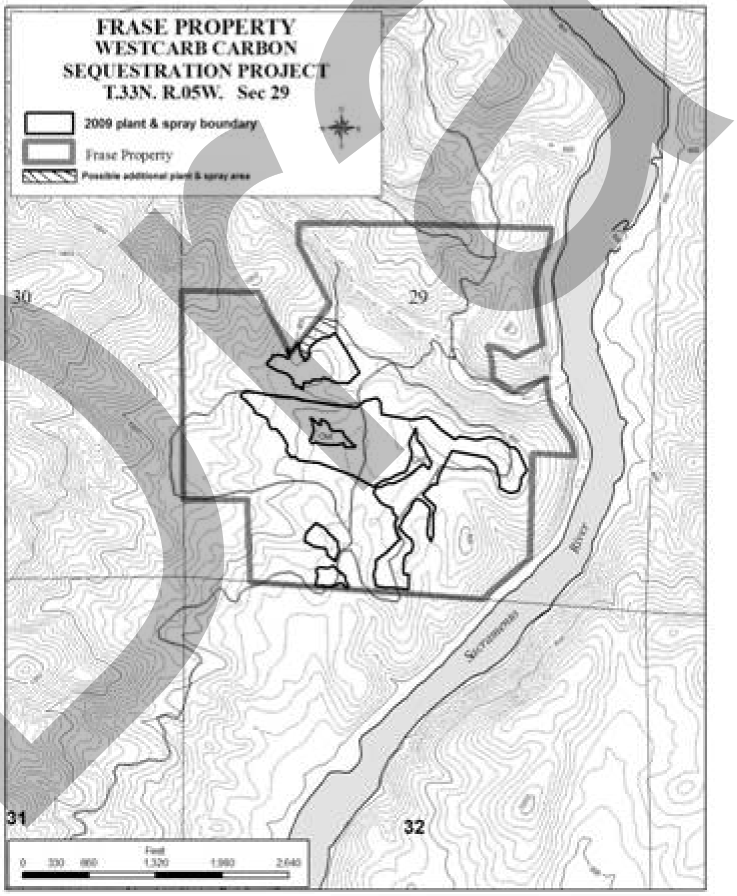

Figure 14. Map of the 43-acre Frase afforestation project

Survival monitoring

On August 25, 2010, fifty-one 1/100th acre plots were sampled with the following results: 263 ponderosa pine trees per acre are very well distributed throughout the project area (Survival after two years = 263/282 = 93%, Figure 15). Only one of the 51 plots was not stocked with at least one ponderosa pine and this plot was within an un-sprayed watercourse buffer where grasses and forbs outcompeted first year conifer seedlings for soil moisture in the summer of 2009. Most of the mortality occurred in the first growing season (summer of 2009) and it occurred in the spray buffer areas near watercourses where grasses and forbs were not treated. The ponderosa pine seedlings that did survive in those untreated buffers are mostly of poor vigor and would benefit from a release treatment. However most of the project area is comprised of ponderosa pine seedlings that exhibit very good vigor (e.g. good stem caliper, buds and needle color and length for two year old seedlings). The tree size and dark green needle color of many seedlings growing in the portion of the project area that was burned by the 2008 Motion Fire indicate that the release of nitrogen by the burning of the dead masticated brush more than outweighed any possible negative effects of the loss of "mulch" on the shallow eroded soils. There is also a significant number of two year-old knobcone or gray pine trees per acre that seeded in, mostly in the northwest portion of the project area where the 2008 Motion Fire released seed from serotinus pine cones. Most of the project area is also occupied by 6 month old whiteleaf manzanita seedlings, forbs and grasses that seeded in during 2010 and were prevalent on many plots. Some coffeeberry, Yerba Santa, poison oak, live oak and blackberry patches have re-sprouted and are scattered throughout the project area.

Figure 15. Ponderosa pine seedlings 18 months after planting on Frase project. Manzanita brush left outside of project area in the background.

Suggested potential future activities

In February or March of 2011 grass and forbs within a 5 foot radius of ponderosa pine seedlings should be treated with a directed foliar spray of a generic glyphosate product and surfactant. This should be the final grass and forb treatment needed because once ponderosa pine seedlings are well established (e.g. "free to grow" for 3 years) they should be vigorous and deeply rooted enough to survive and grow well with grass and forb competition. However aggressive brush competition should be controlled for a few more years. In order to prevent the growth of brushy fuel loads and to maintain conifer vigor and health, a directed spray application on the seedling whiteleaf manzanita germinates is likely to be needed in 2011 or 2012. Sometime around 2016 a pre-commercial thinning treatment is likely to be needed to reduce stocking levels to approximately 170 trees per acre, leaving mostly the most vigorous ponderosa pine at 16 foot by 16 foot spacing. Prior to pre-commercial thinning a registered professional forester (RPF) should be consulted.

Costs

The total cost of afforestation at this site was $25,812 or $600/acre. This cost includes chemical site preparation ($261/ac); seedlings ($46/ac); planting costs ($175/ac); and follow-up spray ($118/ac).

Total operational costs were relatively low because brush removal had been completed prior to the pilot project, reducing the costs of mechanical site preparation.

Baseline carbon stocks

Because the landowner had cleared the project area prior to inception of this pilot project, for the purposes of reducing fire risk, there was no existing vegetation and the baseline carbon stocks are considered to be zero.

Projected growth and carbon benefits

Growth was modeled in FVS over 100 years, based on the survival count done in August 2010, with 282 ponderosa pine (93% survival) planted per acre in 2009. Table 7 shows growth and carbon stocks for a 100 year period, starting in year 10.

Table 7. 100-year growth projections on the Frase 2009 planting

Year	Trees per acre	Board feet/ac	Total C stocks/ac	CO_2 stored/ac	Total CO_2
2019	262	0	5	18	788
2029	257	0	8	29	1,261
2039	252	1,315	20	73	3,153
2049	248	4,900	33	121	5,203
2059	222	7,506	44	161	6,937
2069	201	11,200	55	202	8,672
2079	186	14,338	65	238	10,248
2089	166	16,437	73	268	11,510
2099	143	18,354	79	290	12,456
2109	124	20,514	85	312	13,402

4.7 Kloeppel property

This 51-acre ponderosa pine afforestation project is located at T35N R1W Section 25 (NE¼), at 2,900′ to 3,160′ elevation, on Highway 299E west of Burney, Shasta County, California (**Figure 16**). Like Lammers and Goose Valley Ranch, the proposed afforestation site is in the area burned by the 1992 Fountain Fire, where industry planting on nearby lands indicates strong growth potential along with the potential to achieve carbon storage, improved habitat, and fire risk reduction by returning the brushfield to forest. The proposed site is currently dominated (95% cover) by brush, with 90% consisting of 6-10′ tall deerbrush (*Ceanothus integerrimus*), and in more open areas deerbrush, chinkapin, manzanita, poison oak, dogwood, bracken fern, squaw carpet, and some forbs and grasses. There is an estimated 5 to 10% cover in trees consisting mostly of scattered black oak and a few big-leaf maple. Prior to the Fountain Fire, the area was a mixed conifer forest of primarily ponderosa pine and Douglas fir and some black oak in the understory. Soil is Cohasset Stony Loam, site class Dunning site II or better. Mechanical site preparation and brush disposal by pile burning took place in summer 2008. The area was planted in March 2009 with 16,010 one year-old containerized seedlings (11,920 ponderosa pine & 4,090 Douglas fir), 314 trees per acre.

Figure 16. Map of the 51-acre Kloeppel afforestation project

Survival monitoring

On August 24, 2010, fifty 1/100th acre plots were sampled with the following results: 262 trees per acre including 222 ponderosa pine + 40 Douglas fir trees per net acre (survival after two years ~ 95% for PP & 50% for DF) are very well distributed throughout the project area (**Figure 17**). Almost all of the mortality occurred in the first growing season (summer of 2009) and most of the surviving trees are healthy and vigorous (e.g. good stem caliper, buds and needle color and length for two year old seedlings). Six month old deerbrush seedlings which germinated in 2010 are prevalent along with lesser amounts of manzanita germinates. If this young brush is not treated within a few years it will grow rapidly to cover most of the project area and overtop the conifers, competing aggressively for light and soil moisture. Also if not treated it would grow into a hazardous fuel load. Portions of the project area are also occupied with noxious non-native weeds specifically Scotch broom, yellow star thistle and Himalayan blackberries along with native re-sprouting poison oak, bracken fern, Prunus spp. and black oaks. Grasses and forbs are seeding into the project area but should not cause a problem to conifers that are now well established. After WESTCARB II operational funding expired, the landowner has done an excellent job of treating blackberries and other brush on the limited number of acres he can operationally treat by himself.

Figure 17. Beaty forester conducting 2nd year stocking survey on Kloeppel project

Suggested potential future activities

To minimize future hazardous brushy fuels and to maintain conifer vigor and health, a directed foliar application on brush seedlings should be conducted in 2011. Also treatments should be made on the noxious weeds and re-sprouting native brush. These treatments should avoid spray contact on the conifer seedlings. In 5 or 6 years (~2016) a pre-commercial thinning treatment might be needed to reduce stocking levels to approximately 170 trees per acre, leaving the conifers at 16 foot by 16 foot spacing. Prior to pre-commercial thinning a registered professional forester (RPF) should be consulted.

Costs

The total cost of afforestation at this site was $45,870 or $899/acre. This cost includes site preparation including brush disposal ($517/ac); seedlings ($65/ac); planting costs ($187/ac); and follow-up spray ($130/ac). An additional $1,745 was spent after the planting to install erosion control measures.

Baseline carbon stocks

Based on data from 9 measurement plots installed prior to site preparation at the Kloeppel project site, baseline carbon stocks in brush are estimated at a mean 19.2 t C/ha (28.6 t CO_2/ac) with a standard error of 2.5 t C/ha and a 90% confidence interval of 24% of the mean. The variability in this data indicates that 51 plots would be needed to attain a 90% confidence interval of 10% of the mean. The upper bounds of the 90% confidence interval is 24.8 t C/ha (10 t C/ac).

Projected growth and carbon benefits

Growth was modeled in FVS over 100 years, based on the survival count done in August 2010, with 234 ponderosa pine (95% survival) and 80 Douglas fir (50% survival) planted per acre in 2009. Table 8 shows growth and carbon stocks for a 100 year period, starting in year 10.

Table 8. 100-year growth projections on the Kloeppel 2009 planting

Year	Trees per acre	Board feet/ac	Total C stocks/ac	Net C stored/ac	CO_2 stored/ac	Total CO_2
2019	262	0	5	-5	-18	-941
2029	257	67	12	2	7	368
2039	252	4,282	30	20	73	3,734
2049	222	10,823	48	38	139	7,100
2059	194	18,998	65	55	202	10,279
2069	168	25,670	78	68	249	12,710
2079	138	29,969	89	79	290	14,767
2089	116	34,049	97	87	319	16,263
2099	100	37,389	103	93	341	17,385
2109	87	41,566	108	98	359	18,320

4.8 Sivadas property

This 46-acre ponderosa pine afforestation project is located at T33N R2W Section 9, at 1,700′ to 1,780′ elevation (**Figure 18**). All-season access is good via paved and gravel roads. According to USDA NRCS Shasta County Area Survey, soils at the site are Supan very stony loam, 0 to 30%; parent material is residuum weathered from tuff breccia; well drained, depth to lithic bedrock is 33 to 37″, available water capacity is low 0 to 10″ depth ranging from 0.9 to 1.4 inches and at 10 to 33″ depth ranging from 3.0 to 7.8 inches. Baseline vegetation is dense, tall brush (> 80% cover) consisting primarily of greenleaf and whiteleaf manzanita with some poison oak, whitethorn (*Ceanothus cordulatus*) and deerbrush (*Ceanothus integerrimus*).

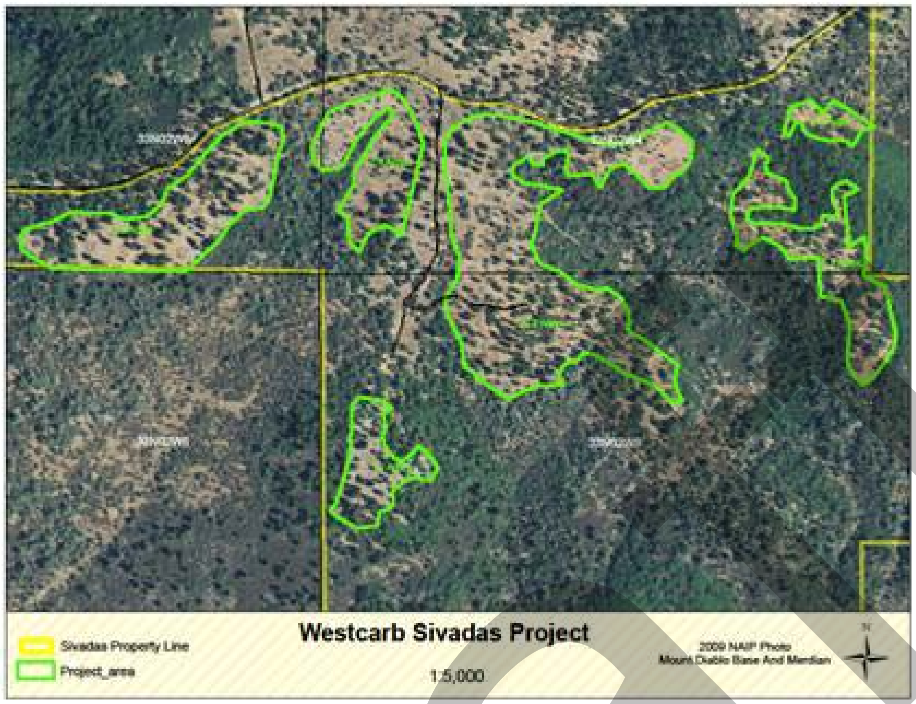

Figure 18. Map of 46-acre Sivadas afforestation project, with yellow outline showing property boundary, and green outline showing project area

Planted ponderosa pine seedlings, along with the existing scattered overstory (~10%) of black oak, blue oak, ponderosa pine and gray pine, and gray pine that will likely naturally seed in for several years after the brush is cleared, will provide a diverse mix of tree species from this afforestation project. For good conifer seedling survival and growth in the long, hot and dry summer climate, controlling manzanita, poison oak and grasses that compete aggressively for limited soil moisture during the first few years of establishment will be critical.

The extreme fuel load and configuration of the tall, dense brush on the proposed afforestation site poses a significant risk of catastrophic wildfire to the surrounding forests and watershed (**Figure 19**). Controlling the re-invasion of manzanita brush has the added benefit of lowering and maintaining lower hazardous fuel loads. The proposed project area is classified as a “high” treatment priority area in the Sugar Pine Community Wildfire Protection Plan; afforestation has the co-benefit of meeting the objectives of the Community Wildfire Protection Plan by greatly reducing the hazardous fuel loads.

Figure 19. Sivadas afforestation site, with dense manzanita brush posing hazardous fuel loads and fire danger to overstory of sparse black oak and ponderosa pines

In 2008 ponderosa pine seedlings were grown in a nursery from appropriate seed zones. Mechanical site preparation by piling took place in summer 2008, retaining conifers, oaks and large woody debris where operationally feasible. The option of brush grinding and removal to a biomass energy facility was considered for this project, due to heavy brush, reasonable haul distance either to Wheelabrator or one of the biomass plants in Burney, and good road access. However, it was determined that the roads into the property were not useable by chip hauling vans and brush removal was not economical, so it was pile-burned in fall 2008. In early 2009, crews planted 9,070 one-year old containerized ponderosa pine seedlings at 197 trees per acre, followed by installation of seedling protection netting. There were a large number of residual pine and oak trees, so although planting specifications were for 300 trees per acre at 12'x12' spacing, far fewer trees were actually planted. In spring 2009, a directed foliar spray application by hand crews was done to control re-sprouting poison oak and germinating manzanita seedlings and grass.

Survival Monitoring

On September 10, 2010, 38 1/100th acre plots were sampled with the following results: 192 ponderosa pine trees per acre are very well distributed throughout the project area (Survival after two years = 97%, **Figure 20**). All of the plots were either stocked with at least one planted ponderosa pine or were not planted because they were fully occupied by residual large oaks and/or ponderosa pine. Most of the mortality occurred in the first growing season (summer of 2009). Surviving trees that are relatively "free to grow" are healthy and vigorous (e.g. good stem caliper, buds and needle color and length for two year old seedlings), but trees that are under competitive stress from heavy grass cover and/or residual overstory oaks and/or pines are smaller and much less vigorous. Most of the project area is also occupied by grasses, forbs, one year old whiteleaf manzanita seedlings and some re-sprouting black oak, live oak, poison oak and buckbrush. The very heavy grass cover in the large middle unit is significantly impacting the growth and vigor of the ponderosa pine seedlings. The western unit is also occupied by wild grape that is competing with some of the ponderosa pine for light and soil moisture. There are several large residual black oak and ponderosa pine in the project area that are impacting the growth and vigor of the ponderosa pine seedlings within their shade and/or rooting zone.

Figure 20. Two-year old Ponderosa pine seedling on Sivadas

Suggested potential future activities

If the landowner plans to harvest oak for personal and/or commercial firewood use, oaks that are stunting ponderosa pine seedlings should be a priority for removal (harvest operations should be conducted so as not to damage the ponderosa pine seedlings). Treating the grasses and forbs within a 5 foot radius of ponderosa pine seedlings in the early spring of 2011 would greatly enhance the survivability of many ponderosa pine, especially in the 20.2 acre middle unit. In order to prevent the growth of brushy fuel loads and to maintain conifer vigor and health, a directed foliar spray application in 2011 or 2012 on the seedling whiteleaf manzanita and re-sprouting poison oak is needed. During any of these treatments avoid spray contact on the ponderosa pine seedlings. Treating the brush in the next few years is critical to maintain the long term fuel reduction benefit of the reforestation work as well as the survivability of the ponderosa pine seedlings. In approximately 6 to 8 years (2016-2018) a pre-commercial thinning treatment might be needed in some areas to reduce stocking levels to approximately 170 trees per acre, leaving the most vigorous ponderosa pine at 16 foot by 16 foot spacing. Please note that these are suggested possible future treatments, and it is necessary to obtain a specific recommendation for spraying from a licensed Pest Control Advisor prior to any treatment. Also to prior to pre-commercial thinning a registered professional forester (RPF) should be consulted.

Costs

The total cost of afforestation at this site was $35,805 or $778/acre. This cost includes site preparation including brush disposal ($474/ac); seedlings ($41/ac); planting costs ($157/ac); and follow-up spray ($107/ac).

Baseline carbon stocks

Based on data from 11 measurement plots installed prior to site preparation at the Sivadas project site, baseline carbon stocks in brush are estimated at a mean 83.3 t C/ha (123.7 t CO_2/ac) with a standard error of 11.7 t C/ha and a 90% confidence interval of 26% of the mean. The variability in this data indicates that 72 plots would be needed to attain a 90% confidence interval of 10% of the mean. The upper bounds of the 90% confidence interval is 109.2 t C/ha (44 t C/ac).

Projected growth and carbon benefits

Growth was modeled in FVS over 100 years, based on the survival count done in September 2010, with 197 ponderosa pine (97% survival) planted per acre in 2009. Table 9 shows growth and carbon stocks for a 100 year period, starting in year 10.

Table 9. 100-year growth projections on the Sivadas 2009 planting

Year	Trees per acre	Board feet/ac	Total C stocks/ac	Net C stored/ac	CO_2 stored/ac	Total CO_2
2019	191	0	5	-39	-144	-6,612
2029	188	0	8	-36	-133	-6,106
2039	184	1,870	19	-25	-92	-4,250
2049	180	4,966	32	-12	-45	-2,058
2059	174	9,488	44	0	-1	-34
2069	157	13,231	55	11	40	1,822
2079	144	17,155	64	20	73	3,340
2089	135	21,359	73	29	106	4,858
2099	118	23,784	81	37	135	6,207
2109	103	26,049	87	43	157	7,219

4.9 Eilers property

This 20-acre combined ponderosa pine and blue oak afforestation project is located at T33N R2W Section 9, at 1,700′ to 1,780′ elevation. The project consists of three small units. All-season access is good via rocked and dirt roads. Soils on the middle and west units are suitable for growing ponderosa pine, but the soils on the third unit (east unit) are shallow and marginal for commercial conifer production. Site class is estimated Dunning IV on west and middle units, V or less on east unit. Current vegetation is comprised of re-sprouting poison oak, live oak and black oak, grasses, forbs and brush (mostly manzanita) germinate seedlings less than one foot tall. There is an overstory of ponderosa pine, gray pine, black oak and blue oak, averaging approximately 10% canopy cover. Large piles of dead brush are in the proposed afforestation units. Due to the small size and economies of scale, the project was feasible because it was done in conjunction with the nearby Sivadas afforestation project.

The landowner’s objective was to reduce fire hazard risk and promote watershed and wildlife resources by establishing long-term tree cover with minor shrub, grass, and forb understory, in place of the dense brush and sparse tree cover that had previously occupied the site. Two acres in the project area are suitable for planting blue oak and ponderosa pine (very low site) and the remaining acres are suitable for ponderosa pine. Experience in operational-scale oak regeneration projects in California is insufficient to provide a reliable basis for estimates of costs and risk for this project. For good conifer seedling survival and growth in this long, hot and dry summer climate, controlling manzanita, poison oak and grasses that compete aggressively for limited soil moisture during the first few years of establishment are critical. Controlling the re-invasion of manzanita brush has the added benefit of reducing hazardous fuel loads. It is likely that some gray pine seedlings will naturally seed in over time following brush removal.

In 2008, ponderosa pine seedlings were grown in a nursery from appropriate seed zones. WESTCARB partners monitored the blue oak acorn crop on the property in fall 2007 in hopes of collecting ripe acorns to plant. During that year, however, the acorn crop was insufficient, and oak planting was delayed a year. Acorns were collected in the fall of 2008, and culls were sorted out using water immersion method. Oak planting occurred in February 2009. Blue oak acorns were planted only on the 2 acres of the low-site unit, at 50 spots per acre, 2 acorns per spot, followed by installation of 100 4' rigid seedling/sapling protectors anchored with posts. Weeds were sprayed within 4' of oak planting spots. Piling of brush had already been completed by the landowner, so the only site preparation needed prior to planting was to burn piles of residual brush. Ponderosa pine planting was done in early 2009, with planting of 4,160 one year-old containerized ponderosa pine seedlings on all 20 acres at 208 trees per acre. Planting was followed by installation of seedling protection netting around ponderosa pine seedlings, and a directed foliar spray application by hand crews to control any re-sprouting poison oak and newly emerging brush germinates, forbs and grasses.

Survival Monitoring

A survival survey was conducted on September 10, 2010. Approximately 150 ponderosa pine trees per acre (tpa) are distributed throughout the project area with approximately 70 blue oak spots (35 tpa) occupied by one or two seedlings on two acres along with the planted ponderosa pine at about 100 tpa. Surviving ponderosa pine that are relatively "free to grow" are healthy and vigorous (e.g. good stem caliper, buds and needle color and length for two year old seedlings), but trees that are under competitive stress from heavy grass and/or Brewer's oak cover and/or residual overstory oaks and/or pines are smaller and much less vigorous. In some of the areas cleared for planting ponderosa pine, gray pine seedlings are seeded in. The blue oak seedlings, which grow slower than most oak species, are still well below the height of the Tubex treeshelters with some showing signs of leaf stress from the shelter and/or from competing vegetation. (**Figure 21**)

Figure 21. Blue oak seedlings that germinated from two planted acorns are still well below height of Tubex Treeshelter (L). Six month old Gray pine seedling that germinated after clearing and initial vegetation control (R)

Most of the project area is also occupied by grasses, forbs, one year old whiteleaf manzanita seedlings and some re-sprouting black oak, live oak, poison oak and buckbrush. It appears that the landowner has invested in treating some of this brush after funding from the WESTCARB II grant expired. The very heavy cover of Brewer's oak in the western portion of the 2-acre pine & oak unit is significantly impacting the survivability and/or growth of the ponderosa pine and blue oak seedlings. There are heavy patches of grass scattered throughout the entire project area which have also impacted conifer seedling survival and continue to threaten the survivability and/or growth of existing ponderosa pine seedlings. There are several large residual black oak and ponderosa pine in the project area that are impacting the growth and vigor of the ponderosa pine seedlings within their shade and/or rooting zone.

Suggested potential future activities

Provided cattle remain excluded from the 2 acre blue oak unit, the Tubex Shelters may be removed at this time from around the blue oak seedlings that have germinated and survived. No evidence of stock or wildlife browsing appears to have occurred to unsheltered blue oak seedlings and as blue oak grows very slowly there might be a negative effect of the shelters on the oaks should they remain in place next summer.

If the landowner plans to harvest oak for personal or commercial firewood use, large residual oaks that are stunting ponderosa pine seedlings should be a priority for removal (harvest operations should be conducted so as not to damage the ponderosa pine seedlings).

Treating the grasses and forbs within a 5 foot radius of ponderosa pine seedlings in the early spring of 2011 would greatly enhance the survivability of many ponderosa pine especially in areas where grass cover is heavy.

In order to prevent the growth of brushy fuel loads and to maintain conifer vigor and health, a directed foliar spray application in 2011 or 2012 on the seedling whiteleaf manzanita and re-sprouting poison oak is needed (**Figure 22**).

During any of these treatments spray contact on the ponderosa pine seedlings should be avoided. Treating the brush in the next few years is critical to maintain the long term fuel reduction benefit of the reforestation work as well as the survivability of the ponderosa pine seedlings.

Please note that these are suggested possible future treatments, and it is necessary to obtain a specific recommendation for spraying from a licensed Pest Control Advisor prior to any treatment. Also to prior to pre-commercial thinning a registered professional forester (RPF) should be consulted.

Figure 22. The heavy grass and forb cover in some areas (L) should be treated in spring of 2011 because it is significantly reducing ponderosa pine seedling vigor compared to "free to grow" ponderosa pine seedlings (R) growing without much weed competition for limited soil moisture.

Costs

The total cost of afforestation at this site was $7,084 or $354/acre. This cost includes pine seedlings and acorn collection ($77/ac); planting costs ($123/ac); and follow-up spray ($154/ac). Brush removal had been completed prior to the pilot project, so there were no costs for mechanical site preparation, resulting in low overall costs.

Baseline carbon stocks

Because the landowner had cleared the project area prior to inception of this pilot project, for the purposes of reducing fire risk, there was no existing vegetation and the baseline carbon stocks are considered to be zero.

Projected growth and carbon benefits

Growth was modeled in FVS over 100 years, based on the survival count done in September 2010. Two separate projections were made for the two different planting regimes. In the first, 208 ponderosa pine trees per acre were planted, with a 72% survival rate. Table 10 shows growth and carbon stocks for the pine planting over a 100 year period, starting in year 10. In the second, 208 ponderosa pine (48% survival) and 35 blue oak (70% survival) were planted per acre in 2009. Table 11 shows growth and carbon stocks for the pine/oak planting over a 100 year period, starting in year 10.

Table 10. 100-year growth projections on the Eilers 2009 pine planting

Year	Trees per acre	Board feet/ac	Total C stocks/ac	CO_2 stored/ac	Total CO_2
2019	150	0	4	15	264
2029	147	0	6	22	396
2039	144	383	11	40	726
2049	141	1,870	18	66	1,188
2059	139	3,497	25	92	1,650
2069	136	4,583	33	121	2,178
2079	133	6,515	41	150	2,706
2089	131	8,650	48	176	3,168
2099	125	10,622	55	202	3,630
2109	119	12,118	61	224	4,026

Table 11. 100-year growth projections on the Eilers 2009 oak/pine planting

Year	Trees per acre	Board feet/ac	Total C stocks/ac	CO_2 stored/ac	Total CO_2
2019	135	0	5	18	37
2029	132	0	6	22	44
2039	129	256	10	37	73
2049	126	1,420	15	55	110
2059	124	2,580	21	77	154
2069	121	3,486	27	99	198
2079	118	5,212	34	125	249
2089	116	7,246	40	147	293
2099	113	9,196	47	172	345
2109	111	10,846	53	194	389

4.10 Wilson property

This 14-acre ponderosa pine afforestation project is located at T34N R1W Section 29 (S½), in two units ½ mile apart, at 1,600′ (east unit) and 1,700′ (west unit) elevation (**Figure 23**). Access is fair, via unpaved roads and a bridge whose weight capacity needs to be confirmed. According to USDA NRCS Shasta County Area Survey, soils on the west unit are Marpa gravelly loam, 30 to 50 percent slopes (slopes on the proposed project area are 0 to 30%); residuum weathered from shale parent material; 26″ to 30″ deep; well drained; moderately suited for hand planting. Although the soil type in general is listed as capable of growing ponderosa pine, black oak, Douglas fir, and white fir, at this elevation and ridge top exposure ponderosa pine would be the most suitable for young seedling survival. On the east unit, soils are Neuns very stony loam, 8 to 50 percent slopes (slopes on the proposed project area are 0 to 30%); residuum weathered from greenstone parent material; 23” to 27” deep; well drained; moderately suited for hand planting. Current vegetation consists mostly of dense, 6 to 15 foot tall non-sprouting manzanita species and a sparse (< 5% cover) black oak, blue oak, ponderosa pine, gray pine and Douglas fir overstory. The brushfields with sparse re-sprouted oaks likely formed after a wildfire many decades ago.

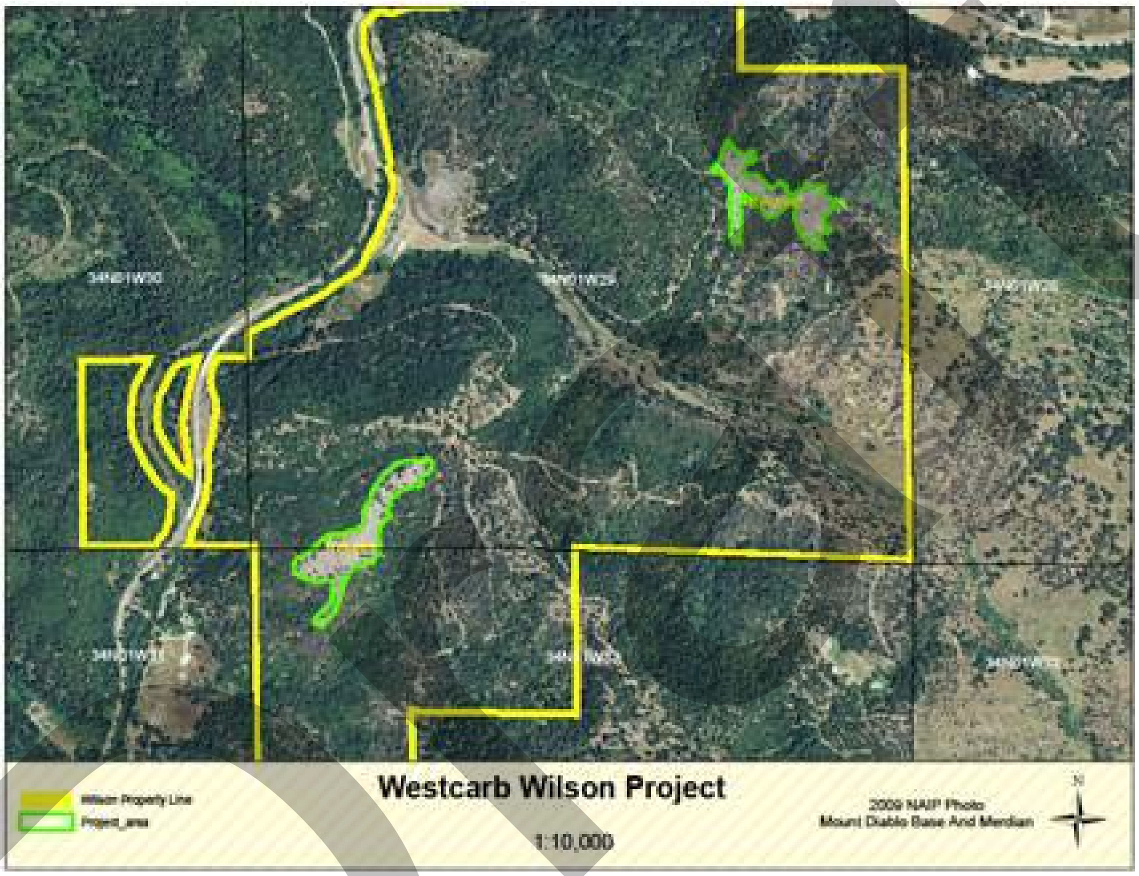

Figure 23. Map of 14-acre Wilson afforestation project, with yellow outline showing property line and green outline showing project area

Site preparation entailed mastication of brush. Due to the relatively low elevation, hot dry summer climate and shallow, somewhat eroded soils, there is a greater risk of plantation failure than at higher elevation sites and better conifer growing, non-eroded soils. The benefits of this proposed project go beyond afforestation because preparing the site for planting by masticating the tall, dense brush on these ridges would also reduce fire hazard risk to the property and surrounding forestland. Mastication rather than mechanical clearing was appropriate because of the shallow, erodible soils and non-sprouting brush species; mastication causes less soil disturbance, provides dead woody material cover that will reduce soil moisture loss from evaporation, and provides shade from the summer sun on the lower stem portion of the young seedlings that will be planted into the site. The mulching effect of the mastication also reduces the amount of weeds competing with the conifer seedlings for limited soil moisture and nutrients.

In 2008, ponderosa pine seedlings were grown in a nursery from appropriate seed zones. Site preparation occurred in summer 2008 using an excavator equipped with a masticating head. In February 2009, crews planted 3,830 one-year old containerized ponderosa pine seedlings at 273 trees per acre, followed by installation of seedling protection netting. Planting was followed by a directed foliar spray application by hand crews to control newly emerging forbs and grasses.

Survival Monitoring

On August 12, 2010, 19 1/100th acre plots were sampled with the following results: 247 ponderosa pine trees per acre are very well distributed throughout the project area (Survival after two years = 90%, **Figure 24**). All of the 19 plots were stocked with at least one ponderosa pine. Most of the mortality occurred in the first growing season (summer of 2009) and most of the surviving trees are very healthy and vigorous (e.g. good stem caliper, buds and needle color and length for two year old seedlings). Most of the project area is also occupied by 6 month old whiteleaf manzanita seedlings that seeded in during 2010. Some poison oak, live oak and blackberry plants have re-sprouted and are scattered throughout the project area.

Figure 24. Control of competing vegetation through chemical treatments & masticated "mulch" has led to very healthy & vigorous seedlings on low conifer timber site soils

Suggested potential future activities

In order to prevent the growth of brushy fuel loads and to maintain conifer vigor and health, a directed foliar spray application on the seedling whiteleaf manzanita should be conducted in the spring of 2011 or spring of 2012, prior to conifer bud elongation. Manzanita can be controlled with 2% LV4 (ester formulation of 2,4D) or with 5% glyphosate product (e.g. Razor) plus 3% to 5% methylated seed oil surfactant. In the summer of 2011 or 2012 re-sprouting poison oak should be treated with 3% to 5% glyphosate product plus 1% surfactant, blackberries should be treated with 2% Garlon 4 or Element 4 (active ingredient triclopyr). During any of these treatments avoid spray contact on the ponderosa pine seedlings. In approximately 6 to 8 years (2016-2018) a pre-commercial thinning treatment is likely to be needed to reduce stocking levels to approximately 170 trees per acre, leaving mostly the most vigorous ponderosa pine at 16 foot by 16 foot spacing. Please note that these are suggested possible future treatments, and it is necessary to obtain a specific recommendation for spraying from a licensed Pest Control Advisor prior to any treatment. Also to prior to pre-commercial thinning a registered professional forester (RPF) should be consulted.

Costs

The total cost of afforestation at this site was $18,198 or $1,300/acre. This cost includes site preparation ($695/ac); seedlings ($54/ac); planting costs ($335/ac); and follow-up spray ($216/ac).

Baseline carbon stocks

Based on data from 8 measurement plots installed prior to site preparation at the Sivadas project site, baseline carbon stocks in brush are estimated at a mean 65.0 t C/ha (96.6 t CO_2/ac) with a standard error of 4.7 t C/ha and a 90% confidence interval of 14% of the mean. The variability in this data indicates that 15 plots would be needed to attain a 90% confidence interval of 10% of the mean. The upper bounds of the 90% confidence interval is 75.8 t C/ha (31 t C/ac).

Projected growth and carbon benefits

Growth was modeled in FVS over 100 years, based on the survival count done in August 2010, with 274 ponderosa pine (90% survival) planted per acre in 2009. Table 12 shows growth and carbon stocks for a 100 year period, starting in year 10.

Table 12. 100-year growth projections on the Wilson 2009 planting

Year	Trees per acre	Board feet/ac	Total C stocks/ac	Net C stored/ac	CO_2 stored/ac	Total CO_2
2019	247	0	5	-26	-94	-1,318
2029	242	0	9	-22	-79	-1,113
2039	237	2,289	22	-9	-32	-446
2049	231	5,983	37	6	23	324
2059	203	10,350	50	19	71	992
2069	185	14,369	61	30	111	1,556
2079	171	18,493	71	40	148	2,070
2089	142	21,516	79	48	177	2,480
2099	123	23,779	86	55	203	2,840
2109	107	25,908	91	60	221	3,096

4.11 Lakey property

This is a 60-acre project located at T37N R4E, and includes portions of SE ¼ Section 27 & SW ¼ of NE ¼ Section 26 (**Figure 25**). The property is at approximately 3,750′-3,880′ in elevation with slopes ranging from 0-40%, and aspects mostly facing north and northwest. Soil types according to the NRCS Intermountain Soil Survey include Chirpchatter-Hunsinger Complex and Jellico-Splawn Complex, about 30 acres each. The site is part of approximately 700 acres that burned in the July 2007 Power Fire, which was a fairly severe burn. Vegetation prior to the project included burned skeletons and stubs of what had been dense, decadent brush consisting of Greenleaf Manzanita, scrub oak, squawbush, deerbrush, and redbud, with some scattered trees consisting of Oregon white oak and California black oak. Prior to the Power Fire, the site and surrounding area consisted of 26 year old brush and oaks that resprouted and/or became well established after the 1982 Chalk wildfire. Although no remnant ponderosa pine stumps were found in the burned area, there are some ponderosa pines growing on these same soil types in the general vicinity.

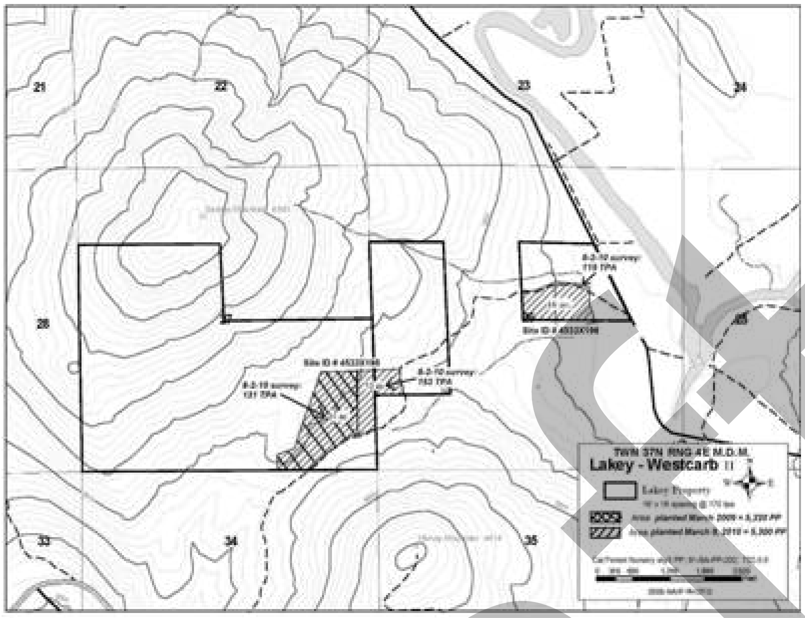

Figure 25. Map of 60-acre Lakey afforestation project, with solid outline showing property boundaries, cross-hatched area showing 2009 planting, and hatched area showing 2010 planting

Implementing this project presented a unique opportunity because the fire was relatively recent and underbrush has not reestablished in the area. This means that there is minimal need for pretreatment activities, saving time and money, and avoiding removal of carbon sequestered in brush species. The project is an excellent pilot project on lands that are typical of the hundreds of acres of non-stocked federal and private forestland in this vicinity that require management to become productive native conifer forests (mostly ponderosa pine and possibly Douglas-fir).

In March 2008, a test planting was conducted to determine how ponderosa pine seedlings would fare on the burned-over soil, and especially to determine if netting would be needed to protect the seedlings from browse. The test planting yielded a 90% survival rate after one growing season. The project area was sprayed in both the early summer and fall of 2008 to reduce competition from resprouting brush and scrub oaks. In March 2009, 5,270 one-year-old containerized ponderosa pine seedlings were planted on 31 acres at 170 trees per acre. In March 2010, a second planting of 4,930 seedlings occurred on 29 acres. The area was monitored for the need for follow-up weed control. Both plantings were followed by a directed foliar spray application by hand crews to control newly emerging forbs and grasses.

Survival Monitoring

On August 25, 2010, 68 1/100th acre plots were sampled with the following results: 132 ponderosa pine trees per acre are very well distributed throughout the project area (Survival after two years = 75%, **Figure 26**). Most of the seedling mortality occurred in the first growing season, during which precipitation levels were about 20% of normal. The ponderosa pine seedlings that did survive in most of the project area exhibit good vigor. The best survival occurred in the 2010 planting on the upper unit (13 ac with survival of 153 tpa) and the poorest survival occurred on the lower unit which was also planted in 2010 (16 ac. with survival of 119 tpa). Although 2010 was a better planting year than 2009 due to more spring rainfall, the upper unit that was planted in 2009 (31 ac. with survival of 131 tpa) had better survival than the lower unit planted in 2010 because the upper unit is comprised of slightly better soils (slightly deeper & higher water holding capacity). There is a negligible amount of competing grasses, forbs or brush in the project area.

Figure 26. Ponderosa pine seedling 6 months after planting (L) and 18 months after planting (R)

Suggested potential future activities

The current stocking of 130 trees per acre is ideal for the landowner's long term objectives to turn the brushfield into an open timber stand with grass and forb forage understory. However if funding and seedlings are available in spring of 2011, interplanting about 800 ponderosa pine seedlings on the lower 16 acre unit could be done to bring that unit up to 170 trees per acre. No grass, forb or brush treatments are necessary for 2011. It is anticipated that no future grass or forb treatments will be needed because once ponderosa pine seedlings are well established (e.g. "free to grow" for 3 years) they should be vigorous and deeply rooted enough to survive and grow well with grasses and forbs. However brush competition should be monitored and controlled if needed for a few more years. The project area should also be monitored for invasive species in future years and treated if necessary. Pre-commercial thinning will not likely be needed in the future due to the wide initial spacing.

Costs

The total cost of afforestation at this site was $28,919 or $482/acre. This cost includes site preparation ($106/ac); seedlings ($31/ac); planting costs ($199/ac); and follow-up spray ($146/ac). Total operational costs were relatively low because shrub cover had not reestablished on the site following the Power Fire, and as a result there was no need for mechanical site preparation and brush removal.

Baseline carbon stocks

Because the land had burned in the Power Fire and vegetation had not regrown prior to inception of this pilot project, there was no existing vegetation and the baseline carbon stocks are considered to be zero.

Projected growth and carbon benefits

Growth was modeled in FVS over 100 years, based on the survival count done in August 2010, with 177 ponderosa pine (75% survival) planted per acre in 2009 and 2010. Table 13 shows growth and carbon stocks for a 100 year period, starting in year 10.

Table 13. 100-year growth projections on the Lakey 2009 planting

Year	Trees per acre	Board feet/ac	Total C stocks/ac	CO_2 stored/ac	Total CO_2
2020	133	0	4	15	880
2030	130	0	6	22	1,320
2040	128	831	12	44	2,640
2050	125	2,861	20	73	4,400
2060	123	4,794	29	106	6,380
2070	120	7,752	37	136	8,140
2080	118	10,563	46	169	10,120
2090	115	13,308	54	198	11,880
2100	107	16,197	62	227	13,640
2110	101	18,782	69	253	15,180

4.12 Bureau of Land Management

This is a 7 acre project located within the San Buenaventura Land Grant, with no township, range, or section number. The land is at approximately 500’ in elevation with mostly flat slopes. According to the NRCS Shasta County Soil Survey, there are two soils in the project area, each about 50% of the total area: Anderson gravelly sandy loam and Reiff gravelly fine sandy loam. Site class is marginal for commercial conifers. The pre-project vegetation was thick, well-rooted grass and forb cover. The soils are low site quality and are best suited for oak trees; the planting entailed primarily valley oak, but also some canyon live oak, based on acorn availability.

Figure 27. Tubex shelters protecting oak seedlings on BLM afforestation project

Site preparation entailed direct foliar spraying to reduce weedy vegetation. Prior to planting, the area was disked to assist with planting and weed control. Acorns were harvested from the nearby area in January 2009, and water-tested to ensure viability. Prior to planting, approximately 75% of the acorns had begun to germinate having an approximate ¼ - ½ inch root tip. Vegetation was scalped out prior to planting one acorn at each spot. In February 2009, 143 spots per acre were planted with acorns. Acorns were planted ½ - 1 inch deep in a hole dug several inches deeper than acorn was actually planted. Whole was backfilled to allow ½ to 1 inch for planting. If germinated, root was planted down, and un-germinated acorns were planted on their side. Three-foot-tall Tubex Treeshelters were installed over planting spots and anchored to 4' wooden white oak stakes (**Figure 27**). The landowner agreed to monitor weed growth, mow the surrounding areas, and retreat with foliar spray as necessary.

Survival Monitoring

During the months after the initial acorn planting, the project area was not maintained to prevent weed growth from competing with the oak seedlings and there was 95% mortality. In order to compensate for this, a second acorn planting was done in January 2010. The site was monitored in August, 2010, and there were a total of 253 successful spots, a 25% survival rate.

Costs

The total cost of afforestation at this site was $13,160 or $1,880/acre. This cost includes acorn collection ($186/ac); planting costs ($1,237/ac); and follow-up spray ($457/ac). The planting costs are far more expensive than for the other projects because they require a great deal of labor to plant each spot and install Tubex shelters. The follow-up spray is relatively expensive in part because initial weed treatment by mowing did not occur as planned, and vegetative regrowth therefore required heavy chemical treatment. Because the landowner covered the site preparation with mowing and disking, these costs are not included in the total. In addition, the replanting following the initial poor survival was done by volunteers as part of a high school biology curriculum and so these costs are also not incorporated in the total.

Baseline carbon stocks

Prior to inception of this pilot project, the area consisted of only herbaceous plants, and no shrubs or trees were removed during site preparation, so the baseline carbon stocks are considered to be zero.

Projected growth and carbon benefits

Growth was modeled in FVS over 100 years, based on the survival count done in August 2010, with 143 acorn spots (25% survival) planted per acre in 2009. Diameter growth projected by FVS was unreasonably low, so look-up tables for afforested western oak stands in the Pacific Southwest (Smith *et al,* 2006) were also consulted, and values were included based on the 25% survival rate on this planting. Table 14 shows growth and carbon stocks from both FVS and look-up tables for a 100 year period, starting in year 10.

Table 14. 100-year growth projections on the BLM 2009 planting

Year	Trees per acre	Total C stocks/ac (FVS)	Total C stocks/ac (look-up table)	CO_2 stored/ac	Total CO_2
2019	36	4	1.6	6.0	41.7
2029	35	5	2.5	9.2	64.5
2039	34	5	4.4	16.0	112.0
2049	33	5	7.8	28.7	200.8
2059	32	5	11.8	43.2	302.2
2069	31	5	15.2	55.7	389.8
2079	30	5	17.9	65.7	459.8
2089	29	5	20.2	73.9	517.5
2099	28	5	22.0	80.7	565.0
2109	27	6	23.6	86.4	604.5

5.0 Summary of Pilot Projects

- Approximately 400 landowners were contacted regarding participation in WESTCARB afforestation pilot projects, through targeted mailings, watershed groups and other mechanisms.
- Forty-four landowners were formally surveyed on their interest in afforestation, willingness to share costs, specific site conditions on their lands, acres available, species preferences and other factors.
- Seventeen site-specific afforestation planting and maintenance plans were developed, detailing acres available, soils, seed zones, site class, precipitation, elevation, slope, terrain, current vegetation and other conditions affecting afforestation, estimated costs, and step-by-step plans for mechanical and chemical site preparation, planting, and early maintenance treatments.
- Twelve landowner agreements for WESTCARB afforestation pilot projects have been signed and implemented, totaling 476 acres of afforestation. Projects range in size from 7 to 98 acres, averaging 40 acres.
- Project baselines consisted of a variety of brush species, mostly fairly dense. Baseline carbon stocks ranged from zero, for a project that had recently burned in a wildfire, to 34 metric tons of carbon per acre, on a project with dense old-growth Manzanita.
- Projects were planted to ponderosa pine, mixed conifer stands, or native oaks. After 60 years, net carbon stocks on conifer plantings ranged from 11 t C/ac to 73 t C/ac. The native oak planting had net carbon stocks of 24 t C/ac after 60 years.
- Survival of planted conifer seedlings was high, despite limited rainfall in the year of planting.

Table 15. Summary of all WESTCARB Shasta County afforestation pilot projects

				Baseline		Afforestation			Net Carbon Stocks (t/ac)				
Project	**Acres**	**Total cost**	**Cost/ac**	**Cover species**	**C stocks (t/ac)**	**Species**	**Trees/ac planted**	**Survival**	**10 years**	**20 years**	**40 years**	**60 years**	**100 years**
Red River Forests Partnership	98	$81,532	$832	manzanita	21	Ponderosa pine	300	99%, plus ingrowth	-16	-10	21	47	73
Brooks Walker	7	$8,854	$1,265	manzanita	3	Ponderosa pine & red fir	300	73%, plus ingrowth	2	6	37	65	100
Hendrix-Phillips Tree Farm	20	$24,453	$1,223	manzanita	24	Ponderosa pine	300	93%	-19	-14	15	40	67
Goose Valley Ranch	60	$61,958	$1,033	whitethorn	20	Ponderosa pine, Douglas fir, incense cedar	290	83%, plus ingrowth	-15	-9	22	51	80
Lammers	50	$42,885	$858	greenleaf, deerbrush, whitethorn	15	Ponderosa pine & Douglas fir	249	69%	-11	-8	14	39	74
Frase	43	$25,812	$600	none	0	Ponderosa pine	282	93%	5	8	33	55	85
Kloeppel	51	$45,870	$899	greenleaf, deerbrush	10	Ponderosa pine & Douglas fir	314	84%	-5	2	38	68	98
Sivadas	46	$35,805	$778	manzanita	44	Ponderosa pine	197	97%	-39	-36	-12	11	43
Eilers	20	$7,084	$354	none	0	Ponderosa pine (18 acres)	208	72%	4	6	18	33	64
						Ponderosa pine & blue oak (2 acres)	258	52%	5	6	15	27	53
Wilson	14	$18,198	$1,300	manzanita	31	Ponderosa pine	274	90%	-26	-22	6	30	60
Lakey	60	$28,919	$482	none	0	Ponderosa pine	177	75%	4	6	20	37	69
BLM	7	$13,160	$1,880	none	0	Oak	143	25%	2	3	8	15	24

Table 15 shows a summary of all of the pilot projects, including cost, baseline carbon stocks, and projected carbon stocks resulting from afforestation.

The projects varied widely in per acre cost, based largely on the intensity of site preparation prior to planting and vegetation control to decrease competition following planting. Eilers and Lakey had the lowest per acre costs, because in both cases there was no brush to remove in the project area when the pilot project began. The BLM had the highest per acre cost, due to both the intensity of hand planting acorns and installing protection and the fact that weed control was not undertaken early and intensive measures were required later. The most expensive conifer plantings, on a per acre basis were Brooks Walker, Hendrix Phillips and Wilson, all of which had extensive brush cover which had to be removed prior to afforestation, as well as fairly intensive needs for post-planting weed control.

The costs listed in this report only address the actual costs of afforestation, and do not include the cost of monitoring, measurement, and registration of a carbon project on a registry. These costs vary depending on the project area and the requirements of the registry, but likely start at $8 per acre per year.

The baseline carbon stocks also varied, ranging from zero to 34 tons of carbon per acre, with the areas with dense Manzanita having the highest carbon stocks.

The variation in net carbon stocks resulting from tree planting was due to a number of factors. In cases where the baseline carbon stock was high, such as Sivadas and Wilson, the net carbon stored in the planted trees will not exceed the baseline stocks until year 30 or later. Site quality, species planted, number of trees per acre planted, and seedling survival all have an impact on forest growth and therefore carbon stocks. Fir, for instance, sequesters more carbon than does ponderosa pine, but across the projects, fir had a much lower survival rate than pine. Oaks grow at a very slow rate and therefore do not store much carbon at all. However, there are other reasons to grow oaks. The pine and oak planting on Eilers shows that it is possible to achieve decent survival in both on a relatively low site, and yield some carbon benefit.

Carbon offsets

By their nature, afforestation projects generally have a lag time before an adequate amount of carbon is accumulated to overcome the baseline deduction, and thus before sufficient offsets are generated for a sale. Of the 12 pilot sites, more than half had negative carbon balance after ten years—that is emissions from the baseline exceeded removals by the planted trees (Table 15). Even after 20 years, five sites were still in a negative balance. But by 40 years after the start of the planting, practically all (one exception) had a positive carbon balance of between 11 to 41 t C/ac.

Given the time lag between initiation of the planting and a positive carbon balance on the pilot sites, we determined what price of carbon offsets would be required for each of these projects to break even. The 40 year time frame was chosen for this analysis as by this time all projects have a net positive gain in carbon. In addition to the establishment costs described above (see Table 15 and individual project descriptions), total project costs used to determine the breakeven price included costs incurred from participation in the carbon market. These costs are monitoring and maintenance costs ($2.30/ac/yr), a one-time carbon market enrollment fee ($4/ac), and carbon market maintenance costs ($2/ac/yr)[7].

Without addressing other deductions for risk factors, the breakeven point differs widely across the projects. Setting aside the project that has not achieved positive net carbon stocks (Sivadas) and the BLM project with low carbon accumulation and very high establishment costs, the minimum breakeven offset price at 40 years is $6.41/t CO_2 (Frase) and the maximum is $67.09/t CO_2 (Wilson). The mean is $17.47/t CO_2 and the median is $10.62/t CO_2. Table 16 shows the breakeven price for carbon offsets for each project at 20, 40, 60, and 100 years.

Table 16. Breakeven price of carbon offsets ($/ton CO_2) for Shasta County afforestation pilot projects; empty cells indicate that the project had not reached net positive carbon stocks

	20 years	40 years	60 years	100 years
Red River Forests Partnership		$13.09	$6.35	$4.73
Brooks Walker	$61.59	$10.62	$6.41	$4.63
Hendrix-Phillips Tree Farm		$25.44	$10.13	$6.74
Goose Valley Ranch		$14.99	$6.93	$5.00
Lammers		$20.14	$7.83	$4.76
Frase	$23.52	$6.41	$4.27	$3.32
Kloeppel	$134.86	$7.72	$4.66	$3.71
Sivadas			$25.79	$7.69
Eilers - pine	$20.18	$8.03	$5.09	$3.36
Eilers - oak/pine	$4.09	$9.64	$6.22	$4.05
Wilson		$67.09	$14.20	$7.88
Lakey	$26.00	$8.97	$5.48	$3.62
BLM	$179.09	$70.09	$38.95	$26.30

6.0 Conclusions and Recommendations

6.1 Conclusions

Landowner interest in conducting afforestation for carbon sequestration appears very strong, and landowners are willing to share costs for projects intended to increase carbon sequestration. The level of interest garnered through the landowner outreach process resulted in many more potential projects than could be funded directly through WESTCARB. Landowners appear to have a range of reasons for their interest, including: interest in multiple revenue streams and other values from afforestation; relatively cautious interest in evolving carbon market opportunities; personal desire to contribute to mitigating climate change; and interest in improving forest health or reducing fire risk.

Despite the high level of interest in implementing projects, landowners had very limited understanding of carbon markets, offset project protocols, potential future carbon prices,

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[7] These costs are estimated based on current information. They may vary for different properties and different carbon registries, and are subject to change over time.

structure and timing of transactions, and other aspects of carbon projects. Some efforts have been made to provide education on these topics, but this was challenging due to the fundamentally uncertain and rapidly changing nature of carbon markets and the underlying policy context.

Projects with lower opportunity costs, such as converting brush fields (caused by lack of forest recovery after fires) to forest, and project designs allowing flexibility to landowners in future management of afforested areas, were understandably more attractive. The opportunity, identified in Phase I, of afforesting past fire sites that have returned to more or less permanent brush, has proved extremely attractive and appears to have significant replication potential. However, conversion costs, although varying by project, were quite high, depending on the requirements for site preparation needed to remove brush and prepare sites for planting. In addition, the potential carbon benefits vary widely, and those projects with high baseline carbon stocks do not yield a net carbon benefit for 30 to 40 years after project implementation. For these reasons, it is critical to thoroughly assess feasibility of individual projects prior to full investment and implementation.

Afforestation of oaks in rangeland posed special challenges for implementation, landowner interest, and landowner cost-share willingness. This may in part be attributable to several decades of landowner education promoting oak eradication to increase forage. This could be in part a perception problem as it appears feasible to allow oaks and cattle to coexist by simply protecting oak seedlings for several years after planting. There have been few examples of operational-sized oak regeneration projects completed in California to provide a reliable track record for success. Thus only two WESTCARB afforestation pilots involved oak planting, one of which was in combination with ponderosa pines. The combined oak/pine mix will produce a mixed-species forest and also give landowners greater carbon market revenue potential than planting oaks alone. The oak planting yielded very limited carbon benefits, and is not a viable project type for carbon purposes alone.

The operational process, requirements and costs for afforestation are well understood. The only significant operational challenge encountered was the attempt to use brush grinding and removal to a biomass energy facility, in place of conventional pile-burning. This practice is only technically and economically feasible on certain sites, and part of the challenge to broader implementation is the scarcity of operators with appropriate expertise and equipment.

In the context of current debates over the role of offset projects in existing voluntary and future regulated markets, afforestation projects such as those implemented under WESTCARB are likely to meet all the criteria for high-quality offsets. The projects are straightforward to measure, monitor and verify, can produce clear carbon benefits net of the baseline, are relatively transparent and enforceable, and are amenable to securing of project risk through various mechanisms. Perhaps most significant in offset project debates is a question of "additionality," which is defined differently in different markets and protocols. Implementing afforestation in project designs similar to the WESTCARB pilots seems clearly to meet all carbon market protocol requirements for biological, regulatory and financial additionality.

Afforestation appears to have substantial environmental co-benefits in creating a healthier forest with mixed species and wildlife habitat diversity, providing timber and biomass fuel values, and reducing fire risk by interrupting the “brush-and-burn” cycle. It may have an additional climate *adaptation* benefit if afforestation projects can be placed strategically in upper watershed locations to help mitigate the expected effects of climate change on water availability and timing (California Energy Commission 2006).

6.2 Recommendations

- WESTCARB states should continue to support efforts to explore the potential of afforestation to contribute to state GHG reduction goals. Many different afforestation project designs are conceivable, some of which were piloted under WESTCARB and could be replicated broadly elsewhere in California and the WESTCARB region. Afforestation can make a significant contribution to carbon sequestration, climate change mitigation and adaptation, and should be considered as part of the broad portfolio of strategies under consideration by the State of California (Climate Action Team and AB32) and analogous policy processes in other WESTCARB states.
- Ongoing outreach and education is necessary to keep landowners informed about the opportunities to conduct afforestation for carbon sequestration, evolving carbon markets and climate change policies, and requirements for participation.
- As discussions continue about GHG accounting and offset project protocols, both in the voluntary and regulated market contexts, flexible mechanisms should be considered to address barriers to broader landowner participation, while maintaining high standards for real, additional, independently verifiable, permanent, enforceable, predictable, and transparent GHG reductions. Important mechanisms to increase accessibility of carbon projects include aggregation of multiple projects on small ownership so that they can improve economies of scale and stacking of project benefits and income streams.

6.3 Benefits to California

The State of California has enacted the Global Warming Solutions Act of 2006 (AB32), which directs the Air Resources Board to develop greenhouse gas emission regulations in order to meet the State's target of statewide emissions at 1990 levels by 2020. Regulations are currently being developed and are scheduled to take effect in 2012. By Executive Order on October 17, 2006, Governor Schwarzenegger directed the ARB to develop a comprehensive market-based compliance program as part of these regulations, which would allow the State to achieve the most cost-effective emission reductions and also permit trading with the European Union and the northeastern states’ Regional Greenhouse Gas Initiative. One of ARB’s tasks has been to decide what types of activities are eligible for trading under the market-based compliance program, including what types of forestry activities and what specific protocols or requirements will need to be met in order for credits from such projects to be traded. Results from WESTCARB afforestation pilot projects in northern California have helped to inform State policy developments and market eligibility questions, while also addressing issues of landowner uptake, project costs, measurement, monitoring and verification.

Significant debate continues over the appropriateness and role of offsets (emission reductions by sources not included in a cap-and-trade program) in achieving GHG reduction goals, what types of offsets should be allowed, what eligibility criteria offsets must meet, and protocols for rigorous measurement, monitoring and third-party verification. Executive Order S-20-06 charged the AB32 Market Advisory Committee with advising the Air Resources Board on the design of a market-based compliance or "cap-and-trade" program. The committee recommended in its June 2007 final report that such a program include offsets, without limitation and both inside and outside California, provided such projects meet a series of stringent criteria. Offsets should be "real, additional, independently verifiable, permanent, enforceable, predictable, and transparent," as well as meeting standards for rigorous accounting methods and environmental integrity (Market Advisory Committee 2007).

Afforestation projects like those being demonstrated under WESTCARB are perhaps the most likely to meet the Market Advisory Committee's criteria for high-quality offsets. Projects are straightforward to measure, monitor and verify; clearly meet biological, regulatory and financial additionality tests; are enforceable, predictable, and transparent; and provide various environmental co-benefits. Projects demonstrated to meet these quality criteria are likely to be attractive to landowners/carbon credit suppliers and to entities purchasing offsets, either under the market-based compliance components of regulatory programs or in rapidly growing voluntary markets.

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Annex A: Invitation and Agenda, WESTCARB Shasta County Landowner Outreach and Stakeholders Meeting (October 26, 2006)

Western Shasta RCD and Winrock International are inviting Shasta County stakeholders – landowners, land managers, ranchers, foresters and others – to a kickoff meeting of the West Coast Regional Carbon Sequestration Partnership (WESTCARB) on Thursday, October 26, 2006.

WESTCARB, led by the California Energy Commission, is one of seven US Department of Energy regional partnerships across the US working to demonstrate ways to sequester carbon dioxide and reduce emissions of greenhouse gases linked to global warming. Terrestrial (forestry and land use) sequestration options being investigated for Shasta County include afforestation of marginal rangelands, improved management of hazardous fuels to reduce emissions from wildfires, biomass energy, and forest management.

In part, this will be a follow-up meeting to the June 2005 "Shasta County Stakeholders Meeting" in Redding. Winrock will report on the results of its research into forestry and land use opportunities that can sequester carbon and provide benefits to landowners.

A second purpose is to provide information to landowners, land managers and other stakeholders about the types of activities planned for Shasta County under WESTCARB, including opportunities to participate in afforestation, fuel management and forest management activities and what the benefits and costs of participation might be. Winrock, Western Shasta RCD and other WESTCARB partners will provide an overview of project opportunities, evolving carbon credit markets, requirements for implementing, measuring and reporting projects, and related issues. The attached flyers provide further information.

Date:	Thursday, October 26, 2006
Time:	1:00 p.m. to 5:00 p.m.
Location:	Lassen Conference Room Western Shasta RCD 6270 Parallel Road, Anderson, CA 96007
RSVP/further information:	Priscilla Benson, (530) 365-7332 ext 216 Priscilla@westernshastarcd.org or

Mike Harris, (530) 365-7332 ext 214

WESTCARB LANDOWNER OUTREACH
&
SECOND SHASTA STAKEHOLDERS MEETING

DATE Thursday, October 26, 2006, 1:00 – 5:00 PM

LOCATION
Lassen Conference Room
Western Shasta RCD
6270 Parallel Road, Anderson, CA 96007

PURPOSE The West Coast Regional Carbon Sequestration Partnership (WESTCARB), led by the California Energy Commission, is one of seven US Department of Energy regional partnerships working to demonstrate ways to sequester carbon dioxide and reduce emissions of greenhouse gases linked to global warming. Terrestrial (forestry and land use) sequestration options being investigated for Shasta County include afforestation of marginal rangelands, improved management of hazardous fuels to reduce emissions from wildfires, biomass energy, and forest management.

This meeting will provide an opportunity to report back to those who attended a June 2005 "Shasta County Stakeholders Meeting" in Redding on the results of Winrock's research into forestry and land use opportunities that can sequester carbon and provide benefits to landowners. Secondly, the meeting will provide information to landowners, land managers and other stakeholders on the WESTCARB activities planned for Shasta County. WESTCARB partners will provide an overview of project opportunities, evolving carbon credit markets, benefits and costs of implementing carbon projects, and requirements for measurement, monitoring and reporting.

AGENDA

1:00 Welcome
Mary Schroeder, Western Shasta RCD

1:05 Meeting Overview
John Kadyszewski, Winrock International

- Review of State- and County-level research to date funded by California

Energy Commission – Public Interest Energy Research Program
- Overview of WESTCARB terrestrial sequestration activities in Shasta County

1:15 WESTCARB objectives
Rich Myhre, WESTCARB

1:30 Afforestation of Marginal Rangelands
- Summary of findings for Shasta County on carbon sequestration from afforestation of rangelands: *Silvia Petrova, WI*
- Overview of WESTCARB afforestation plans: *Tim Pearson, WI*
- Afforestation planting and maintenance techniques: *Bob Rynearson, WM Beaty & Associates*
- PG&E's Climate Protection Tariff - opportunities for landowners conducting afforestation to supply carbon credits: *Dave Goehring, PG&E / Robyn Camp, California Climate Action Registry*

2:10 Open discussion - landowner questions and concerns on afforestation

2:45 Break

3:00 Improved Management of Hazardous Fuels
- Summary of findings for Shasta County on improved fuels management to reduce greenhouse gas emissions from wildfire: *Nick Martin, WI*
- Commercial timberland perspective on fuel reduction: *Bob Rynearson, WM Beaty & Associates*
- Public lands perspective on fuel reduction: *TBD*
- Non-industrial private lands perspective on fuel reduction: *Jack Bramhall, Western Shasta RCD*

3:40 Open discussion - landowner questions and concerns on fuel reduction

4:15 Conservation-Based Forest Management for Carbon Sequestration
John Nickerson, Pacific Forest Trust

4:30 Overview of the California Climate Action Registry: opportunities and requirements for landowners, summary of existing forest sector protocols, and new protocol development outlook
Robyn Camp, California Climate Action Registry

4:45 Wrap up and next steps
John Kadyszewski, Winrock International

5:00 Adjourn

Annex B: Shasta County Landowner Willingness to Participate Survey

Purpose
To identify the types of landowners who may be interested in committing themselves to future participation in climate-change mitigation forest plantation programs and to understand the conditions under which landowners may be interested.

Objectives

1. To understand the willingness of Shasta County[8] range landowners to plant trees on their lands for the purposes of carbon sequestration.
2. To determine cost-share levels at which landowners will be willing to plant additional lands to trees.
3. To assess the extent and type of land that individual landowners would be willing to plant if their expectations for cost-share support were met.
4. To evaluate species preferences for plantation on their lands.
5. To validate survey commitments by providing selected landowners with opportunities to plant their lands with pilot project funding.

Background
Finding landowners willing to plant additional lands to trees for the purposes of carbon sequestration is an important part of the Shasta County pilot project under the West Coast Regional Carbon Sequestration Partnership (WESTCARB). A survey was proposed and agreed to ensure the landowner selection process will be as objective as possible and at the same time provide valuable data on how landowners perceive the potential opportunities from forest carbon sequestration projects.

Methods
This study will be implemented by the Western Shasta County Resource Conservation District, supervised by Leslie Bryan of the RCD with guidance from Winrock International.

Landowner target groups will be those who own range, scrub or disturbed forest lands on which natural forest or plantations do not currently exist. Three categories of landowner have been identified as a useful stratification of the sample population of landowners:

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[8] Shasta County is the official location of WESTCARB pilot activities. However landowners in neighboring counties, interested in similar activities and with similar land types, may also be surveyed for potential involvement.

A. Family landholdings that have been held for two or more generations in the same family, and for which the current owners have made some form of commitment that these lands will remain in family ownership well into the future.
B. Landowners who have part-time interests in the land, are most likely absentee-owners and have few financial investment constraints for their properties.
C. Owner-occupants who are first-generation owners of the land

The survey will be administered to at least 20 owners in each of these three strata, or about 60 landowners total, if possible. Landowners will be selected by the RCD using their records, selecting landowners in each of the three classes above. If feasible, a minimum landholding size of 100 acres should be targeted, but landowners with smaller holdings but strong interest should not be excluded. Phone contact with potential interviewees will be made by the RCD as the list of survey participants is constructed.

The survey is designed to take 15 minutes or less after the initial introductory explanations and pleasantries. It is assumed that the RCD will be able to identify the land holdings and have cadastral and vegetation data for each of them before the interviews take place.

Survey methods will be determined by the RCD based on their experience. Options include phone interviews, on-site interviews by an RCD staff member (preferable to phone interviews if time permits), or possibly administering the survey in conjunction with a watershed group meeting. The interviewer should begin by providing a brief explanation about WESTCARB, climate change, afforestation opportunities for landowners, opportunities to market carbon credits from afforestation in California, and the purpose of the survey. If done in a watershed group meeting, this general introduction could be made to the group and then the survey administered individually.

The interviewer should complete the attached interview data sheet during or immediately after the interview.

Data from the interview data sheets will be entered by the RCD into an Excel spreadsheet to be provided by the Winrock survey coordinator. Original data sheets will be retained by the RCD until the completion of the Project. The completed Excel worksheet will be provided by the RCD to the Winrock survey recorder for statistical analysis by Winrock.

The RCD interviewer may bring along with them a map of the land holding (preferably with cadastral boundaries over an aerial photo backdrop) so that specific land areas where a landowner is interested in planting trees can be marked. Alternately, this can be done in a follow-up meeting if the RCD believes landowners would be more comfortable with a two-step process.

Interview Data Sheet
Shasta County Landowner Willingness to Participate Survey

Interviewer name: ______________________________
Date of interview: ______________________________

This section to be completed before the interview:
Landowner name: ______________________________
Site identifier: (RCD to use their own resources to positively identify the parcel(s) the owner(s) will discuss during the interview)
Land holding size: _____________acres
Ownership strata: _________ Family-owned (A)
_________ Absentee/part-time occupant (B)
_________ Full-time occupant, first-generation (C)

Following information to be collected during the interview:

Question	**Response**
1. Confirm parcel information noted above, correct as needed	
2. What would you need in order to be willing to plant additional trees on your land?	Circle all that apply: A. Nothing needed, plan to do anyway B. Cost-sharing for planting cost C. Cost-sharing for planting and maintenance cost D. Cost-sharing for irrigation, tree protector systems, or associated costs E. Opportunity to market wood products from project F. Opportunity to market carbon credits from project G. Seedlings H. Additional information I. Other:
3. If cost-sharing is required: What level of cost-sharing would you require?	_________ $ per acre or ________% of total cost

4. If everything specified above was provided (e.g. cost-sharing, information, seedlings, etc) how much land would you potentially be willing to plant with trees?	_________ acres or ________% of total holding
5. Willingness to participate in annual photo documentation and 2 page survey for 10 years	Yes or No
6. Landowner Objectives	Record landowner property objectives in rough order of priority: A. Income production B. Aesthetics C. Recreation D. Timber production E. Homestead F. Other (list here):
7. If interested and prepared to do so, can you designate which parts of your land you would be willing to plant? [OPTIONAL]	[This question should only be asked if the landowner is strongly interested and ready to designate on the map of their landholding specific areas/vegetation types they would be willing to plant. Otherwise, this step can be done in a follow-up meeting with interested landowners.]
8. What is the current state of the proposed site?	Record any site description information available such as accessibility, slope, existing vegetation, etc.
9. Which tree species would you most like to plant on your lands?	Circle all that apply: A. Commercial hardwoods B. Commercial softwoods C. Mixed hardwoods/softwoods D. Non-commercial hardwoods E. Non-commercial softwoods F. Brush species to improve wildlife

	habitat and privacy G. No preference H. Not sure I. These species (list here):
10. What concerns do you have about tree planting on your property?	Circle all that apply: A. No Concerns B. Decreased forage C. Increased fire risk D. New Federal or state regulations E. Increased land management costs F. Other (list here):
11. Please feel free to add any other comments.	Record landowner's comments or concerns.

Annex C: Site-specific planting and maintenance plans for WESTCARB afforestation pilots

WESTCARB II – REFORESTATION PROPOSAL
RED RIVER FORESTS - SHINGLETOWN

BACKGROUND

Legal: T31N R01E Sec 24

Acres: 160 (project estimate is for just 50 acres, but could do more if needed)

Access: Excellent. paved county road to unit & less than one mile from to State Hwy 44..

Annual Avg PPT: approx. 45" to 50" (rain & snow)

Seed Zone: 522

Elev: 3,880'

Slope: 0%

Aspect: n/a

Site Class: III?? Dunning.

Soil Type(s): Windy and McCarthy Stony Sandy Loam; depth 40-60"; well drained & mod. To high permeability

Vegetation: mostly greenleaf manzanita brush w/ some prunus.

Frost-free period = ________ days,

Brushfield well defined on photos but would need to delineate specific project area and flag, GPS and precisely map. The following plan was based upon previous visits (fall 2006) to the property and also from examining aerial photos, soils maps, etc..

PROJECT PLAN

1. Summer 2007: Pile brush w/ cat equipped w/ brush rake.
2. Fall 2007: burn piles
3. November 2007 (or immediately after snow melt in Spring 2008): Broadcast by helicopter pre-emergent Velpar DF spray to keep brush, forb and grass seeds from germinating and competing w/ seedlings.
4. Late March – mid April 2008: plant 15,000 NSTIA lot 1N PP seedlings.
5. Spring/Summer 2009: Follow up directed foliar release spray by handcrews. If no release occurs within Grant time limits, then a spray will likely be needed in 2010 or 2011 after the Grant has expired.

WESTCARB II – REFORESTATION PROPOSAL
BROOKS WALKER ET AL – TABLE MT. BRUSHFIELD

BACKGROUND

Legal: T33N R2E Sec 36 (S½)

Acres: 14

Access: Fair-poor. Several miles of maintained, seasonal dirt logging roads to access unit which is ¼ mile away from road.

Annual Avg PPT: approx.60" (mostly snow)

Seed Zone: 522

Elev: 5,440'

Slope: 25-30%

Aspect: S to SW

Site Class: III? Dunning.

Soil Type(s): Need to verify: Nanny Gravelly Sandy Loam & Windy & McCarthy very stony sandy loam

Vegetation: mostly greenleaf manzanita brush w/ some snowbrush and Fremont silktassle

Frost-free period = 90? days,

Brushfield well defined on photos . The following plan was based upon previous visits (fall 2006) to the property and also from examining aerial photos, soils maps, etc.. Even though this is only 14 acres on some tough brush, there are nearby operational projects that would keep some of the fix costs low if funding were available from the grant to reforest this brush field on stony soils.

PROJECT PLAN

1. Summer 2007: Pile brush w/ cat equipped w/ brush rake.
2. Fall 2007: burn piles
3. Fall 2007 Broadcast by hand pre-emergent Velpar DF spray to keep brush, forb and grass seeds from germinating and competing w/ seedlings.
4. April - May 2008: plant pond pine, red fir and doug fir seedlings that are in excess of adjacent operational planting job.
5. Spring/Summer 2009: Follow up directed foliar release spray by handcrews. If no release occurs within Grant time limits, then a spray will likely be needed in 2010 or 2011 after the Grant has expired.

WESTCARB II – REFORESTATION PROPOSAL
HENDRIX – PHILLIPS TREE FARM

BACKGROUND

Legal: T33N R1W Sec 16 (SW¼)

Acres: (very approx.) 20
Access: seasonal dirt road into unit a few miles from paved county road.
Annual Avg PPT: approx. _____" (mostly rain)
Seed Zone: 522
Elev: approx. 2,200'

Slope: 0% - 30%

Aspect: none to all
Site Class: II to IV Dunning

Soil Type(s):

Aiken Stony Loam: loam, deep (60"+) well drained, rocky

Aiken Loam: loam, deep well drained, not rocky.

Cohasset Stony Loam: 48"-60" deep, well drained

1. Supan very Stony Loam: 24-40" deep; very stony

Vegetation: scattered trees (black oak, grey pine & pond pine) and brush: primarily whiteleaf manzanita with some greenleaf manzanita, buckbrush, buckeye and poison oak; and some forbs and grasses.
Frost-free period = ________ days,

Specific project area needs to be laid out if project is approved. The following plan was based upon a site visit w/ landowner. Due to configuration of brush vs. timber edges only a very rough approximation of acres was possible (20 acres), needs field layout of boundaries to calculate actual acres that would be suitable for reforestation. Although grey pine and very low vigor ponderosa pine are growing in the brush, the area can support good ponderosa pine growth provided brush (that is competing aggressively for limited summer soil moisture and light) is controlled during establishment and early growth phase. The 20 acre understocked area consists of 4 soil types with Cohasset and Aiken being deep, well drained loams and very suitable for ponderosa pine establishment and growth and the Supan soils being shallower and poorer, but still adequate for growing ponderosa pine.

PROJECT PLAN

1. Summer 2007: Pile brush w/ cat equipped w/ brush rake. Do not pile live black oaks.
2. Fall 2007: burn piles
3. Feb.-early March 2008: In conjunction w/ planting and seedling protection installation, first: Broadcast by hand pre-emergent Velpar DF spray to keep brush, forb and grass seeds from germinating and competing w/ seedlings.
4. Feb.-early March 2008: Immediately after broadcast spray plant 6,000 seedlings w/ 1foot x 1 foot scalp to remove Velpar and weed seeds away from seedlings.
5. Feb.-early March 2008: immediately after planting install mesh netting around seedlings.

6. Spring/Summer 2009: Spray re-sprouting poison oak (and if needed manzanita seedlings) if there is satisfactory window within confines of Grant term. If no release occurs within Grant time limits, then a spray will likely be needed in 2010 or 2011 after the Grant has expired.

WESTCARB II – REFORESTATION PROPOSAL

Denny Land & Cattle Co. - Goose Ranch (Lake Margaret)

BACKGROUND the following information pertains to proposed reforestation area(s):

Location of Potential Reforestation Area: T35N R2E Sec 8 (NE ½ of NE ¼; NE ¼ of NW ¼; SE ¼ of NW ¼ and NE ¼ of SW 1/4) North and west of Lake Margaret approximately 5 miles west of Burney, CA. On lands burned in the 1992 Fountain Fire.

Acres: approx. 60 to 100+ (*suitable & feasible for reforestation project*)

Access: Excellent. Via two locked gates on good rocked road that provides excellent access through the northern portion of proposed reforestation unit about 4 miles from Hwy 299E. Crews have access into the unit and a D7 crawler tractor can be transported by low-bed into the unit. Further access throughout the unit can be opened for hand planting and spray crews after a dirt road within proposed reforestation unit is cleared during piling operations.

Survey lines & corner locations: (if feasible GPS closest known surveyed corner/s)
Located and GPS'd NE Corner of Sec. 8 T35N, R2E and found some old blazed trees South and West of corner. Where proposed unit borders adjacent ownerships, lines are easily Identifiable by 10+ year old planted PP on adjacent ownership or blazed line in timber.

Easements & Utilities (location of all easements, including above and underground utilities on or near project) The landowner's RPF, Dennis P. indicated that there are no easements or utilities etc. within the proposed area.

Sensitive areas (e.g. streams, springs, unstable areas, archeological sites etc.): Lake Margaret. Landowner's RPF. requested a 150 foot buffer from high water mark for clearing and spraying. Dennis P. does not know of any arch. sites or unstable areas in clearing area and none observed on quick walk down brush covered road. Landowner does not want to use soil active herbicides such as Velpar or atrazine. But would allow use of glyphosate and possibly imazapyr products.

Annual Avg PPT: Approx. 50" to 60" in the form of rain and snow (according to "Mean Annual Precipitation for California" isohydel map compiled by S.E. Rantz)

Seed Zone: __521__

Elev: approx. 3,680' to 3,900'

Slope:__0__% - __20__%

Aspect(s): __South & East facing__

Site Class:_ Dunning Site II; CACTOS site index 74;

Soil Type(s):

1) ***Depner Gravelly Sandy Loam*** *(Approximately 30 acres): Tephra parent material; sandy loam, deep (40" to 60"), well drained, moderately rapid permeability; very high available water capacity;*

2) ***Wyntoon Sandy Loam*** *(Approximately 30 acres in N ½ of NE ¼ Sec. 8):: parent material = alluvium derived from igneous rock; sandy loam; deep (> 60"); high available water capacity, well drained.*

Vegetation:

Brush: Primarily Ceanothus cordulatus (whitethorn), approx. 5' high, thick, 15+ years old; with some bracken fern, manzanita, squaw carpet & gooseberry. Trees: 2 to 10% cover of scattered black oak and some willows. Some grasses & forbs.

Frost-free period = 80 to 100 days,

THPs, CFIP, FIP projects etc.:.

In hopes of getting CFIP funding, or cost share funding from another source, Landowner's RPF contracted to grow at Cal Forest in Etna the following for outplanting spring 2008:

PP:	10,800	Fruit Growers seed, Lot #5
DF	3,600	Fruit Growers seed, Lot #7
IC	3,600	521-4.0, 95-IC-11

General comments: Landowner's RPF said that they would like to use WESTCARB II funds to site prep in 2007 and plant in spring 2008 seedlings that they have currently growing in nurseries which would reforest about 60 acres. He would then apply for CFIP funding to site prep and plant later the remaining 100+ understocked areas of the ownership. So he needs to know fairly soon if Winrock is interested in using WESTCARB II funds for planting the seedlings currently growing in the nursery.

A portion of Landowner's share would be paid for by contribution of 18,000 seedlings at approximate value of: $3,640

Note: Although the following plan is based upon planting only 60 acres using only Goose Ranch's 18,000 seedlings under contract @ Cal Forest, this site is also suitable for NSTIA 1N seedlings owned by WESTCARB II grant and currently growing at Cal Forest Nursery for outplanting in Spring 2008. So, if no other landowner is agreeable to planting the 10,500 NSTIA 1N seedlings which are still not attached to an agreed upon 2008 planting project, then another 35 acres can be site prepped in 2007 for planting in 2008 in addition to the proposed 60 acres.

PROJECT PLAN

1. Summer 2007: Pile 60 acres with a D-7 Cat equipped with a brush rake.
2. Fall 2007: Activity: Burn piles on 60 acres (if conditions are not right and/or piles not sufficiently dry, then burn piles in fall 2008).
3. March or April 2008: Plant 60 acres at 300 trees per acre with: 10,800 Ponderosa pine 3,600 Douglas- fir and 3,600 incense cedar (seedlings from landowner)
4. late April to May 2008: Directed foliar spray application by hand crews equipped with backpack sprayers and seedling protector shields. Spray 5% generic glyphosate formulation (e.g. Buccaneer, Razor etc.) mixed w/ 5% methylated seed oil (e.g. Hasten, MSO or MOC etc.)
5. Spring 2009: Monitor for need to apply follow-up spray treatment. If needed and WESTCARB II funds are still available, negotiate spray agreement (cannot determine need or estimate cost until summer of 2008 or spring of 2009).

WESTCARB II – REFORESTATION PROPOSAL

The Lammers Ranch – Lammers Properties, L.L.C. - Robert Lammers

BACKGROUND the following information pertains to proposed reforestation area:

Legal: T35N R1E, S ½ of NE ¼ of Section 34

Acres: 53 (*suitable for proposed reforestation project*)

Access: Excellent: Less than 2 miles south of Hwy 299E off of the Moose Camp Rd and accessed by private rocked road across Roseburg Resources Co. to the rocked road that borders the west side of project area. A crawler tractor can be low-bed transported directly to the project area. Spraying and planting crews can access all sides of the unit via rocked main road on west edge and a 4WD dirt road around the remainder of the project area.

Survey lines & corner locations: (if feasible GPS closest known surveyed corner/s)
Property lines between Lammers and Roseburg Resources on the North and East side of the proposed project are clearly identified by a fence that separates Lammers' road encircling the project area and Roseburg's 10+ year old plantation. The east ¼ corner of Section 34 and the N 1/16 corner Sections 34/35 were located.

Easements & Utilities (location of all easements, including above and underground utilities on or near project): Robert Lammers stated that there were no easements or utilities within the project boundaries.

Sensitive areas (e.g. streams, springs, unstable areas, arch. sites etc.): There are no streams or wet areas within the proposed project area. There is an unnamed tributary to Goat Creek west of the project area. This tributary flows out of the Lammer's meadow property in a NE direction through Roseburg Resources Co. Summer flows in this portion of the tributary are dependent upon irrigation water that is piped into the meadow by gravity flow from Goat Creek and several springs to the east of Lammers' property. Rainbow and brown trout have been observed in the tributary and Goat Creek (as per Lammers' 1998 Forest Management Plan prepared by Lloyd Keefer, RPF). The landowner does not know of any pre-historic or historic sites within the project area.

Annual Avg Precipitation: 50 to 60" almost all in rainfall *(according to "Mean Annual Precipitation for California" isohydel map compiled by S.E. Rantz)*

Seed Zone: 522 (NE portion of 522, only about one mile from the SE portion of zone 521).

Elevation: approx. 3,900'

Slope: 0% - 5%

Aspect(s): n/a

Site Class: Dunning site III (estimated).

Soil Type: Windy & McCarthy stony sandy loams: Parent material = residuum weathered from basalt. Stony sandy loam; well drained; moderately deep (48" to 52" depth to bedrock); rapid permeability; slightly to moderately acid.

Vegetation: Prior to the 1992 Fountain Fire the vegetation in the proposed project area was Sierra Mixed Conifer forest. After the 1992 Fountain Fire the mixed conifer forest was replaced by brush, mostly greenleaf manzanita (Arctostaphylos patula) with very minor amounts of whitethorn (Ceanothus cordulatus) and deerbrush (Ceanothus integerrimus), and less than 5% cover of re-sprouted black oak trees (Quercus kelloggii) interspersed in the brush, primarily in the southern portion of the project area.

General comments:

The landowner is interested in planting ponderosa pine and Douglas fir which are well suited to the site and would not easily naturally seed into the area as would more shade tolerant conifer species (white fir and incense cedar) that produce more frequent crops of lighter weight seed that disperses much further in the wind. This is a suitable site for "High" NSTIA ponderosa pine orchard seed which should provide at least 10% or greater volume (i.e. carbon) growth than seed collected in the wild from unknown pollen sources.

All of the brush species in the project area are vigorous resprouters. Unlike the two manzanita species at lower elevations, Arctostaphylos viscida and A. manzanita, that do not normally resprout, the manzanita species at this elevation (Arctostaphylos patula) is a resprouter. So the most appropriate method of site preparation would be to clear and pile the brush. The most appropriate disposal method for the brush piles likely would be burning. However, Burney Mountain Power is twelve miles to the east in Johnson Park and depending on wood fuel market conditions, might be interested in removing the brush for biomass energy fuel.

Although there are other brushfield reforestation projects proposed in the 1992 Fountain Fire area, this proposed project is on a different soil type and different main brush type (manzanita), and at a higher elevation. The landowner has also demonstrated a commitment to reforesting his forest lands that were burned in the 1992 Fountain Fire by his cost share work with the NRCS to treat brush and plant other portions of his property.

PROJECT PLAN

1. Summer/Fall 2007 Winrock (or its consultant, Bob Rynearson) locate and purchase Douglas-fir seed from appropriate zone and elevation and NSTIA H 521/522 ponderosa pine seed from CDF or another NSTIA cooperator (private company).
2. Fall 2007: Winrock (or its consultant, Bob Rynearson) contract with Cal Forest Nursery to grow 10,570 styro 5 containerized ponderosa pine and 4,530 styro 8 Douglas-fir seedlings for outplanting in spring 2009. Ship seed to Cal Forest Nursery by November 2007.
3. Summer 2008: General Contractor (or its subcontractor) clear and pile brush on 53 acres, retaining black oaks where feasible and leaving brush around some of the oaks as micro-site cover for wildlife.
4. Late October or early November 2008 (after start of fall rains but before winter snow): General Contractor obtain necessary permits and broadcast spray 3 lbs. Velpar DF per acre on 53 acres.
5. Late Fall 2008: General Contractor prepare and submit Smoke Management plan and obtain necessary permits and burn piles.
6. January, February or early March 2009 (after seedlings lifted and packed at nursery): General Contractor transport seedlings from Cal Forest Nursery and place in cold storage.
7. Late March or April 2009 (after snowmelt when soil temperature is at 42 degrees or higher): General Contractor plant 10,570 styro 5 containerized Ponderosa pine and 4,530 styro 8 containerized Douglas-fir seedlings on 53 acres at 285 trees per acre (12' x 12' spacing & 12' from existing black oak trees).

WESTCARB II – REFORESTATION PROPOSAL

David Frase – George Belden (landowner - RPF)

BACKGROUND the following information pertains to proposed reforestation area:

Legal: T33N R5W Section: S ½ 29

Acres: 50 gross and approx. 43 net plantable (*suitable for reforestation project*)

Access: Very good: 3 miles from pavement, a dirt road accesses the project area. In June 2007, BLM constructed a road which accesses the project area on the east end along the ridge and was then GPS'd by Bob Rynearson w/ Garmin 76CSx . According to BLM, plans are to rock the road within the next few years.

Survey lines & corner locations: (if feasible GPS closest known surveyed corner/s)
No surveyed lines or corners were located during the site visit. The landowner's RPF, George Belden said that all of the masticated area is within the ownership. note: The project area including masticated units, roads and property lines was mapped using NAIP photos controlled by a Shasta County assessors map to fit USGS public land survey lines and some portions of masticated areas mapped out as being south of the property line. So the property line on the south needs to be confirmed and/or a surveyed corner needs to be GPS'd to establish better control for more accurate mapping of property lines.

Easements & Utilities (location of all easements, including above and underground utilities on or near project): Need to check with the landowner and/or RPF to see if there are any easements or utilities that would be impacted by the proposed reforestation project.

Sensitive areas (e.g. streams, springs, unstable areas, arch. sites etc.): There is a "wet" area in the draw east of the dirt 4WD road which was not masticated and will be excluded from spraying and planting operations.

Annual Avg. Precipitation: 50" to 60" almost all in rainfall *(according to "Mean Annual Precipitation for California" isohydel map compiled by S.E. Rantz)*

Seed Zone: 521 (SW portion of seed zone).

Elevation: approx. 800'

Slope: 0% - 20%

Aspect(s): slightly East, South or West facing

Site Class: possibly low Dunning site III to site IV.

Soil Type: The Shasta County Soils Map provided by the NRCS lists the soil as "Goulding very rocky loam, 30 to 50 percent slopes, eroded" which is described as a shallow (16" to 20") soil. However the actual slope within the project area is only 0 to 20 percent. Although the soil description does not indicate it is a forest soil there are many healthy ponderosa pine trees growing within the project area. The landowner's RPF, George Belden, indicated that the site class on the slopes is a Dunning IV and on flatter areas a low III. The parent material of Goulding very rocky loam is residuum weathered from greenstone.

Vegetation: Until 2005 the project area consisted of dense, 8 to 15 foot tall manzanita (90% to 100% cover) with a very scattered ponderosa pine, knobcone pine and gray pine overstory (5% to 10% cover). This vegetation type likely formed after a ponderosa pine forest was killed in the very early 1900's as a result of mining and copper smelting operations. In the spring of 2005 the landowner mechanically masticated approximately 50 acres (net 43 acres with approximately 7 acres of brush left for habitat and/or riparian protection). This low elevation manzanita does not significantly re-sprout, so the current brush includes a dense population of manzanita seedlings (about 1′ tall) over the entire area that germinated from seed after mastication; sparse to moderate cover over the entire area of Toyon (2′ to 6′ tall), coffee berry (2′ to 6′ tall) and poison oak (2 to 4′ tall); and a moderate cover of blackberries on only about 4 acres. Grasses and forbs cover about 60% of the area where the masticated slash layer is not covering the ground or is very shallow. Current trees include: 2′ to 3′ tall black and live oak and scattered ponderosa pine, gray pine and knobcone pine from seedling size to 80′ tall. Small knobcone and gray pines seedlings that seeded in after the ground was exposed in 2005 are sparsely populated throughout the area, but the ponderosa pine has not seeded in much after the mastication so most of the sparsely populated ponderosa pine are large trees ranging from approximately 12″ to 24″ dbh.

General comments:

This area is typical of tens of thousands of acres below 2,000 foot elevation where fumes from the copper smelting circa 1910 killed all the vegetation from Kennett south to Red Bluff, along the west side of the Sacramento River. Prior to the ponderosa pine die-off from the smelting, some of the forest in this general area was probably harvested in the very late 1800s and/or very early 1900's for fuel and mine timbers. Most of the ponderosa pine that has regenerated in the general neighboring vicinity of the project area were planted by the CCC in the 1930s. Survival was spotty but where seedlings survived the trees have grown fairly tall, even on steep slopes that were heavily impacted by gully erosion. Most of the general area, however, is occupied by decadent brush which periodically burns. Soil erosion subsequent to the smelting-caused vegetation die-off has likely degraded the site productivity, but more so on the steeper slopes in the general vicinity. The scattered naturally regenerated trees on the project area seem to be growing well possibly due to soil build up over the many decades of litter fall from the brush on the gentle slopes within the project area.

Since there are still several thousand acres of this former ponderosa pine habitat that is now occupied mostly by brush, this project would make an excellent pilot project for reforestation. Due to the very low elevation, hot dry summer climate and somewhat eroded soils, there is a greater risk of plantation failure than there is for projects at higher elevation sites with non-eroded soils. The landowner seems willing to try planting the site back to ponderosa pine even though conifer seedling establishment is a little risky on this site.

Since the soils were eroded several decades ago, after the forest was denuded, and it is a low elevation, hot summer site, masticating the old brush rather than piling it was a wise choice for site preparation. Instead of mechanically clearing the 2 to 4 foot tall brush that has now invaded the project area, a chemical treatment would be much more appropriate to prepare the site for planting conifers. This treatment will not only preclude the need to mechanically disturb the shallow soils, it will also provide dead shade during the hot summer for young seedlings that will be planted into the site.

There is another 30 to 40 acres of heavy brush on gentle slopes on the north portion of the property which can be masticated in preparation for planting ponderosa pine. The landowner indicated interest in possible participation for this work under WESTCARB II grant cost share funding. However at this time, with the uncertain progress of the BLM road construction that would provide better access, this project proposal does not include plans for that reforestation work. But it is a project to consider under WESTCARB II (if time allows) or the California Forest Improvement Program (CFIP) when the road construction is completed.

PROJECT PLAN

1. Summer 2007: Winrock (or its consultant, Bob Rynearson) locate and purchase ponderosa pine seed from lowest elevation 521 source available.
2. Fall 2007: Winrock (or its consultant, Bob Rynearson) contract with Cal Forest Nursery to grow 11,610 styro 5 containerized ponderosa pine seedlings for outplanting in winter 2008/09. Ship seed to Cal Forest Nursery by November 2007.
3. February – early April 2008 (depends on seasonal growth stage of target vegetation): General Contractor purchase chemical & conduct chemical site preparation consisting of three distinct treatments using handcrews equipped with backpack sprayers:
    1. On 43 acres, to control manzanita (6” to 2’ tall), poison oak, forbs and grasses: Broadcast foliar spray application of 2,4D Low Volatile ester, 4 lb/gal a.i., @ 3qt/ac (or 2 qt/ac @ 6 lb/gal a.i.) + generic Roundup original formulation (e.g. Buccaneer, Razor etc.) @ 1.5 qt/ac.
    2. On 43 acres, to control Toyon and Coffeeberry (2’ to 6’ tall): Directed foliar application of 2% Chopper (a.i. imazapyr) + 2% generic Roundup original formulation (e.g. Buccaneer, Razor etc.) mixed w/ 5 % methylated seed oil
    3. On 4 acres to control Himalayan blackberries: Directed foliar application of Garlon 4 @ 1%.
4. Winter 2008/09 (Dec. ’08 or Jan. ’09): General Contractor transport from Cal Forest Nursery, place in cold storage and then plant 11,610 styro 5 containerized Ponderosa pine seedlings on 43 net acres at 270 trees per acre (12’ x 12’ spacing & 12’ from existing ponderosa pine).
5. Winter 2008/09 (Immediately after planting): General Contractor purchase & install seedling protection netting (8 mil “light” netting should be sufficient) on 11,610 styro 5 containerized Ponderosa pine seedlings.
6. February or March 2009: General Contractor purchase chemical & conduct directed foliar spray application by hand crews equipped with backpack sprayers and seedling protector shields. Spray newly emerging forbs and grasses with 2% generic Roundup original formulation (e.g. Buccaneer, Razor etc.) mixed w/ ¼ % non-ionic adjuvant.

WESTCARB II – REFORESTATION PROPOSAL

Kloeppel (landowner name)

BACKGROUND the following information pertains to proposed reforestation area:

Legal: T35N R1W Section: NE ¼ 25

Acres: approx.50 to 120 (*suitable for reforestation project*)

Access:. Excellent: Paved roads (Woodhill Rd, Cove Rd and Hwy 299E) are very close to reforestation units and a seasonal dirt/gravel roads access unit from these paved roads.

Survey lines & corner locations: (if feasible GPS closest known surveyed corner/s)
Property lines fairly well identified. NE section corner of 25 located and GPS'd. property line to north is Roseburg Resources young plantation.

Easements & Utilities (location of all easements, including above and underground utilities on or near project): PGE easements for above ground lines (500 KV and smaller line) are located on property and are fairly well delineated.

Sensitive areas (e.g. streams, springs, Unstable Areas, Arch. sites etc.): A ditch and/or water line runs on south side of property. There is one draw in or near the project area, but there are no seasonal or permanent watercourses. Landowner has a well for domestic use. He is OK with glyphosate, but would rather not use a soil active chemical that could leach into the water table on this high rainfall site.

Annual Avg PPT: approx. 60" mostly rainfall

Seed Zone: 521/522 (Just north of boundary between 521 and 522). This area is an excellent fit for the NSTIA 1N seed lot that is currently being grown at Cal Forest Nursery for 2008 outplanting.

Elevation: approx. 2,900' to 3,160'

Slope: 0% - 20%

Aspect(s): slightly west and/or south facing

Site Class: Dunning site II or better. (ponderosa and Douglas-fir trees planted on same soil type on adjacent ownership (Roseburg) about a decade ago are growing very well).

Soil Type: Cohasset Stony Loam: Soil texture: loam ; depth:48-60 inches; rockiness: stony; drainage: well drained, moderate permeability;

Vegetation: brush: 95% brush cover w/ 90% consisting of 6 to 10 foot tall deerbrush (Ceanothus integerrimus). In more open areas of lighter brush areas of deerbrush, chinkapin, manzanita, poison oak, dogwood, bracken fern and squaw carpet and some forbs and grasses. 5 to 10% cover of trees consisting mostly of scattered black oak and a few big leaf maple. Prior to 1992 Fountain Fire, the area was a mixed conifer forest primarily ponderosa pine and Douglas fir and some black oak in the understory.

THPs, CFIP, FIP projects etc.: THP approved in 1992 a few months before Fountain Fire. .

General comments:

The landowner is interested in planting ponderosa pine and was concerned that Douglas fir (DF) would not fit since many residual DF have recently died. I pointed out that those DF were likely weakened from fire damage and have finally died. I noted stumps and logs on the ground of large DF trees that were killed in the fire. The site is very good for growing both ponderosa pine and DF.

This is an excellent site and elevation to plant the NSTIA 1N seedlings growing at Cal Forest Nursery for planting in 2008. Since there are currently about 10,500 seedlings that still need a site for 2008 planting, I recommend that 50 acres be planted at 300 trees per acre w/ 70% NSTIA 1N ponderosa pine (50 acres x 300 TPA x 0.7 = 10,500 NSTIA 1N PP) and 30% Douglas-fir. I would need to contact some other foresters in the area to see if we could purchase 4,500 DF that are now growing in a nursery.

Also, there are many more acres in need of reforestation, so if Winrock decides that the grant could/should fund more, then I could write up a proposal for 30 to 50 more acres to reforest in addition to the 50 acres in the following plan and estimates.

PROJECT PLAN

1. Summer 2007: Pile 50 acres with a D-7 Cat equipped with a brush rake. Contact neighboring industrial landowners for availability of 4,500 Douglas-fir seedlings to purchase for 2008 outplanting.
2. Fall 2007: Activity: Burn piles on 50 acres. (if conditions are not right and/or piles not sufficiently dry, then burn piles in fall 2008)
3. Early Spring 2008: Plant 50 acres at 300 trees per acre with 10,500 Ponderosa pine and 4,500 Douglas-fir (need to purchase 4DF seedlings). If no DF seedlings are available then plant 35 acres with NSTIA 1N PP in 2008 and the remaining 15 acres in 2009.
4. Immediately after planting, install seedling protection netting (8 mil "light" netting should be sufficient).
5. Spring 2008: Directed foliar spray application by hand crews equipped with backpack sprayers and seedling protector shields. Spray 5% generic glyphosate formulation (e.g. Buccaneer, Razor etc.) mixed w/ 5% methylated seed oil (e.g. Hasten, MSO or MOC etc.)
6. Spring 2009: Monitor for need to apply follow-up spray treatment. If needed negotiate spray agreement (cannot determine need or estimate cost until summer of 2008 or spring of 2009).

WESTCARB II – REFORESTATION PROPOSAL

Darryl Deaton property

BACKGROUND the following information pertains to proposed reforestation area:

Legal: T29N R9W, N½ Section 17

Acres: 50 acres (*suitable for proposed reforestation project*)

Access: Excellent: Project area is approximately ¼ to one mile NW of Hwy36 and accessed by ¼ mile of rocked road (where a lowbed trailer could unload a crawler tractor) and then ¼ mile of dirt road that transects most of the project area.

Survey lines & corner locations: (if feasible GPS closest known surveyed corner/s)
According to the landowner all of the reforestation units proposed for planting are well within his property.

Easements & Utilities (location of all easements, including above and underground utilities on or near project): The PG&E transmission easements (overhead lines) on the property should be excluded from the project area. The landowner did not mention any other easements or utilities within the proposed project area.

Sensitive areas (e.g. streams, springs, unstable areas, arch. sites etc.): There are no streams or wet areas within the proposed project boundary units.

Annual Avg. Precipitation: 30" to 40" mostly in rainfall *(according to "Mean Annual Precipitation for California" isohydel map compiled by S.E. Rantz)*

Seed Zone: SW edge of 332 (about one mile north of the NW portion of zone 371).

Elevation: Approx. 2,600' to 2,700'

Slope: 0% - 20%

Aspect(s): around ridges with aspects facing all directions

Site Class: Very low. Marginal for commercial conifers.

Soil Type: According to the NRCS Shasta County Soil Survey the two soils in the project area are listed as "Maymen very stony loam, 30 to 80 percent slopes, eroded" with "depth to lithic bedrock at 13 to 17 inches" and Millsholm gravelly loam, 30 to 50 percent slopes" with depth to lithic bedrock at 16 to 20 inches". However the project area is on flat to 20% slopes and the soils are at least 24" deep based upon digging a few test holes and observation of soil profile at road cuts. The parent material for both soil types is described as: "residuum weathered from sedimentary rock". The Available water capacity class for both soil types is listed as "very low", 1.5 inches (Maymen) to 2.1 inches (Millsholm) of water in the top 5 feet.

Vegetation: Old, dense brush consisting mostly of chamise (*Adenostoma fasciculatum*) and buckbrush (*Ceanothus cuneatus*) with some greenleaf manzanita (*Arctostaphylos patula*).

General comments: The landowners objectives are to reduce the high fire hazard risk and protect and enhance the watershed and wildlife resources over time by replacing dense, decadent brushfields with a forest of native pines (gray and ponderosa) and oaks. Effects from historical grazing and fire management practices (and possibly other practices) in the general area have combined with the climate and soils to create tens of thousands of acres of brush that grows old and decadent and then periodically burns such that few conifers, especially ponderosa pine, are left on the landscape. Oaks which re-sprout after fire and gray pine which seeds into poorer sites better after catastrophic wildfire provide sparse to moderate cover over some of the general area. But it appears some of the long past grazing practices in combination with fire and climate regime has left many thousands of acres in the general area with much less oak forest cover than is possible.

The proposed project area is a typical example of a brushfield in the general area that likely could support blue oak and gray pine and possibly even ponderosa pine. The landowner is interested in planting ponderosa pine even though the site is marginal for commercial conifers and there is less chance of seedling survival than there is on better conifer sites. Experience in the area indicates that after brush removal a fair amount of gray pine seedlings are likely to naturally seed into the project area, even with the very sparse overstory of gray pine (<1% cover). The landowner is also interested in establishing some blue oaks in the project area. There has not been enough operational sized oak regeneration projects completed in California to provide a reliable track record for success with this proposed large scale oak regeneration project, but the landowner seems willing to try. Regardless of seedling survival success, clearing the brush for site preparation will have the added benefit of reducing hazardous fuel conditions along key ridge tops.

Considering the very low water holding capacity of the soils and the long, hot and dry summer climate, controlling vegetation which would compete aggressively for limited soil moisture during the first few years of conifer and oak seedling establishment is critical. Controlling the re-invasion of brush would have the added benefit of keeping hazardous fuel loads from growing back to the current very hazardous fuel loads.

PROJECT PLAN (*Although the soils and climate make the chance of successfully afforesting this proposed pilot project area less than it would be for the other sites proposed to date for WESTCARB II afforestation, the careful implementation of the following plan should provide the best chance of success.*)

1. Summer/Fall 2007 Winrock (or its consultant, Bob Rynearson) locate and purchase ponderosa pine seed from zone 332 or 371 and as close as possible to 2,700’ elevation.
2. Fall 2007: Winrock (or its consultant, Bob Rynearson) contract with Cal Forest Nursery to grow 13,250 styro 5 containerized ponderosa pine for outplanting in spring 2009. Ship seed to Cal Forest Nursery by November 2007.
3. Summer 2008: General Contractor (or subcontractor) using crawler tractor equipped with a brush rake, clear and pile brush on 50 acres, retaining oaks and gray pines and leaving as much small woody debris to cover the ground as operationally feasible.
4. Late Fall 2008: General Contractor prepare and submit Smoke Management plan and obtain necessary permits and burn piles on 50 acres.
5. Fall 2007 or 2008: Landowner and Winrock’s consultants monitor blue oak acorn crop on his property and if there is a good healthy crop then when acorns are ripe: Winrock or WSRCD? or General Contractor? collect acorns, sort out culls w/ water immersion & store sound seed.
6. Late December - January 2007 or 2008 (after sufficient rainfall replenishes soil moisture) General Contractor plant blue oak acorns on 50 acres averaging 30 spots per acre (precise, equal distant spacing not required or even desired) @ 2 acorns per spot. Install 1,500 4’ tall Tubex Treeshelters and anchor with 5’ lightweight metal fence posts. Spray any weeds, if present, within 4’ of planting spots.
7. January 2009 (after seedlings lifted and packed at nursery): General Contractor transport ponderosa pine seedlings from Cal Forest Nursery and place in cold storage.

8. Late January or February 2009: General Contractor plant 13,250 styro 5 containerized Ponderosa pine seedlings on 50 acres at 265 trees per acre (12′ x 12′ spacing & 12′ from existing trees and Tubex Treeshelters/planted oaks).
9. Late January or February 2009 (Immediately after planting): General Contractor purchase & install seedling protection netting (8 mil "light" netting should be sufficient) on 13,250 styro 5 containerized ponderosa pine seedlings.
10. March or April 2009 (After emergence of resprouting brush leaves, if any, and germinate brush seedlings and grass): General Contractor purchase chemical & apply directed foliar spray application by hand crews equipped with backpack sprayers and seedling protector shields. Spray resprouting chamise, if present, and newly emerging brush germinates, forbs and grasses with 2% generic glyphosate formulation (e.g. Buccaneer, Razor etc.) mixed w/ ¼ % non-ionic adjuvant.

WESTCARB II – REFORESTATION PROPOSAL

Raja Shiva Das property

BACKGROUND the following information pertains to proposed reforestation area:

Legal: T33N R2W, of Section 9

Acres: 40 (*suitable for proposed reforestation project*)

Access: Very good: Approximately four miles of rocked road (Backbone Ridge Rd via Seamans Gulch Rd. of off Hwy 299E near the Diddy Wells CDF station) provides good all season access to the project area. The intersection of the Backbone ridge road and the paved Sugar Pine road is ½ mile east of the property, but access via the sugar pine road is subject to permission and might not be available for heavy equipment use.

Survey lines & corner locations: (if feasible GPS closest known surveyed corner/s)
Two surveyed corners at each end of the property line (a portion of which would be the south boundary of one of the reforestation units) were located and GPS'd by Bob Rynearson on the site visit. There was no surveyed line found however.

Easements & Utilities (location of all easements, including above and underground utilities on or near project): The landowner did not mention that there are any easements or utilities within the project boundaries.

Sensitive areas (e.g. streams, springs, unstable areas, arch. sites etc.): There are no streams or wet areas within the proposed project area. There are a few draws which should be buffered from operations.

Annual Avg. Precipitation: 40" to 50" almost all in rainfall *(according to "Mean Annual Precipitation for California" isohydel map compiled by S.E. Rantz)*

Seed Zone: 521 (S portion of 5212, about 3 miles from the N portion of zone 522).

Elevation: Approx. 1,700' to 1,780'

Slope: Mostly flat with a few areas up to 25%

Aspect(s): Flat to slightly S or SW facing

Site Class: Dunning site.

Soil Type: According to USDA NRCS Shasta County Area Survey: Supan very stony loam, 0 to 30%; parent material = residuum weathered from tuff breccia; well drained, depth to lithic bedrock is 33 to 37 inches; Available Water Capacity is low @ 0" to 10" depth ranging from 0.9 to 1.4 inches & @ 10" to 33" depth ranging from 3.0 to 7.8 inches; moderately suited for hand planting.

Vegetation: Mostly dense, tall brush (> 80% cover) consisting primarily of greenleaf and whiteleaf manzanita with some poison oak, whitethorn (Ceanothus cordulatus) and deerbrush (Ceanothus integerrimus). There is a overstory of ponderosa pine, gray pine, black oak and blue oak, averaging approximately 10% canopy cover in the project area. The extreme fuel load and configuration of the tall, dense brush in the proposed reforestation area poses a significant risk of severe damage from catastrophic wildfire to the existing trees and surrounding forests and watershed.

General comments: Although Supan soils in general are considered low for timber productivity, the soils within the proposed project area are relatively deep (for this soil type) and support dense and tall manzanita brush and also a sparse overstory of numerous large, vigorous ponderosa pine that apparently seeded in many decades ago prior to the brushfield establishment. Some ponderosa pine seedlings were planted a few years ago by the landowner in the shaded fuelbreak adjacent to the proposed project area on the same soil type. Most of these survived and are growing adequately. The ponderosa pine seedlings that did not survive, or survived but are growing poorly, would have done better had the competing vegetation been controlled around them.

Ponderosa pine would be the most appropriate species to plant. Planted ponderosa pine seedlings along with the existing scattered overstory of black oak, blue oak, ponderosa pine and gray pine (and the gray pine that will likely naturally seed in for several years after the brush is cleared) will provide a diverse mix of tree species over time. For good conifer seedling survival and growth n this long, hot and dry summer climate, controlling vegetation (mostly manzanita, poison oak and grasses) which would compete aggressively for limited soil moisture during the first few years of establishment is critical. Controlling the re-invasion of manzanita brush would have the added benefit of keeping hazardous fuel loads from growing back to the current very hazardous fuel loads.

The proposed project area is classified as a "high" treatment priority area in the Sugar Pine Community Wildfire Protection Plan. The following proposed plan will provide the added benefit of meeting the objectives of the Community Wildfire Protection Plan by greatly reducing the hazardous fuel loads.

PROJECT PLAN

1. Summer/Fall 2007 Winrock (or its consultant, Bob Rynearson) locate and purchase ponderosa pine seed from the southern portion of zone 521 or the northern portion of zone 522 and from the lowest available elevation.
2. Fall 2007: Winrock (or its consultant, Bob Rynearson) contract with Cal Forest Nursery to grow 10,800 styro 5 containerized ponderosa pine for outplanting in spring 2009. Ship seed to Cal Forest Nursery by November 2007.
3. Summer 2008: General Contractor (or subcontractor) clear and pile brush on 40 acres, retaining conifers, oaks and large woody debris (LWD) where operationally feasible.
4. Late Fall 2008: General Contractor prepare and submit Smoke Management plan and obtain necessary permits and burn piles.
5. January 2009 (after seedlings lifted and packed at nursery): General Contractor transport seedlings from Cal Forest Nursery and place in cold storage.
6. Late January or early February 2009: General Contractor plant 10,800 styro 5 containerized Ponderosa pine seedlings on 40 acres at 270 trees per acre (12' x 12' spacing & 12' from existing trees).
7. Late January or early February 2009 (Immediately after planting): General Contractor purchase & install seedling protection netting (8 mil "light" netting should be sufficient) on 10,800 styro 5 containerized Ponderosa pine seedlings.
8. March or April 2009 (After emergence of poison oak leaves and germinate manzanita seedlings and grass): General Contractor purchase chemical & conduct directed foliar spray application by hand crews equipped with backpack sprayers and seedling protector shields. Spray resprouting poison oak and newly emerging brush germinates, forbs and grasses with 2% generic glyphosate formulation (e.g. Buccaneer, Razor etc.) mixed w/ ¼ % non-ionic adjuvant.

WESTCARB II – REFORESTATION PROPOSAL

Curt Eilers property

BACKGROUND the following information pertains to proposed reforestation area:

Legal: T33N R2W, of Section 9

Acres: 8 acres in three units (*suitable for proposed reforestation project*)

Access: Good: Approximately four miles of rocked road (Backbone Ridge Rd) off of Hwy 299E just east of the Diddy Wells CDF station provides good all season access to within a few hundred feet of 2 of the units and ½ mile from the third unit which is accessible via a dirt road off of the rocked road.

Survey lines & corner locations: (if feasible GPS closest known surveyed corner/s)
According to the landowner all of the reforestation units proposed for planting are within his property.

Easements & Utilities (location of all easements, including above and underground utilities on or near project): The landowner did not mention that there are any easements or utilities within the project boundaries.

Sensitive areas (e.g. streams, springs, unstable areas, arch. sites etc.): There are no streams or wet areas within the proposed project boundary units.

Annual Avg. Precipitation: 40" to 50" almost all in rainfall *(according to "Mean Annual Precipitation for California" isohydel map compiled by S.E. Rantz)*

Seed Zone: 521 (S portion of 521, about 3 miles from the N portion of zone 522).

Elevation: Approx. 1,700' to 1,780'

Slope: 0% - 30%

Aspect(s): N, W and E facing

Site Class: west & middle units: Estimated Dunning Site IV; Site V or less on east unit.

Soil Type: Soils on two of the three units (middle and west units) are suitable for growing ponderosa pine, but the soils on the third unit (east unit) are shallow and marginal for commercial conifer production.

Vegetation: Prior to clearing and piling with a crawler tractor the vegetation was mostly dense brush. Current vegetation is comprised of resprouting poison oak, live oak and black oak, grasses, forbs and brush (mostly manzanita) germinate seedlings less than one foot tall. There is a overstory of ponderosa pine, gray pine, black oak and blue oak, averaging approximately 10% canopy cover. Large piles of dead, brush are in the proposed reforestation units.

General comments: The proposed project area is very small, consisting of 3 units totaling 8 acres, ¼ to ½ mile apart. So this proposed project would only be feasible if most operations were done in conjunction with operations on the proposed Araja Sivadas afforestation project adjacent to the south. So the Shiva Das project would need to be approved by Winrock and the landowner for this project on Eiler's property to be feasible.

To reduce fire hazard risk and promote watershed and wildlife resources, the landowner is primarily interested in establishing long term tree cover w/ minor shrub, grass, forb understory instead of the dense, decadent brush with sparse tree cover that would occur without further management. Two of the eight acres are suitable for planting blue oak and ponderosa pine (very low site) and about 6 acres are suitable for ponderosa pine reforestation. The landowner is interested in planting blue oak. There has not been enough large operational scale oak regeneration projects completed in California to provide a reliable basis for estimates of costs and risk for this project. For good conifer seedling survival and growth in this long, hot and dry summer climate, controlling vegetation (mostly manzanita, poison oak and grasses) which would compete aggressively for limited soil moisture during the first few years of establishment is critical. Controlling the re-invasion of manzanita brush would have the added benefit of keeping hazardous fuel loads from growing back to the current very hazardous fuel loads. It is likely that some gray pine seedlings will naturally seed in over time after brush removal.

<u>PROJECT PLAN</u>

1. Summer/Fall 2007 Winrock (or its consultant, Bob Rynearson) locate and purchase ponderosa pine seed from the southern portion of zone 521 or the northern portion of zone 522 and from the lowest available elevation.
2. Fall 2007: Winrock (or its consultant, Bob Rynearson) contract with Cal Forest Nursery to grow 1,400 styro 5 containerized ponderosa pine for outplanting in spring 2009. Ship seed to Cal Forest Nursery by November 2007.
3. Late Fall 2007: General Contractor prepare and submit Smoke Management plan and obtain necessary permits and burn piles on 8 acres.
4. Fall 2007 or 2008: Landowner or Winrock (its consultant or WSRCD?) or General Contractor monitor blue oak acorn crop and if there is a crop then collect when ripe. Sort out culls by water immersion and store.
5. December or January 2007 or 2008 (after sufficient rainfall replenishes soil moisture) General Contractor plant blue oak acorns on 2 acres at 50 spots per acre (30 x 30 spacing @ 2 acorns per spot), install 100 4′ rigid seedling/sapling protectors anchored with posts. Spray any weeds if present.
6. January 2009 (after seedlings lifted and packed at nursery): General Contractor transport seedlings from Cal Forest Nursery and place in cold storage.
7. Late January or early February 2009: General Contractor plant 1,400 styro 5 containerized Ponderosa pine seedlings on 6 acres at 200 trees per acre (12′ x 12′ spacing & 16′ from existing trees) and on 2 acres at 100 trees per acre (21′ x 21′ spacing).
8. Late January or early February 2009 (Immediately after planting): General Contractor purchase & install seedling protection netting (8 mil "light" netting should be sufficient) on 1,400 styro 5 containerized ponderosa pine seedlings.
9. March or April 2009 (After emergence of poison oak leaves and germinate manzanita seedlings and grass): General Contractor purchase chemical & conduct directed foliar spray application by hand crews equipped with backpack sprayers and seedling protector shields. Spray resprouting poison oak and newly emerging brush germinates, forbs and grasses on 8 acres with 5% generic glyphosate formulation (e.g. Buccaneer, Razor etc.) mixed w/ 5 % Methylated Seed Oil (e.g. Hasten, MOC, MSO etc.). If the General Contractor conducts this as a site prep treatment during the late spring of 2008 instead of as a release treatment in 2009, it would be preferred, but would not be able to do in conjunction with spray operations on Shiva Das.

WESTCARB II – REFORESTATION PROPOSAL

Fred Wilson property

BACKGROUND the following information pertains to proposed reforestation area:

Legal: T34N R1W Section: S ½ 29

Acres: 15 acres total in two units (*suitable for reforestation project*)

Access: fair: Units are accessed via 4WD dirt roads about one mile from HWY 229E near mile marker 49 via a private bridge crossing over Cedar Creek. Prior to project approval need verification from landowner that the bridge weight capacity and width is suitable for moving in an excavator equipped with masticating head.

Survey lines & corner locations: According to the landowner and WSRCD property maps and photo, the proposed project boundaries are well within the property lines.

Easements & Utilities (location of all easements, including above and underground utilities on or near project): According to the landowner there are no easements or utilities within the proposed reforestation project boundaries.

Sensitive areas (e.g. streams, springs, unstable areas, arch. sites etc.): According the landowner there are no know archeological sites within the project boundaries. There are no watercourses or wet areas within the project boundaries. There is a draw south of the east unit which should have a minimum 50′ equipment buffer. There is an excavated and and/or dammed spring area in, or very near, the southeast portion of the east unit. Prior to equipment operations Winrock's consultant(s) and landowner would need to set up appropriate protection measures if any that will be needed.

Annual Avg. Precipitation: approximately 50″ almost all in the form of rainfall *(according to "Mean Annual Precipitation for California" isohydel map compiled by S.E. Rantz)*

Seed Zone: 522/521 (in zone 522 less than one mile south of the border with zone 521).

Elevation: approx. 1,600′ (east unit); 1,700′ (west unit)

Slope: 0% - 30%

Aspect(s): primarily west and/or south facing or flat on ridge.

Site Class: west unit: moderate to low; east unit: very low.

Soil Types: The Shasta County Soils Map provided by the NRCS lists the following:

West unit: Marpa gravelly loam, 30 to 50 percent slopes (slopes on the proposed project area are 0 to 30%); residuum weathered from shale parent material; 26" to 30″ deep; well drained; moderately suited for hand planting; although the soil type in general is listed as capable of growing ponderosa pine, black oak, Douglas-fir, and white fir, at this elevation and ridgetop exposure, ponderosa pine would be the most suitable for young seedling survival.

East unit: Neuns very stony loam, 8 to 50 percent slopes (slopes on the proposed project area are 0 to 30%); residuum weathered from greenstone parent material; 23″ to 27″ deep; well drained; moderately suited for hand planting.

Vegetation: The vegetation in the proposed project area consists mostly of dense, 6 to 15 foot tall non-sprouting manzanita species and a sparse (< 5% cover) black oak, blue oak, ponderosa pine, gray pine and Douglas-fir overstory. These brushfields w/ re-sprouted oaks likely formed after a wildfire many decades ago.

General comments:

The proposed project area is approximately 15 acres, consisting of two units that are about ½ mile apart. Due to the relatively low elevation, hot dry summer climate and shallow, somewhat eroded soils, there is a greater risk of plantation failure than there is for projects at higher elevation sites and better conifer growing, non-eroded soils. The landowner is willing to consider planting even though tree seedling establishment is a little risky on this site. The benefits of this proposed project go beyond reforestation because preparing the site for planting by masticating the tall, dense brush on these ridges would also provide the benefit of reducing fire hazard risk to the property and general forestland.

The brush is mostly non-sprouting species and the soils are not very deep and appear to have been slightly eroded several decades ago, prior to the presence of the current brush, and it is a low elevation, hot, dry summer site. Therefore, masticating the dense brush rather than piling and burning it would be the most appropriate treatment to prepare the site for planting. This site preparation treatment should cause less disturbance to the shallow soils and it will also provide dead woody material cover that will reduce soil moisture loss from evaporation. The masticated material will also provide some shade from the summer sun on the lower stem portion of the young seedlings that will be planted into the site. The mulching effect of the mastication would also reduce the amount of weeds competing with the conifer seedlings for limited soil moisture and nutrients. Ponderosa pine is the most suitable seedling to plant on this hot, dry summer site. There are numerous oaks throughout the general property and the scattered oaks in the project area will either be retained or, if inadvertently masticated during site preparation, they will resprout vigorously.

PROJECT PLAN

1. Summer 2007: Winrock (or its consultant, Bob Rynearson) locate and purchase ponderosa pine seed from lowest elevation 521 or 522 source available.
2. Fall 2007: Winrock (or its consultant, Bob Rynearson) contract with Cal Forest Nursery to grow 4,300 styro 5 containerized ponderosa pine seedlings for outplanting in winter 2008/09. Ship seed to Cal Forest Nursery by November 2007.
3. Summer 2008: General Contractor (or its sub-contractor) using an excavator equipped with a masticating head, masticate brush on 15 acres.
4. January or early February 2009: General Contractor transport from Cal Forest Nursery, place in cold storage and then plant 4,300 styro 5 containerized Ponderosa pine seedlings on 15 acres at 285 trees per acre (12’ x 12’ spacing & 12’ from existing oak trees).
5. January or early February 2009 (Immediately after planting): General Contractor purchase & install seedling protection netting (8 mil “light” netting should be sufficient) on 4,300 styro 5 containerized Ponderosa pine seedlings.
6. February or March 2009: General Contractor purchase chemical & conduct directed foliar spray application by hand crews equipped with backpack sprayers and seedling protector shields. Spray newly emerging forbs and grasses on 15 acres with 2% generic glyphosate formulation (e.g. Buccaneer, Razor etc.) mixed w/ ¼ % non-ionic adjuvant.

Annex D: Annual Landowner Survey for WESTCARB Afforestation Projects

Date ____________________

Name ____

Mailing Address ____

____

Telephone _____________ **Fax** ___________________ **E-mail** _______________

Winrock International Agreement Number ___________________

Please indicate that you have attached four project photos (electronic format preferred)
Looking North ___ Looking South ___ Looking West ___ Looking East ___

Estimate of trees from initial planting currently surviving:
75-100% ___
50-74% ___
25-49% ___
0–24% ___

Reason for loss during past year:
Live trees intentionally removed ___ Accidentally removed ___
Trees died/damaged by: Fire ___ Infestation ___ Drought ___ Unknown ___
Other ___ (Please explain below)
____
____
____

Maintenance Performed during Past Year:
Did you irrigate? ___
How much? ____
How often? ____

Was hand and/or mechanical weeding performed? ___
When? ____

Was chemical weed control used? ___
Herbicide ______________________
Concentration ______________________________
Method of application _________________________
Date of application ___________________________

Was fertilizer used? ___
Analysis of fertilizer ___________________________
Concentration _______________________________
Method of application _________________________
Date of application ___________________________

Was pruning conducted? ___
When? ____
For what purpose(s)? ____

Tree health within past year:
Do the trees seem healthy? Please comment on observed health and growth:
____
____
____

Is the project currently registered with a carbon registry organization (e.g. California Climate Action Registry)? ___
If yes, how have you found the experience?
____
____
____

If no, why not? ____
____

If participating in a registry, have you sold carbon credits? ___

How would you rate your current level of satisfaction in participating in the Winrock/WESTCARB afforestation pilot project:
Very High ___ High ____ Moderate ___ Low ___ Very Low ___
Comments: ____
____

What is your level of interest in participating in additional afforestation projects, and why?
Very High ___ High ____ Moderate ___ Low ___ Very Low ___
____
____
____

Is there anything else you would like to add to help us understand the success of your project?
____
____
____

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BASELINE GREENHOUSE GAS EMISSIONS FOR FORESTS AND RANGELANDS IN CALIFORNIA

Pearson, T, S. Brown, and M. Netzer.

Winrock International

DOE Contract No.: DE-FC26-05NT42593

Contract Period: October 1, 2005 - May 11, 2011

Arnold Schwarzenegger
Governor

BASELINE GREENHOUSE GAS EMISSIONS FOR FORESTS AND RANGELANDS IN CALIFORNIA

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
Winrock International

PIER FINAL PROJECT REPORT

October 2009

Prepared By:
Winrock International - Ecosystem Services Unit
1621 N. Kent St, Suite 1200, Arlington, Virginia 22209
Commission Contract No. 500-02-004
Commission Work Authorization No. MR-045

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Acknowledgements

Many colleagues provided data and insights for this work, including: Aaron Dushku, John Kadyzewski, Y. Qi, Mark Rosenberg, Tian-Ting Shih, Chris Fischer, Lianne Mahon, Doug Wickizer, Dean Cromwell, and David Shoch.

Please cite this report as follows:

Pearson, T, S. Brown, and M. Netzer. 2009. *Baseline Greenhouse Gas Emissions and Removals for Forests and Rangelands in California.* Winrock International, for the California Energy Commission, PIER Energy-Related Environmental Research. XXXX.

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies

What follows is the final report for the Measurement, Classification, and Quantification of Carbon Market Opportunities in the U.S.: California Component project, contract number 100-98-001, conducted by Winrock International. The report is entitled *Baseline Greenhouse Gas Emissions and Removals for Forests and Rangelands in California*. This project contributes to the PIER Energy-Related Environmental Research program.

For more information on the PIER Program, please visit the Energy Commission's Web site www.energy.ca.gov/pier or contact the Energy Commission at (916) 654-4628.

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Abstract

This report titled *Baseline Greenhouse Gas Emissions and Removals for Forests and Rangelands in California* sought to quantify the baseline of changes in carbon stocks on forest and range lands in California for the 1990s—filling the gaps for those sectors that existed in the 2002 California Energy Commission report, *Inventory of California Greenhouse Gas Emissions and Sinks: 1990–1999*. The report replaces an earlier assessment that only included three out of the five California regions and in addition enhances the estimates of forest carbon sequestration. These baselines provide an estimate of the emissions and removals of GHGs attributable to changes in the use and management of forest and rangeland.

The analysis revealed that forests and rangelands were responsible for a net removal of carbon dioxide from the atmosphere of 24.95 million metric tons of carbon dioxide per year ($MMTCO_2eq/yr$). Non-CO_2 GHG emissions from forest and range lands were estimated to be 0.21 $MMTCO_2eq/yr$, or equivalent to about 0.86% of the removals by these systems. The overall net result was a removal of 23.0 $MMTCO_2eq/yr$ by forests and 1.9 $MMTCO_2eq/yr$ by rangelands.

Executive Summary

Objectives

This report's goal is to quantify the baseline of changes in carbon stocks on forest and range lands in California for the decade of the 1990s. The focus here is on carbon but first approximation estimates are also given for non-CO_2 greenhouse gases (GHGs) where appropriate.

Baselines provide an estimate of the emissions and removals of greenhouse gases due to changes in the use and management of land. In addition they are useful for identifying where, within the landscape of California, major opportunities could exist for enhancing carbon stocks and/or reducing carbon sources to potentially mitigate greenhouse gas emissions.

The 2002 California Energy Commission report[1] estimated the emissions and removals of GHGs from all economic sectors of the State for the period 1990–1999, generally at one-year intervals. However, the sections of the Energy Commission's 2002 report on the forest and rangeland sectors were incomplete and did not include all the changes taking place on these lands.

In 2004 Winrock published a report on baseline emissions from forests, rangelands and agriculture from the same time period (Brown et al. 2004), however, in this earlier report data for only three out of the five regions were available for assessment. In this report all five regions are included and enhancements have been made in how the carbon sequestration of forest and rangeland areas with no measureable changes in canopy cover is accounted.

Outcomes

In this report, methods for estimating baseline carbon emissions and removals from forests and rangelands are presented with corresponding results. However, given the nature of the databases used in this analysis, the time periods encompassed by the baselines vary. Across the five regions of California the assessment periods varied with different periods for each region of 4 to 6 years between 1994 and 2002.

To develop the baselines, three types of data were used: (1) the area of the forests and rangelands at the start and end of the time interval, (2) the area and magnitude of change in canopy cover during the time interval, and (3) the carbon stocks in each land-use type for each time. Areas were derived from the California Land Cover Mapping and Monitoring Program (LCMMP). Carbon estimates for various forests and rangeland types with corresponding canopy cover were derived from Forest Inventory and Analysis (FIA) datathe literature and California Department of Forestry's Fire and Resource Assessment Program (FRAP)staff.

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[1] California Energy Commission. November 2002. *Inventory of California Greenhouse Gas Emissions and Sinks: 1990–1999.* Staff Report. 600-02-001F.

Conclusions

The analysis revealed that forests and rangelands were responsible for a net removal of carbon dioxide from the atmosphere of 24.95 MMTCO_2eq/yr (Table S-1). Non-CO_2 GHG emissions from forest and range lands were estimated to be 0.16 MMTCO_2eq/yr, or equivalent to about 0.76% of the removals by these systems. The overall net result was a removal of 23.01 MMTCO_2eq/yr by forests and 1.94 MMTCO_2eq/yr by rangelands.

Table S-1. Emissions and Removals of Greenhouse Gases by Land-use Sector. – Indicates an Emission, + Indicates a Removal

	C	*N_2O*	*CH_4*
		MMTCO_2eq/yr	
Forests[1]	**+ 23.19**	**- 0.015**[2]	**- 0.166**[3]
Rangelands[1]	**+ 1.97**	**- 0.003**[2]	**- 0.031**[3]
	+25.16	**-0.017**	**-0.197**

[1] Measurement interval between 1994-2002 (actual period and number of years varies between regions)

[2] Calculated only for fire

[3] Calculated only for fire and harvest

The baseline was estimated by combining two approaches. The areas of satellite-detectable change in forests and rangelands, with a measured change in canopy coverage, were available through the California Land Cover Mapping and Monitoring Program (LCMMP). Carbon estimates for various forests and rangeland types with corresponding canopy closures were derived principally from Forest Inventory and Analysis (FIA) data. The analysis of change, measured from satellite images, only identifies a measurable change in canopy coverage of forests and rangelands that occurred in the time interval, and does not include those forests with a closed canopy that continue accumulating biomass carbon that is undetectable from a satellite. For these reasons we tracked measurable decreases in canopy cover and the resulting decreases in carbon stocks (emissions of carbon) separately from the measurable increases in canopy cover and resulting increases in carbon stocks. For decreases in carbon stocks, we estimated both the gross and net changes, which varied by the cause of the change (e.g., fire, harvest, development). We then estimate the likely magnitude of the increase in carbon stocks resulting from the non-measured change in canopy and assumed increase in carbon stocks using U.S. Forest Service data. In other words, the baseline includes all changes in carbon stocks, from measured and unmeasured changes in canopy coverage.

The previous version of this assessment used a single carbon sequestration rate per forest type across all three regions to estimate the sequestration in forests with no measurable change in canopy cover. In addition, this rate was calculated from a data set that itself was for net emissions. Here we calculate a sequestration rate from FIA data for each forest and rangeland type in each of the five regions.

A change in canopy cover was measured on 4,622 km^2 of forests and rangelands across California. This is approximately 1.8% of the total area of forests and rangeland in the regions. For 83% of the changed area, the cause of change was identified and verified.

For forests, a removal of 27.10 MMTCO_2eq/yr and an emission of 4.09 MMTCO_2eq/yr were estimated (Table S-2). The greatest emissions were found in the North Sierra region with its dry conditions and resultant fires, as well as timber harvesting. The greatest removal was found in the forests of the North Coast with its dominance by fast-growing redwoods and Douglas-fir.

Rangelands were a net sink of carbon with a removal of 2.57 MMTCO$_2$eq/yr exceeding an emission of 0.63 MMTCO$_2$eq/yr (Table S-2).

Table S-2. Emissions and Removals by Forests and Rangelands by Region

MMTCO$_2$eq/yr	*FORESTS*		*RANGELANDS*	
	Emissions	*Removals*	*Emissions*	*Removals*
North Coast	1.39	15.16	0.07	0.54
Cascade Northeast	0.88	5.44	0.08	0.45
North Sierra	1.49	4.74	0.12	0.22
South Sierra	0.22	1.10	0.05	0.47
South Coast	0.11	0.66	0.30	0.89
TOTAL	**4.09**	**27.10**	**0.63**	**2.57**

Fire and harvest were the dominant causes of emissions on forestlands; these causes were responsible for 1.83 MMTCO$_2$eq/yr and 1.42 MMTCO$_2$eq/yr respectively. On rangeland, harvest was less important, accounting for just 5% of the total emissions as opposed to 54% for fire on rangelands (Table S-3). Development is a minor cause of carbon emissions through land-use change in both forest- and range-land in California. However, much of the unverified change could include development that tends to occur in smaller patches than those recorded under the pattern of verified changes.

Table S-3. Emissions and Removals by Cause of Change.
– Indicates an Emission; + Indicates a Removal

MMTCO$_2$eq/yr	*FORESTS*	*RANGELANDS*
Fire	-1.83	-0.34
Harvest	-1.42	-0.03
Development	-0.01	-0.01
Other/Unverified	-0.83	-0.24
Regrowth	+ 27.10	+ 2.57

- The counties with the largest decrease in carbon stocks (largest emissions) were located in areas affected by fire especially in North Sierra and parts of Cascade Northeast. The largest increases in carbon stocks (detectable and undetectable canopy change) are in the high volume fast-growing conifer forests of the North Coast and Cascades Northeast. Despite a high fire incidence the lower carbon stocks of the forests in the southern regions leads to emissions levels that are not greatly elevated.

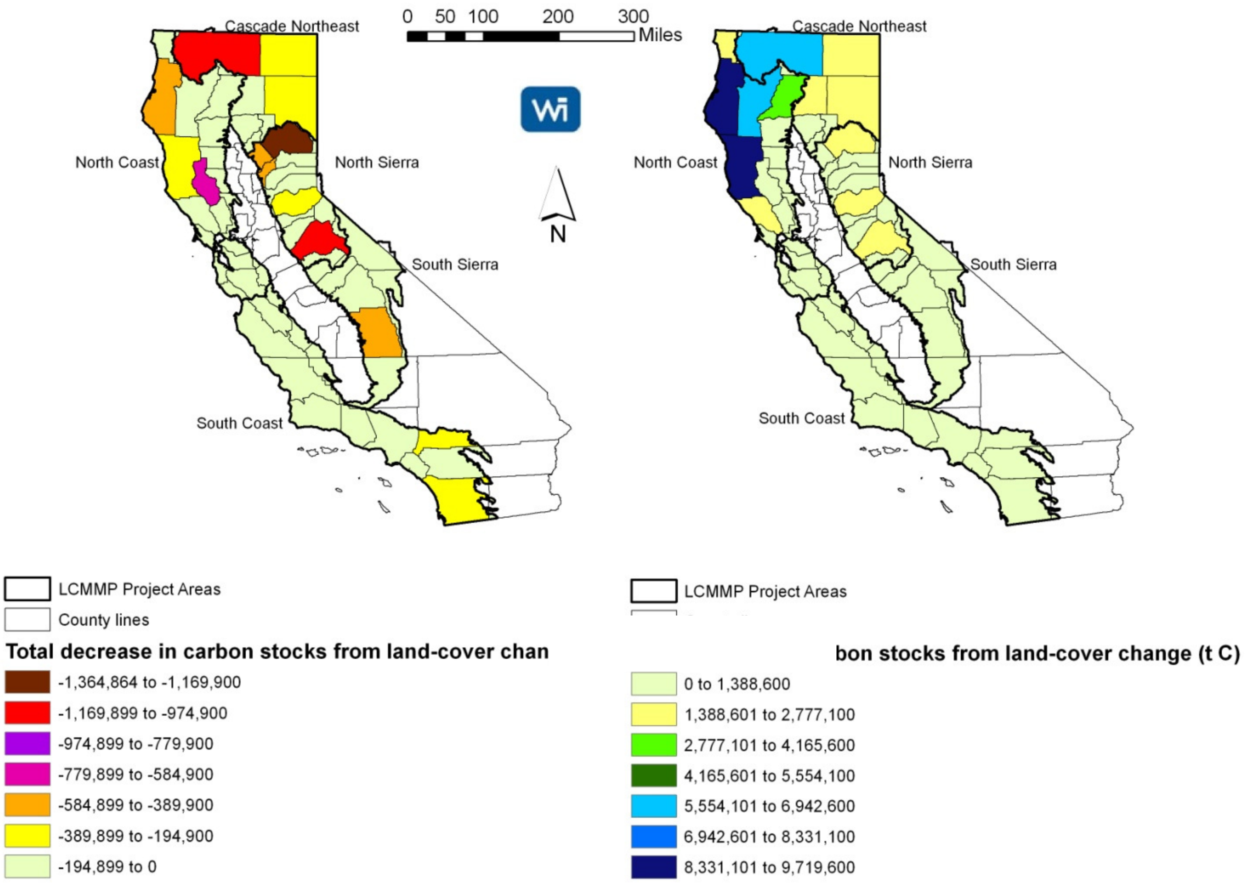

Figure S-1. County Level Summary of the Decreases (Left figure), and Increases (right figure) in Carbon Stocks on Forests and Rangelands in the North Coast (1994-1998), the Cascades Northeast (1994-1999), North Sierra (1995-2000), South Sierra (1995-2001) and South Coast (1997-2002).

The estimated total removals of 27.10 MMTCO_2eq/yr and emissions of 4.09 MMTCO_2eq/yr (net 23.01 MMTCO_2eq/yr) for the forest sector differ markedly from the reported removal of 17.3 MMTCO_2eq/yr in the California Energy Commission's report (CEC, 2002). We conclude that despite the relatively high uncertainty, the finer detail, and inclusion of areas with measured changes in canopy, and thus carbon stocks, our estimate should be considered to be representative of the real changes occurring on forest and range lands during the period of 1994/1995-2002.

The estimated removal also differs from the previous Winrock assessment of 10.96 MMTCO_2eq/yr and emissions of 3.76 MMTCO_2eq/yr, based on only three regions of California. The difference between the previous estimate and the one produced in this report is accounted for through the inclusion of the final two regions (South Coast and South Sierra) and the use of an improved method for calculating sequestration in the forests with no canopy cover change[2].

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[2] The lower emissions, even with the two added regions, are due to low emissions from forests in the South Sierra and South Coast regions and a recalculation for the North Coast region - standardized to a five year period instead of

1.0 General Approach

This report follows from and builds on an earlier assessment of baseline sequestration and emissions for Californian forests and rangelands (Brown et al. 2004). Due to data availability, the earlier assessment only examined three out of five forest and rangeland regions in California. This report includes the additional two regions – South Sierra and South Coast. In addition, improvements have been made in the methodology of calculating the annual sequestration from forests with no measurable change (could be a loss of gain) in canopy cover.

The goal of this section is to develop a baseline of carbon emissions and/or removals in the forest and rangeland sector of California for the period of the 1990s, including identification and quantification of the main sources or sinks of carbon. The focus of this work is carbon, as carbon dioxide, although where appropriate, first order approximations will be made of the baseline emissions for non-CO_2 gases (N_2O and CH_4).

To develop the baseline for a specified time period, two types of data are needed: (1) the area of forests and rangelands undergoing a change, and (2) the change in carbon stocks in the same areas. To develop a trend in the baseline, a minimum number of two time intervals (three points of time) are needed. For California however, data for two time points with one interval only are suitable for the analysis.

The areas of change in forests and rangelands, with a measured change in canopy coverage, were obtained from maps developed by the California Land Cover Mapping and Monitoring Program (LCMMP). Carbon estimates for various forests and rangeland types with corresponding canopy closures were derived from Forest Inventory and Analysis (FIA) data, the literature, California Department of Forestry's Fire and Resource Assessment Program (FRAP) staff, and the equations of Smith et al. (2003). Using the canopy change data only would likely underestimate all changes in carbon stocks. When the canopy of a forest closes, trees continue accumulating biomass carbon that is undetectable from a satellite. For this reasons we tracked three processes: 1) measurable decreases in canopy cover and the resulting decreases in carbon stocks (emissions of carbon), 2) measurable increases in canopy cover and resulting increases in carbon stocks, and 3) gains in carbon stocks for forests and rangelands that had no detectable measure of change in canopy closure in the remote sensing imagery. For decreases in carbon stocks, we estimated both the gross and net changes, which varied by the cause of the change (e.g., fire, harvest, development). We assumed an increase in carbon stocks for all forests and rangelands that showed no detectable change in canopy closure. We used data from the U.S. Forest Service reports (based on FIA data) on carbon stock changes in Californian forests to estimate the likely changes in carbon stocks in the forests with no measured changes in canopy. The details of all these steps are given in the next section.

2.0 Classification of Forests and Woodlands

The California Land Cover Mapping and Monitoring Program (LCMMP) uses Landsat Thematic Mapper satellite imagery to map vegetation and changes in vegetation over 5 year

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four years used in the original calculation periods. Vegetation is classified using the Wildlife Habitat Relationship (WHR) classifications. The WHR is an information system for California's wildlife. In the WHR database, there are 59 wildlife habitats—27 tree, 12 shrub, 6 herbaceous, 4 aquatic, 8 agricultural, 1 developed, and 1 non-vegetated.

Vegetation classification data are verified by "ground truth" field data. The WHR classes are further classified at the individual pixel level by tree-size class and canopy crown closure. Causes of changes in vegetation distribution and/or canopy crown closure are deduced by GIS modeling, aerial photographs, and further field and site data. Causes of land-cover change include: fire, harvest, development, regrowth, seasonal (a cause used in the first phase of the LCMMP), pest-related (pest-related only in the second phase of the LCMMP), and other and unverified changes.

The California LCMMP data are divided into five regions (Figure 1):

- North Coast
- Cascade Northeast
- North Sierra
- South Sierra
- South Coast

The Central Valley and South Interior regions are not included in the analysis, as these areas are not covered by the CDF-FRAP data.

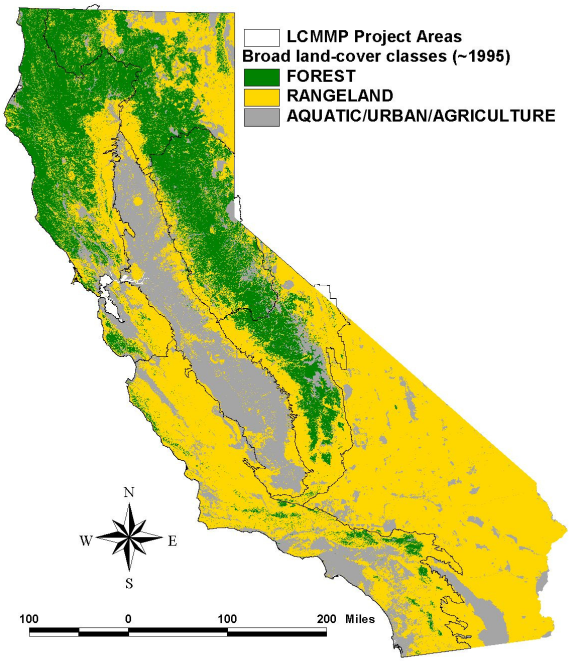

Figure 1. The CDF-FRAP Multi-source Land-cover Map Reclassified into Three Broad Classes with the LCMMP Regions Superimposed on Top in Black

3.0 Area of Forests and Rangelands

3.1. Calculating Areas from Satellite Data

3.1.1. LCMMP Background

The FRAP has embarked on a comprehensive effort to map land cover and track land-cover changes across the California landscape in a semi-automated and systematic way. This project is called the Land-Cover Mapping and Monitoring Program (LCMMP). The first task of LCMMP was to derive a classified 30-meter resolution land-cover map for each of five regions in California. The images were derived from a large archive of Landsat satellite imagery and posted on the CDF-FRAP website in files reduced to the county-level. Change analyses are conducted at regular intervals (about every five years but staggered across the State—i.e., different regions are analyzed for different five-year periods) whereby the changes in land cover are automatically incorporated into the old land-cover maps. Simultaneously, a separate map of the amount of change that occurred is created. Efforts are made by field crews and CDF-FRAP staff to also determine the likely cause of this change for each of the change-areas mapped. For a large proportion of canopy changes a cause is attributed by the LCMMP data, for the remainder, the cause is unverified. For the analyses presented in this section, CDF-FRAP staff made certain assumptions, based on their experience about the likely cause of change for many of the unverified causes, to increase the accuracy and precision of our analyses.

The analysis of change, measured principally from satellite images, only identifies a measurable change in canopy coverage of forests and rangelands that occurred in the time interval. Other forest and rangeland habitats in California are likely to be undergoing change in carbon stocks even though a change in canopy cannot be detected. For example, 97.8% of the vegetated land area in the North Coast region had no discernable change between 1994 and 1998. The canopy change detection method is liable to underestimate sinks of carbon because negative canopy changes (sources) are often large after fire or development but accumulation of carbon through regrowth (sinks) is gradual and in a given 5 year period will often not exceed the 15% canopy change threshold necessary to be measurable. In addition even when the canopy is closed, trees keep accumulating biomass carbon that may not be detectable from a satellite. For these reasons we track measurable decreases in canopy cover and the resulting decreases in carbon stocks (emissions of carbon) separately from the measurable increases in canopy cover and resulting increases in carbon stocks. We then estimate the likely magnitude of the increase in carbon stocks resulting from the non-measured change in canopy but assumed increase in carbon stocks.

3.1.2. Methods for baseline analysis

Upon update of the land-cover maps, most previously existing land-cover maps of the regions are deleted from the principal archiving system of the LCMMP computer hardware. By consulting tape archives of several that were actually retained, it was evident that the updates also incorporated a number of other factors that prohibited direct comparison between previous land-cover maps from the archives and their updated versions of the same regions. Such factors as georeferencing error and refined classification due to field-crew ground-truthing made it necessary to depend on the change maps and some other source of “Time 1” land-cover data.

The "Time 1" data that we selected was the CDF-FRAP "Multi-source Land-cover Map." This map was produced in 2003 using a variety of data inputs from several organizations and mapping projects (Figure 2). To encompass all of California in one manageable grid, the multi-source map was transformed, from the finer-scale maps that were used to create it (generally 30m x 30m imagery), to a 100mx100m grid. In a similar manner, all LCMMP data used in the analysis were also aggregated into 100-meter grid cells from their original 30-meter resolution. In most cases, the Multi-source Land-cover map incorporated satellite data that came from the same year as had the LCMMP "Time 1" data (+/- 1-2 years in some areas).

Thus, the carbon emissions baseline study used **two** products from the CDF-FRAP's LCMMP and **one** from CDF-FRAP's "Multi-source Land Cover Mapping Project":

- The Multi-source Land-cover map = "Time 1"
- The LCMMP change detection maps = the difference between LCMMP's "Time 1" and "Time 2" land cover maps
- The LCMMP change cause maps = in the changed areas, what happened between LCMMP's "Time 1" and "Time 2" to cause the detected change

Creation of the multi-source land-cover map involved the synthesis of a variety of different datasets into one comprehensive map. For the CDF-FRAP synthesis, it was necessary to crosswalk the various classifications present in these datasets to yield a map with a uniform habitat-type classification. The WHR classification system was chosen. The WHR-classification system includes information on many vegetation and habitat attributes that are included within the databases accompanying the GIS files. Some examples of these attributes are canopy density, tree size and timber productivity class.

The WHR standards for canopy coverage are:

- Dense: 60 -100% (midpoint 80%)
- Moderate:40 - 59% (midpoint 50%)
- Open: 25 - 39% (midpoint 32%)
- Sparse:10 - 24% (midpoint 17%)

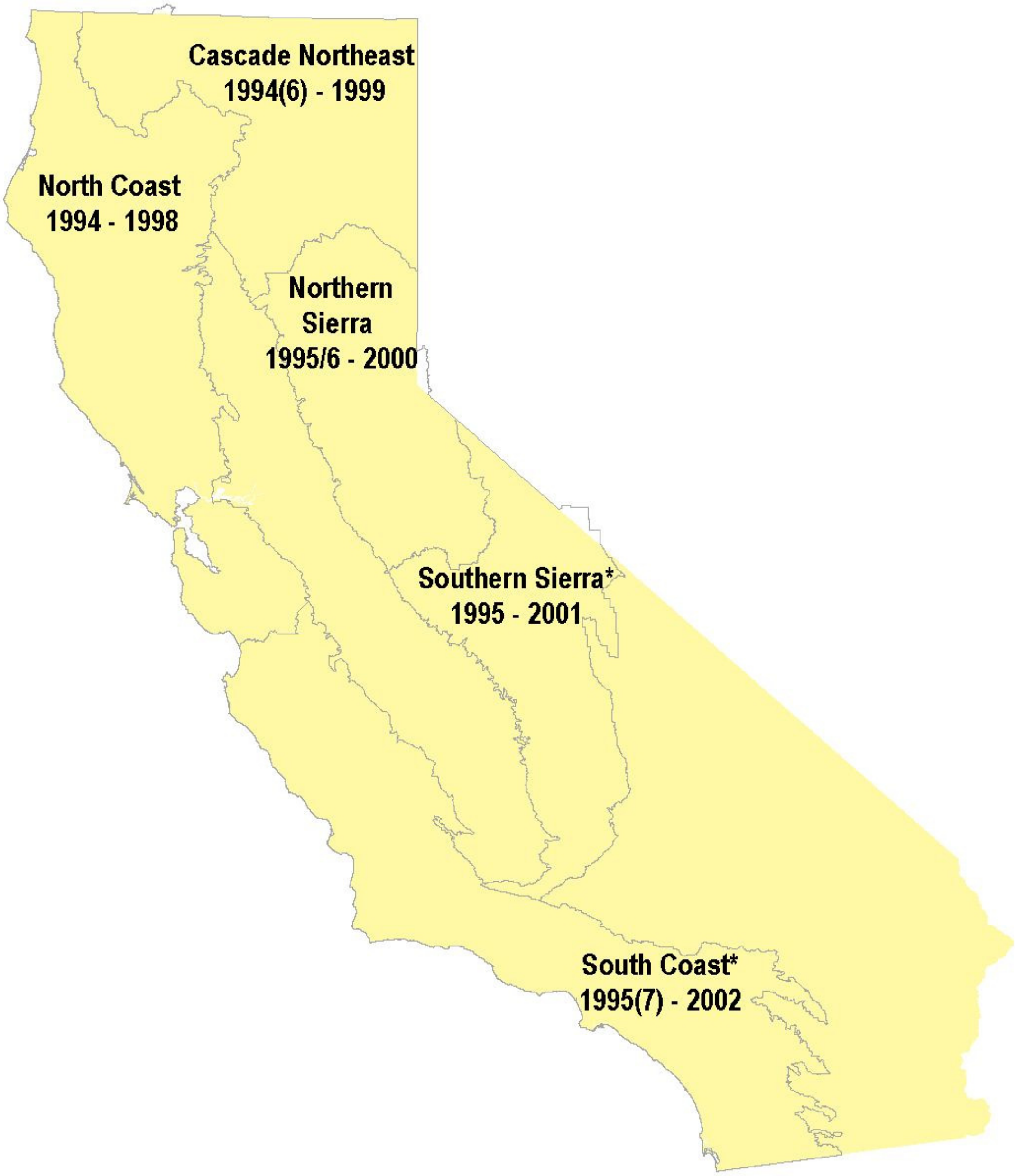

Figure 2. Satellite Image Dates for CDF-FRAP's LCMMP Change Analysis (Time 1–Time 2).

The LCMMP change analyses are conducted by comparing the raw satellite imagery from the baseline year with other satellite imagery of the same location at another year. The LCMMP attempts to collect images with a five-year time difference for change analysis although availability of imagery does not always allow this. The change analysis for the first LCMMP cycle presented changed grid cells along with the following qualitative degree-of-change scale:

- Large Decrease in Vegetation
- Moderate Decrease in Vegetation
- Small Decrease in Vegetation

- Little or No Change
- Small Increase in Vegetation
- Moderate Increase in Vegetation
- Large Increase in Vegetation
- Non-vegetative Change
- Terrain Shadow or Wet (or "Cloud or Cloud Shadow" in some regions)

After each region was mapped in the first cycle, a second cycle of mapping produced results classified along the following improved quantitative degree-of-change scale:

- 71 to 100% cover decrease
- 41 to 70% cover decrease
- 16 to 40% cover decrease
- +15 to -15% (Little or No Change)
- 16 to 40% cover increase
- 41 to 100% cover increase
- Shrub/Grass Decrease > 15%
- Shrub/Grass Increase > 15%
- Non-vegetative Change Including Urban (or "Change within Existing Urban Area" in some regions)
- Cloud/Shadow/Smoke (includes "fog" in some regions)

To produce the quantitative measures of changes in carbon stocks from the various change-causing agents as mapped by CDF-FRAP, it was possible to use only the second cycle of the LCMMP analysis. Additionally, the dates from the first images in the second cycle analyses were the only ones that corresponded to those of the Multi-source land-cover map. The dates of the analyses are summarized in Table 1 and Figure 2.

Table 1. California Regions and Dates of Baselines, Cause and Change Data

Area	Baseline years	Assumed # years
Cascade Northeast	1994– 1999	5
North Coast	1994 - 1998	4
North Sierra	1995/6 - 2000	5
South Coast	1995(7) - 2002	6
South Sierra	1995 - 2001	6

Verified cause of change data for the different LCMMP regions were available for the identified changed cells. These data are available on the CDF-FRAP website along with all of the LCMMP data and the multi-source Land-cover Map. The causes attributed to the changes are:

- fire,
- harvest,
- development,
- regrowth,
- pest-related, and
- other and unverified

The cause maps offered incomplete coverage of the changed areas. To assist in our analysis, CDF-FRAP conducted additional work to map the changed areas' "potential cause" by augmenting the verified cause data for the regions with other information gathered and archived, yet, unverified by field teams. This yielded a higher proportion of change cause coverage and enabled a more realistic estimate of the effects that land-cover change had on existing carbon stocks in a given location.

The importance of knowing the cause of the change is related to the fate of the change in carbon stocks. For example, the fate of the change in biomass carbon stocks from fire versus logging is different—a large proportion of the biomass carbon is immediately oxidized from a wildfire, whereas a large proportion of the biomass carbon can go into long term storage from logging. The change without cause provides information on the gross changes in carbon stocks, whereas the addition of known cause allows for an estimation of the net change in carbon stocks.

3.1.3. Calculating the Change in Area

The data on changes in canopy cover between specified dates for each pixel were summarized by the use of pivot tables in Excel, producing a table of the areas of each WHR class (vegetation type) that changed and by how much (% change in canopy cover) and the by which cause. The number of hectares with an increase or decrease in canopy cover was then summed across causes and vegetation types. The WHR classes were regrouped into fewer classes to match the data availability on biomass and canopy cover relationships (see next section).

4.0 Carbon Stocks in Forests and Rangelands

4.1. Above- and Below-ground Biomass

Two additional databases are needed for use with the area change data: relationships between biomass of forests and canopy crown cover and the allocation or fate of the biomass resulting from different causes of land-use change. To develop the relationships between biomass and canopy crown cover, data on timber volume for specific WHR habitat types at different canopy crown coverages were used (T. Shih, FRAP, personal communication). To convert timber volume to above- and belowground biomass, five equations that relate volume to biomass for five forest types across the Pacific Northwest were used (from Smith et al., 2003) to produce biomass estimates across canopy crown coverage classes (Figure 3). As only equations were available that represented five general forest types in California, the WHR forest and woodland types were reclassed as follows (decisions on the classifications are based on a division between rangelands and forests, divisions implied by the use of the Smith et al. (2003) equations and the division between tree and non-tree vegetation) (Table 2):

- Forests
    - Douglas fir
    - Fir-Spruce
    - Redwood
    - Other Conifer
    - Hardwood
    - Shrubs and Grasses[3]
- Rangelands
    - Woodland Vegetation
    - Shrubs and Grasses

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[3] A shrub/grass category of increase or decrease in crown cover exists for each of the forest classes.

Table 2. WHR Classes Matched with the Inferred Smith et al. (2003) Classes for Forests and Rangelands

FOREST ***WHR CLASS***	***INFERRED SMITH CLASS***	**RANGELAND** ***WHR CLASS***	***INFERRED SMITH CLASS***
Douglas Fir	Douglas Fir	Blue Oak Woodland Valley Oak Woodland Coastal Oak Woodland Blue-Oak Digger Pine	Woodland Vegetation
Redwood	Redwood		
White Fir Red Fir	Fir-Spruce		
Subalpine Conifer Lodgepole Pine Sierran Mixed Conifer Klamath Mixed Conifer Jeffrey Pine Ponderosa Pine Eastside Pine Closed-Cone Pine Cypress Montane Hardwood-Conifer	Other Conifer	Alpine Dwarf-Shrub Low Sage Bitterbrush Sagebrush Montane Chapparal Chemise-Redshank Chapparal Coastal Scrub Desert Succulent Scrub Juniper Pinyon-Juniper	Shrubs
Aspen Montane Hardwood Montane Riparian Valley Foothill Riparian Desert Riparian	Hardwood	Annual Grassland Perennial Grassland Wet Meadow Fresh Emergent Wetland	Grasses

To estimate the change in biomass caused by changes in crown cover, the ability to predict biomass from any given canopy crown coverage was needed. This was achieved by developing a regression equation that related the midpoints of the given crown cover classes against the biomasses calculated using the equations of Smith et al. (2003). The resultant regression equations can be used to make the desired estimates (Figure 4).

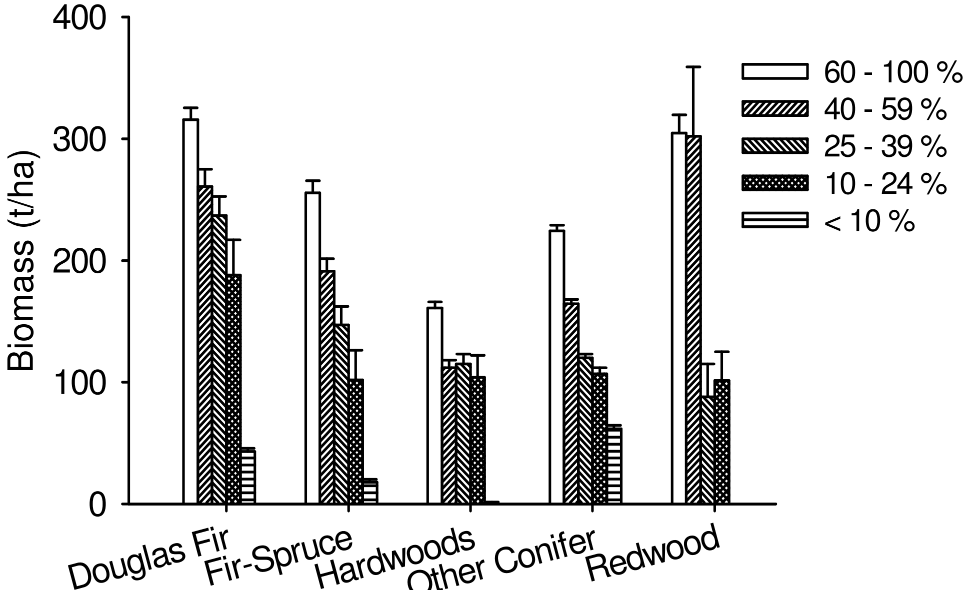

Figure 3. Mean Above- and Below-ground Biomass Estimates (± 1 SE) Calculated for Each Canopy Crown Coverage Class (in %)

Significant regression equations were obtained for the Douglas fir, fir-spruce, other conifer and hardwood classes. The shape of the relationships for these species is logical given established patterns of tree growth (Richards, 1959, Pienaar and Turnbull, 1973). For other conifer, however, a more significant relationship between the data is obtained if a linear relationship is applied. There was no significant equation for redwood largely because very few data were recorded for any but the most dense canopy crown coverage.

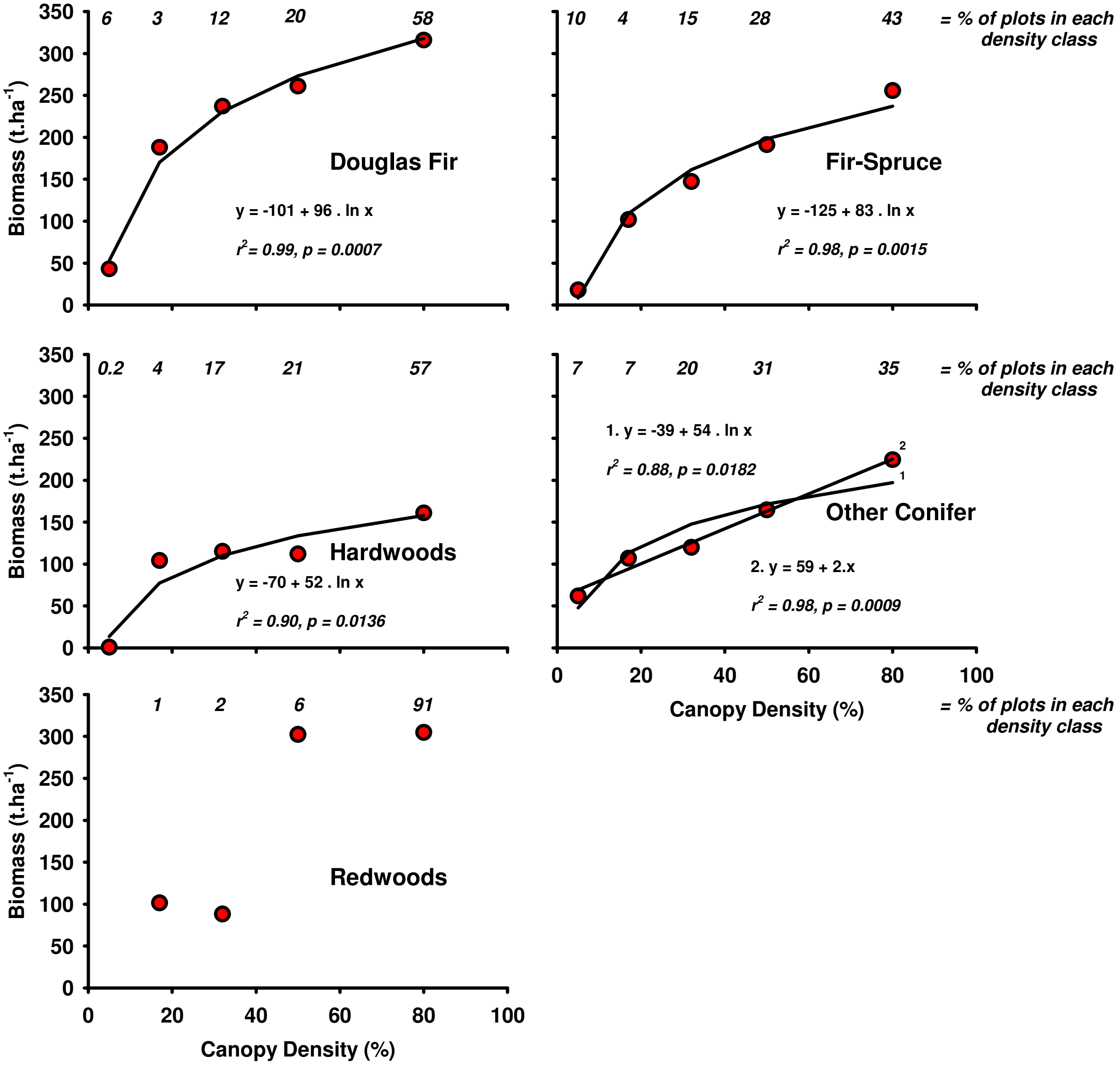

Figure 4. Relationships between Biomass (t/ha) and Canopy Coverage (%). Regression Equations, r^2 and p Values are Indicated. For Each Species the Percentage of Individual Plot Data Recorded in Each Density Class is Indicated above the Graphs

For redwood it is apparent that one biomass value can be given to canopy coverages in excess of 40% and a second value for coverages of less than this density.

Changes in canopy coverage between two points in time are recorded as percentage increases or decreases. The LCMMP incorporates a range of percentage changes into seven broad categories. Assuming an even distribution of % change within categories, the %-change midpoint can be taken as representative of the given category:

- 71 to 100% cover decrease = - 85%
- 41 to 70% cover decrease = - 55%
- 16 to 40% cover decrease = - 28%
- 16 to 40% cover increase = + 28%
- 41 to 100% cover increase = + 70%
- Shrub/Grass Decrease > 15% = - 43%
- Shrub/Grass Increase > 15% = + 43%

The application of these midpoint values to the midpoints of the WHR canopy coverage classes (see above) generates a post-change % canopy coverage, which can be used to calculate post-change biomass density using the regression equations determined in Figure 4. For example, for an “Other Conifer” forest with a moderate coverage (40-59%, midpoint 50%) that experiences a large decrease in canopy coverage (midpoint value, - 85%) gives a new canopy coverage of 7.5%. Biomass carbon is estimated for the initial and final canopy cover and the difference represents the gross change in carbon from 80 t C/ha to 37 t C/ha, a net loss of 43t C/ha.

Changes in carbon stocks for non-tree vegetation were estimated from values reported in the literature.

- For shrubs, a value of 30 t C/ha was used for all regions except the North Coast region where the higher biomass of 40 t C/ha is more appropriate (Riggan and Dunn 1982, Schlesinger 1997, Pierce et al. 2000, Morais 2001).
- For the grasslands, a value of 3.5 t C/ha was used (Bartolome et al. 2002, Higgins et al. 2002, Micheli and Kirchener 2002). This value is taken as 100% coverage. For grassland vegetation types where typically no coverage density is given, it was arbitrarily assume to be 50% coverage density.
- Shrubs and grasses within forest and woodland categories are combined. Here the value of 20 t C/ha was used, which is a midpoint between the grasses and the shrubs value.
- The values above (except for grasslands) will be taken as 100% coverage. Any increase or decrease in biomass is assumed to be directly proportional to the change in coverage. For the shrub/grasses within the forest and woodland categories increases and decreases are in a single unit of > 15%—the midpoint was used (i.e., an increase or decrease of between 15 and 100% - midpoint = 43%).

4.2. Additional Biomass Components

Above- and belowground biomass of trees form the dominant components of total biomass but the additional components of dead wood, litter and understory vegetation may contribute significantly to carbon stocks.

- Standing dead trees are added using additional equations from Smith et al. (2003).
- Understory vegetation contributes an extra 2% to the biomass density (Winrock unpublished data).
- Litter and downed dead wood adds either 7% (Douglas fir, redwood, other conifer), 10% (hardwoods) or 15% (fir-spruce) (from Vogt et al. 1986, Birdsey 1996).

Soil organic carbon was not included as changes in the soil carbon pool are slow and of a small magnitude (Carter et al. 2002, Laiho et al. 2002), and the occurrence of any change in soil carbon due to fire or harvest without a subsequent land-use change is unlikely (Binkley et al. 1992, Markewitz et al. 2002).

4.3. Above- and Below-ground Biomass for Unmeasured Forests

We use data from the USFS FIA database to estimate the likely magnitude of the increase in carbon stocks resulting from the non-measured change in canopy. Although the LCMP database contains much additional information about the structure of the forests it is difficult to correlate these to rates of carbon accumulation. .

For California, FIA data are available for 1994 and then from annual inventory data between 2001 and 2007. The data from 1994 do not include plot data from the National Forests and so the later time period is used here. The West Coast is on a ten year cycle for plot remeasurement so data are used from across the 2001-2007 period. Although this only barely overlaps with the spatial analysis time period the resulting growth rates are used with the assumption that the distribution of species groups and age classes is likely to be broadly consistent through time and space. In this analysis the current distribution of biomass values is used to approximate the rate at which carbon in biomass accumulates through time.

From the FIA web site, we downloaded total aboveground oven-dried biomass stocks and total forest areas by forest type, by five-year age classes and by county. Dividing total stock by area gives a biomass stock per hectare for each forest type[4]. These biomass values were plotted against age and a curve fitted for each forest type (Figures 5 and 6).

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[4] For Western White Pine, Hemlock Sitka Spruce and Elm Ash Cottonwood FIA data were used from plots in all Western states (CA, OR, WA, ID, MT, CO, NV, AZ, NM, WY, UT) rather than just California alone due to the paucity of data in CA alone.

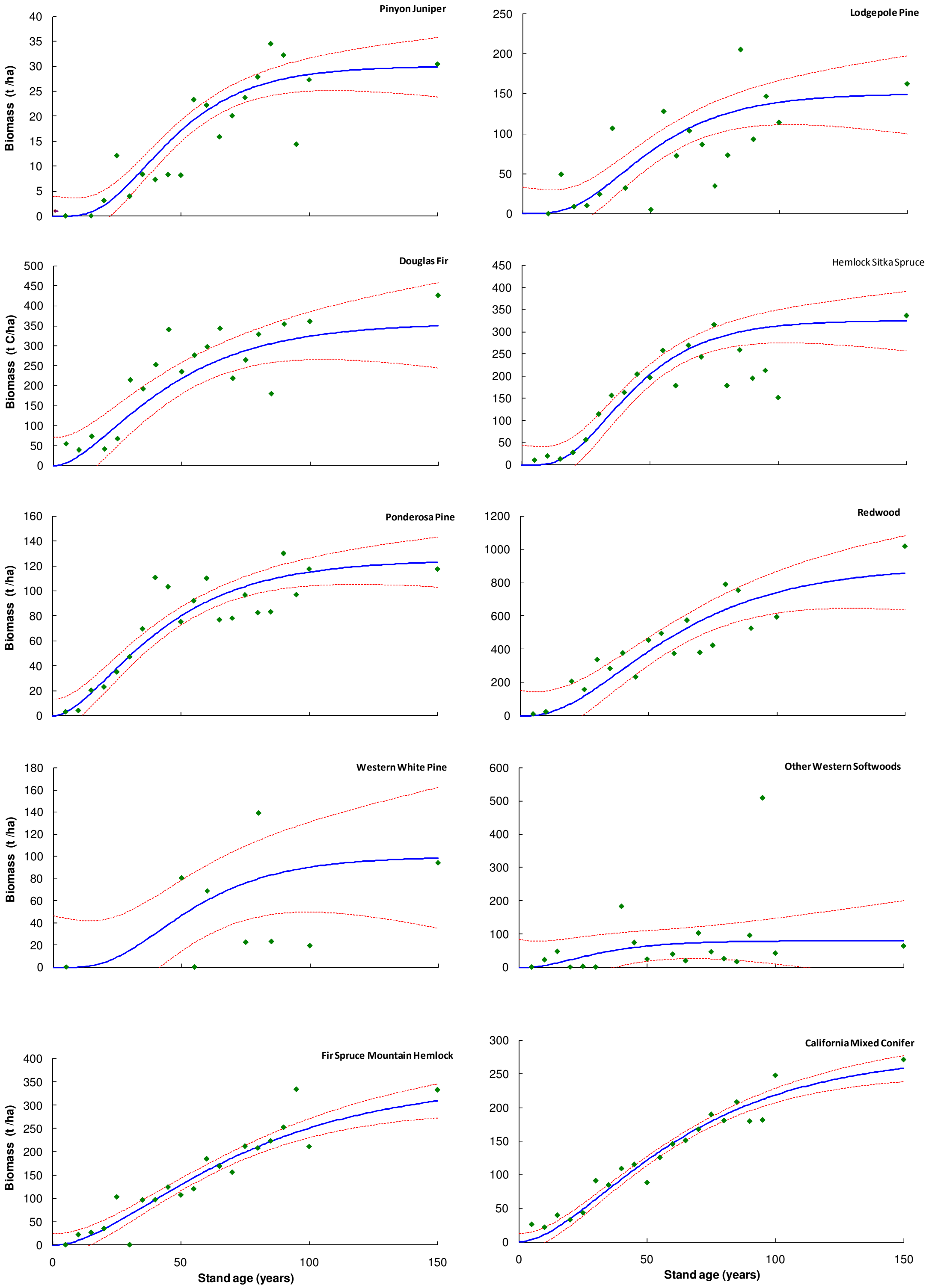


Figure 5. Relationships between aboveground biomass and age for softwood forest species groups in California derived from USFS FIA data. Shown are the FIA data for each age class and the curve giving the best fit to the data (blue line) plus and minus 95% confidence interval (red lines)

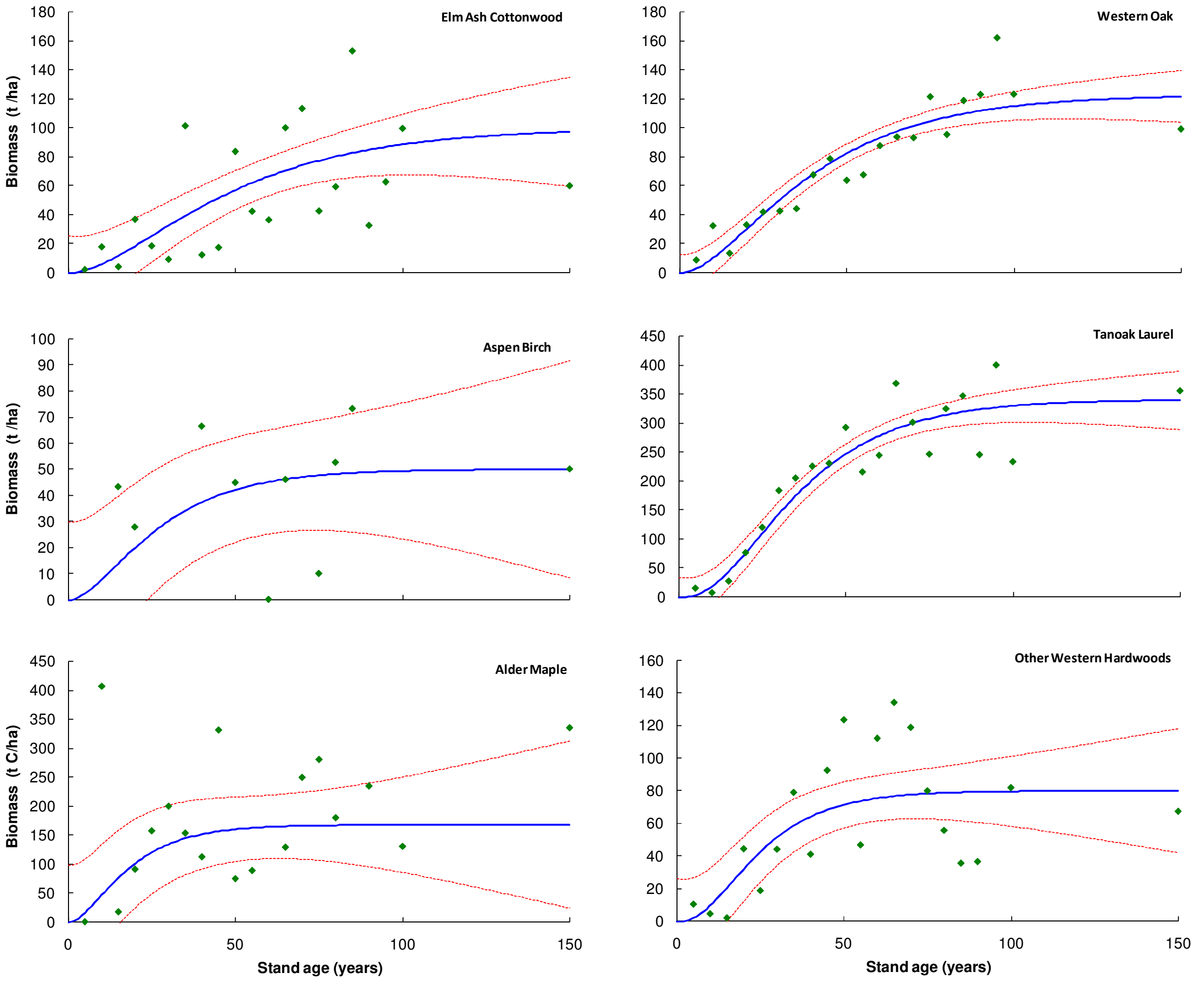


Figure 6. Relationships between aboveground biomass and age for hardwood forest species groups in California derived from USFS FIA data. Shown are the FIA data for each age class and the curve giving the best fit to the data (blue line) plus and minus 95% confidence interval (red lines

From the models in Figs 5 and 6, the mean annual sequestration rate was calculated in each 5-year age class for each forest type (see Figure 7).

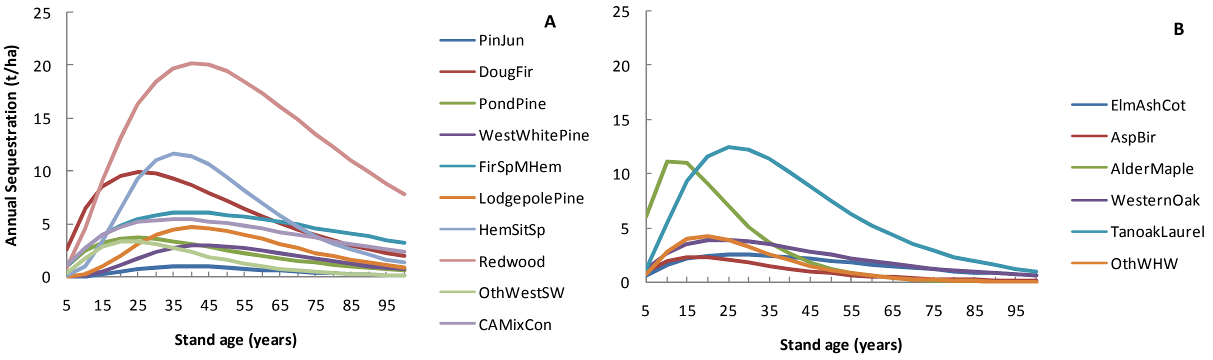


Figure 7. Aboveground biomass accumulation curves for each of the FIA species groups. A – softwoods; B - hardwoods

The FIA forest types were cross-walked to the Smith categories (Table 3). Within each forest type the distribution of forest areas across FRAP regions, FIA forest type and age classes were used to generate a weighted average rate of biomass accumulation for each of the forest and rangeland types in each FRAP region (Table 3). Where the FIA analysis did not reveal forest cover within a specific forest type for a given region, but this type is present in the same region in the analysis of the FRAP imagery a biomass accumulation rate from an adjacent region was applied.

For rangelands with no tree cover it was assumed that the shrubs and grasses are at a steady state and are not accumulating biomass unless an increase in canopy coverage is recorded.

Table 3. Aboveground carbon accumulation rates calculated for each of the FRAP regions and the division of FIA species groups in order to derive rates

Baseline Forest Type	FIA Forest Types	North Coast	Cascades NE	North Sierra	South Sierra	South Coast
				t C ha^{-1} yr^{-1}		
Redwood	Redwood	5.6			2.3	
Fir-spruce	Fir-Spruce-Mountain Hemlock / Hemlock-Sitka Spruce	2.2	1.4	1.1	0.4	
Douglas fir	Douglas fir	2.5				
Other Conifer	Western White Pine / Ponderosa Pine / Lodgepole Pine / California Mixed Conifer / Other Western Softwoods	0.9	1.0	1.0	0.4	0.3
Hardwood	Elm-Ash-Cottonwood / Aspen-Birch / Alder-Maple / Tanoak-Laurel / Other Western Hardwoods	2.7	0.7	0.6	0.4	0.9
Hardwood Range	Western Oaks / Pinyon Juniper	0.5	0.4	0.5	0.3	0.4

The values in Table 3 compare with the following rates used in the original baseline assessment (Brown et al. 2004):

Redwood:	2.59 t C ha^{-1} yr^{-1}
Fir-Spruce:	1.21 t C ha^{-1} yr^{-1}
Douglas Fir:	1.36 t C ha^{-1} yr^{-1}
Other Conifer:	1.93 t C ha^{-1} yr^{-1}
Hardwood:	1.05 t C ha^{-1} yr^{-1}
Hardwood Rangeland:	0.3 t C ha^{-1} yr^{-1}

It is apparent that the new analysis gives lower rates for the "other conifer" class. In addition, across all other types the new rates are higher in the North Coast region but lower in the two Sierran regions and in the South Coast region. These differences will lead to significant disparities in total annual sequestration from the findings of Brown et al. (2004).

5.0 Carbon Stock Changes in Forests and Woodlands

There are eight causes for changes in canopy cover (Table 4) determined by the LCCMP separately from this study. Fire, harvest (commercial timber extraction) and development (construction) each reduce canopy cover and carbon stocks. The regrowth of forests and woodlands on abandoned land or after a catastrophic event such as a fire increase canopy cover and carbon stocks. In cycle one (north coast) the "other" category is dominated by pest-related factors and it is assumed that there is no net effect on carbon stocks. By cycle two (in all other regions) "pest-related" becomes its own category and the "other" category is dominated by reductions in canopy coverage and carbon stocks. Unverified effects can both increase and decrease carbon stocks but are predominantly a decrease. Details of each of the causes are given in the sections below.

The *gross* change in carbon stocks would be the change that is directly proportional to the decrease or increase in canopy coverage. The *net* change deducts carbon that is not released to the atmosphere such as charcoal from fire, slash from harvesting that slowly decomposes, or long-term products from harvesting. The net deductions are detailed in the sections below.

For shrubs and grasses the cause of the change is assumed to have no impact on the relative increase or decrease, e.g., fire will burn all vegetation, all vegetation will be cleared and destroyed by development.

Events that cause large changes in canopy cover such as fire, harvest or development are assumed to have occurred on average at the midpoint between two censuses.

Table 4. Causes of Changes in Canopy Crown Coverage and Effect on Carbon Stocks

Cause	Increase in Carbon Stocks	No Change in Carbon Stocks	Decrease in Carbon Stocks
FIRE			X
HARVEST			X
DEVELOPMENT			X
UNVERIFIED	(X)		X

OTHER	(X)	X †	X
PEST-RELATED		X †	
SEASONAL		X †	
REGROWTH	X		

† “Seasonal,” “pest-related,” and “other” (in cycle one) may result in a decrease in crown cover but for “seasonal” this is temporary and for “pest-related” and “other” (in cycle one) this is predominantly caused by insects and disease leaving standing dead trees which release carbon into the atmosphere very slowly.

5.1. Fire

The effects of fire on carbon stocks are dependent on the intensity of the fire. An intense fire will destroy biomass and release a great proportion of the carbon to the atmosphere, while a less intense fire will even fail to kill the majority of the trees. Here fires are divided into three potential intensities: high, medium and low. Based on discussions with FRAP staff, we assumed that the three intensities are associated with the magnitude of change in crown cover, so that a large decrease in crown cover would be due to a high intensity fire or a small decrease is caused by a low intensity fire.

Pre-fire carbon has five potential destinations during and after a fire (Figure 8). The first proportion will survive the fire to continue as live vegetation, a second proportion will be volatilized during the fire and immediately released to the atmosphere and the remainder will be divided between the pools of dead wood, soot, and charcoal. Soot and charcoal are stable forms of carbon and can remain unchanged for very many years; in contrast dead wood decomposes over time.

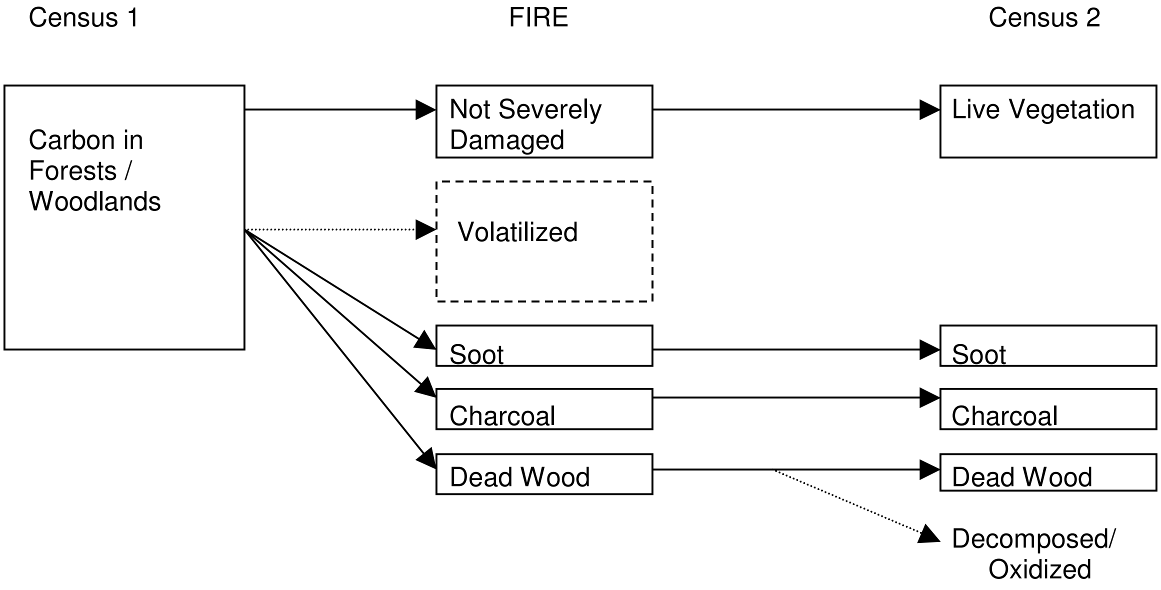


Figure 8. Flow Diagram Illustrating the Various Destinations of Pre-burn Carbon after a Fire

The assumption is made that the midpoint of each decrease in canopy coverage class is the proportion of the vegetation killed by the fire. The proportion volatilized is dependent on fire intensity (Table 5, McNaughton et al. 1998; Carvalho et al. 2001). If the volatilized proportion is subtracted from the proportion of vegetation killed, then the remaining fraction is the dead wood, soot and charcoal pool.

The remaining fraction is divided using the following proportions: 22% charcoal, 44% soot, 32% dead wood (Table 5; Comery 1981, Raison et al. 1985, Fearnside et al. 1993, Neary et al. 1996). Dead wood decomposition occurs for two years from the fire-occurrence midway between the two censuses to the endpoint at the second census. Decomposition occurs at a rate of 0.05 yr^{-1} as determined by Harmon et al. (1987) for the Sequoia National Park in California (but see Chambers et al., 2000).

Table 5. Assumptions for the Fate of Carbon after Fire-induced Decreases in Canopy Coverage

	Fire Intensity		
	High (%)	**Mid (%)**	**Low (%)**
Volatilized	60	40	20
Not volatilized	25	15	8
Charcoal	5.5	3.3	1.8
Soot	11	6.6	3.5
Dead wood	8.0	4.8	2.6
Surviving vegetation	15	45	72

5.2. Harvest

The net destination of carbon after commercial harvest is illustrated in Figure 9. Initially, at the time of harvest, trees are either cut or mortally damaged. The remaining proportion (taken here as the proportion of canopy coverage remaining after the harvest mid-point decrease) endures as live vegetation.

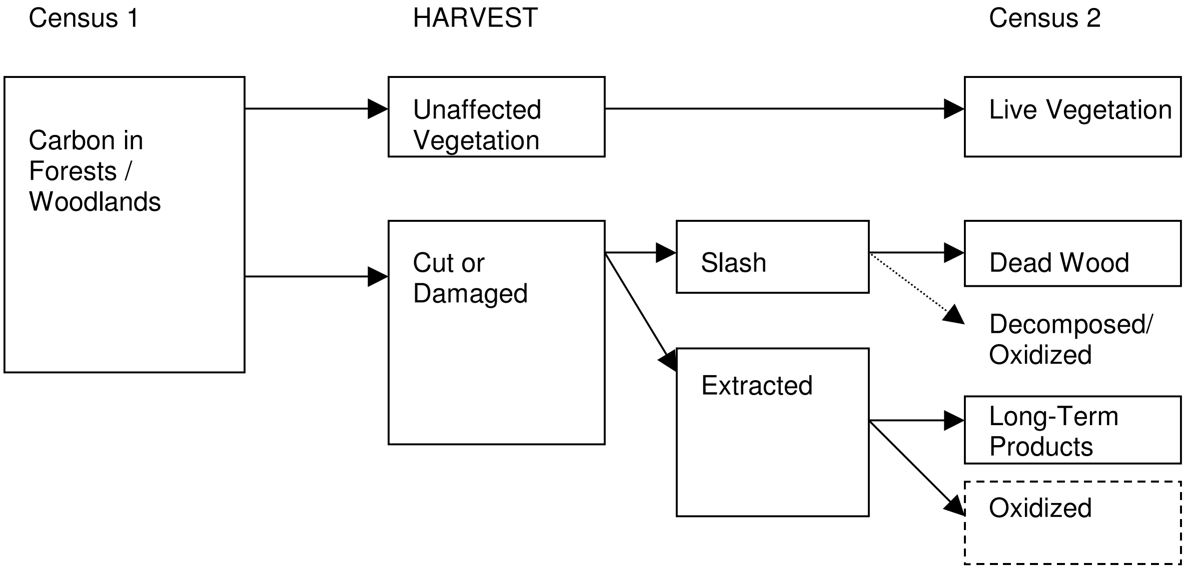


Figure 9. Flow Diagram Illustrating the Various Destinations of Pre-harvest Carbon after Commercial Harvest

The cut and damaged vegetation is divided into two pools, one of which is extracted for timber processing. The remaining fraction is either left on-site to decompose (in the wetter forest areas) or piled and burned on site (in the drier areas). For simplicity, we assume that all slash oxidizes for two years at 0.05/yr (Harmon et al. 1987). Finally the extracted portion is further divided into long-term products and other pools. Other pools can include waste, chipping and fuel; all are assumed to rapidly release carbon to the atmosphere. The proportions extracted from the forest and transformed into long-term products are detailed for the California region by Birdsey (1996). For softwoods 75% is extracted from the forest and 44% of the extracted volume becomes long-term products. For hardwoods 73% is extracted and 23% becomes long-term products.

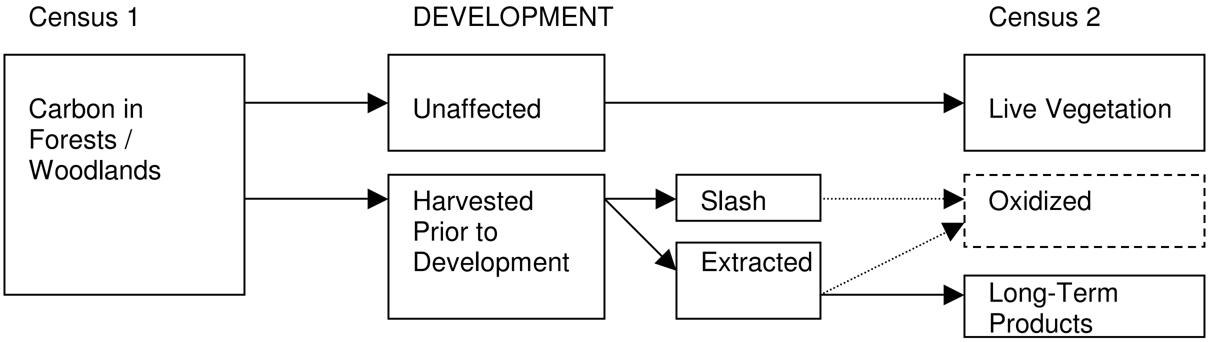
5.3. Development

Developed land is typically cleared to allow for construction. Consequently it can be assumed that the mid-point decrease in canopy coverage represents vegetation that has been removed from the site.

For Douglas fir and redwood it was assumed that the value of the timber is too high for it not to be used commercially. We apply the same proportions as in the harvest scenario (see Section 4.2.) except here it is assumed that slash will not be permitted to decompose onsite and instead is immediately destroyed and all carbon rapidly oxidized. The fate of carbon during development for Douglas fir and redwood is illustrated in Figure 10a.

For fir-spruce, other conifer and hardwoods it was assumed that the extracted trees are destroyed and all carbon rapidly oxidized. The fate of carbon during development for these vegetation types is illustrated in Figure 10b.

a. Douglas Fir / Redwood



b. Fir-Spruce / Other Conifer / Hardwoods

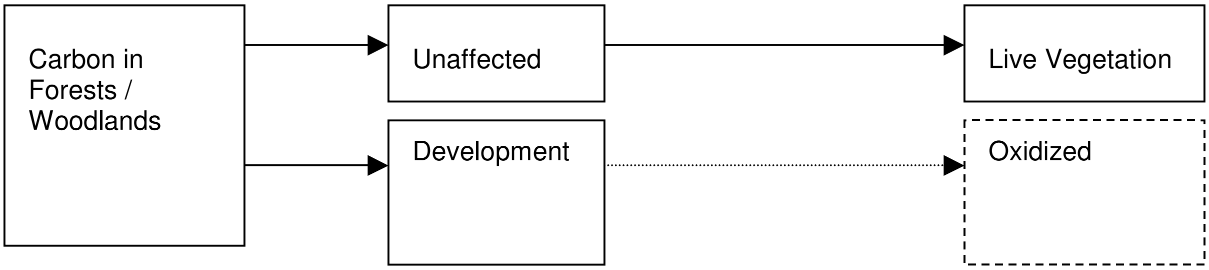


Figure 10. Flow Diagram Illustrating the Various Destinations of Pre-development Carbon after Development has Occurred

5.4. Regrowth

Ostensibly regrowth represents the simplest scenario. An increase in canopy coverage represents a net increase in biomass. Complications are introduced, however, as trees keep growing even when the canopy is closed, and at the other extreme tree growth often may be insufficient to reach the change-detection threshold. Consequently it is possible that the potential biomass accrual is underestimated.

Support for the strength and sensitivity of these data comes from the fact that substantial areas in the highest density class report a large increase in canopy coverage. This translates to areas of forest with an initial canopy coverage of between 60 and 100% reporting an increase in coverage of between 40 and 100%. For example, in the North Coast region 402 hectares of Douglas fir and 827 hectares of redwood fall into this category. A second, and potentially a greater, weakness is the threshold of 15% for change detection. Decreases in vegetative land cover are typically large (e.g., fire or development). Regrowth is gradual, and it is a fair assumption that areas exist which did not achieve the 15% threshold, and so are not included in direct regrowth calculations leading to an underestimation of sink size. In order to include these unmeasured changes, standard factors are applied. These factors are discussed in detail in Section 4.3. (above).

5.5. Seasonal and Pest-related Changes

While decreases in canopy coverage do result from seasonal and pest-related causes, these causes of change are not considered in depth in this study. For seasonal, the area involved is small and by definition all changes will be reversed annually or semi-annually. For pest-related, the principal causal agent is disease and specifically in California, Sudden Oak Death. Following onset of disease, canopy coverage declines as foliage is lost but it is unlikely that carbon stocks will be significantly affected, at least in the near to mid term. The end point of the disease will be standing dead trees, which decompose very slowly (Rizzo and Garbelotto 2003).

5.6. Other Changes

The pest-related category only exists in the Cascades Northeast region. In the other regions, pest effects dominate the "other" category resulting in no net effects on carbon. In the Cascades, "pest-related" was separated into its own category and "other" was composed of such effects as conversion to agriculture, road-related changes and changes due to floods, land-slides and avalanches. Each of these causes leads to a net change in carbon. Regarding the timber, "other" is treated identically to development (see Section 1.4.3.), with redwood and Douglas fir timber converted to long-term products.

5.7. Unverified Changes

A large proportion of the measured changes in canopy coverage have causes that remain unverified. Some assumptions, however, can be made with regard to the likely causes to increase the precision of our final estimates of net carbon stocks.

Fire as a cause is carefully traced by the California Department of Forestry and Fire Protection and it can safely be assumed none of the unverified area of change is caused by fire damage.

Instead it is likely that all decreases in canopy coverage are caused by small-scale harvesting and development operations. Again due to the value of Douglas fir and redwood timber it is assumed that the cause of change for these forest types is "harvested" and is the cause for change for the other forest types is "development".

Increases in canopy coverage are caused by regrowth and all decreases in carbon stock values are reported as net gains through regrowth.

5.8. Non-CO_2 Gases

Other gases influence climate change as directly as carbon dioxide. Two gases in particular are the focus of growing attention scientifically and politically: methane and nitrous oxide. Although these gases are produced in smaller quantities than carbon dioxide, their effect for a given mass on global warming is greater. This is illustrated by the calculated global warming potential. Over a hundred year period methane is expected to have a global warming potential equal to 23 times that of carbon dioxide and nitrous oxide has a potential equal to 296 times that of CO_2 (Houghton et al. 2001). Consequently these gases need only be produced in quantities equal to 4% and 0.3% respectively of the mass of CO_2 to have an equal effect (over 100 years) with respect to climate change.

Methane and nitrous oxide are produced mainly as the result of anthropogenic activities, for example the draining of wetland regions, the fertilization of land and the storage and processing of livestock effluent (Houghton et al 2001). None of these causes are of direct concern to the current section (baseline for forests and rangelands in California) as the area of wetland forest in California is minimal and fertilization of planted forests in California is rarely cost effective and consequently is very infrequently employed (R. York, 2003, Center for Forestry, University of California, personal communication). The potential for CH_4 and N_2O release, for each of the causes of canopy coverage change discussed previously in this section, will be examined.

Fire—Biomass burning is the greatest natural (or semi-natural) source of non-CO_2 gas production (IPCC GPG, 2003). The quantity released can be estimated using emission factors based on the quantity of C released (IPCC GPG, 2003).

CH_4 emissions = (carbon released) x 0.012 x 16/12 (IPCC GPG 2003)

N_2O emissions = (carbon released) x 0.007 x 0.01 x 44/28 (Crutzen and Andreae 1990)

Fires in California are likely to be of the “flaming” rather than the “smoldering” variety consequently it may be more appropriate to apply the lower emissions ratio (0.009 instead of 0.012 for CH_4 and 0.005 instead of 0.007 for N_20 [IPCC GPG 2003, Crutzen and Andreae 1990]).

Harvest—Methane is sequestered in undisturbed forest soils at an estimated rate of 2.4 kg/ha.yr (Smith et al. 2000), disturbance will alter this rate but it is unclear to what extent. Nitrous oxide is widely associated with fertilization (Houghton et al. 2001), but natural sequestration and release in forest environments is very poorly understood. It has been suggested that forest management activities such as clear cutting may increase emissions but the available data are insufficient and is contradictory (IPCC GPG 2003).

In order to make an estimation of CH_4 response to harvesting, estimations of harvest-induced emissions from a single study are examined. Gasche et al. (2003) studied the flux of non-CO_2 gases from the nitrogen-saturated soils of a German spruce forest before and after clear-cutting. Gasche et al. (2003) measured a decrease in sequestration of CH_4 from 1.46 kg CH_4/ha.yr to 0.52 kg CH_4/ha.yr spanning a clear cut. The net effect is a reduction in CH_4 sequestration of 0.94 kg/ha.yr as a consequence of clear cutting. Simultaneously in the study of Gasche et al. (2003), N_2O release increased by an order of magnitude. However, the direct relationship between fertilization and N_2O release and the fact that these forest soils were nitrogen saturated and Californian forests are very rarely fertilized means that this study cannot be applied for the analysis for Californian forests.

Development, regrowth, seasonal, pest-related changes, other changes and unverified changes—For development, the lack of information regarding subsequent land-use prevents any estimation of non-CO_2 gas fluxes. For example, if development involves construction then gradual emissions from the soil will not be possible.

For the remainder of the causes a similar paucity of information and an entire lack of scientific consensus means that the most conservative approach is to make no estimates.

5.9. Evaluating Sources of Error

As has been described above, many steps are involved in estimating the baseline for the forests and rangelands sector. As expected, each step has a degree of uncertainty (source of error) associated with it. Here we describe each source of error, its likely magnitude, and an estimate of the total error for the baselines. The magnitude of the error for each source is expressed as the percent of the average value represented by the 95% confidence interval.

STEP 1: Calculating areas from satellite data

The LCMMP program reports an accuracy value for the North Coast region of 89.8%. This represents an error of 10.2%. Reported precision for the other regions is not yet available but is assumed to be equivalent.

STEP 2: Calculating carbon stocks

A: FIA data–

The FIA program determines a maximum allowable sampling error of 9.5% at the county scale at the 67% confidence level.

Using - t = 1.036 @ 67%; t = 1.960 @ 95% - the equivalent error at the 95% confidence level is 18%.

B: FIA data to canopy coverage classes–

Excluding Redwood (for which 91% of the measurements were in only one of the four > 10% canopy coverage classes), the 95% confidence interval around the coverage averages 15.1%.

STEP 3: Creating a regression for biomass to canopy coverage

The 95% confidence prediction interval was calculated around each of the regressions of canopy coverage to biomass. The mean deviation of the confidence intervals from the original curves was 27.3%.

STEP 4: Assumptions for calculating net emissions

Fire:

Altering the proportion oxidized in the fires by 10% changes the net emissions by 9%.

Harvest:

Altering the proportion extracted by 10% changes the net emissions by 7.8% for softwoods and 8.3% for hardwoods.

Altering the proportion converted to long-term products by 10% changes the net emissions by 7.5% for softwoods and 2.2% for hardwoods.

ESTIMATED TOTAL ERROR

The total error is estimated as equal to the square root of the sum of the squares of the component errors (we assume that each source of error is independent).

Fire = 38.5%

Harvest (softwood) = 39.0%

Harvest (hardwood) = 38.4%

All other causes = 37.4%

The single largest source of error is derived from the regression equations used to estimate biomass from canopy coverage (Table 6). Reducing this error may be one of the more difficult steps as it is related to the initial remote sensing interpretation of canopy coverage classes. To reduce most of the other sources of error would require additional field data, but the potential to significantly reduce the error would be worth the effort.

Table 6. Sources of Errors and their Potential Magnitude in the Estimated Baseline for the Forest and Rangelands Sector

	Source of Error	% Error	Potential for Decreasing Error
1.	Image processing	10.2	Outside the expertise or control of Winrock (but see Step 4)
2.	a. FIA	18	Outside the control of Winrock. More plots could be used to increase precision.
	b. FIA to canopy coverage	15.1	If more plots were examined in each canopy coverage class then more precision could be attained.
3.	Regression biomass to canopy coverage	27.3	To increase precision more canopy coverage classes would be required (remote sensing step). Four or five classes are not sufficient to create a tight regression.
4.	Net emission assumptions		
	a. FIRE	9.0	Additional field work related to California would be needed to validate and refine the assumptions
	b. HARVEST		Detailed assessment of the forestry and milling industries to refine estimations of extracted proportion and proportion entering long-term products
	softwoods	10.8	
	hardwoods	8.6	
	TOTAL		
	Fire	38.5	
	Harvest-softwood	39.0	
	Harvest-hardwood	38.4	
	All other causes	37.4	

As the carbon values applied to regrowth that was not measured by the LCMMP resulted directly from FIA data the FIA error of 18% will be used.

6.0 Results

Each of the following sections will include data tables by area as well as gross and net changes in carbon stocks.

6.1. North Coast

The area showing a change in canopy cover between 1994-98 (a 4 year period) was only 124,000 ha which is just 1.8% of the land area of the north coast region. All causes are limited to small patches except for a single area with a large extent of fire damage in Lake County (Figure 11). Harvest is a significant cause, albeit in small patches, through the redwood and Douglas fir forests of Humboldt and Mendocino Counties.

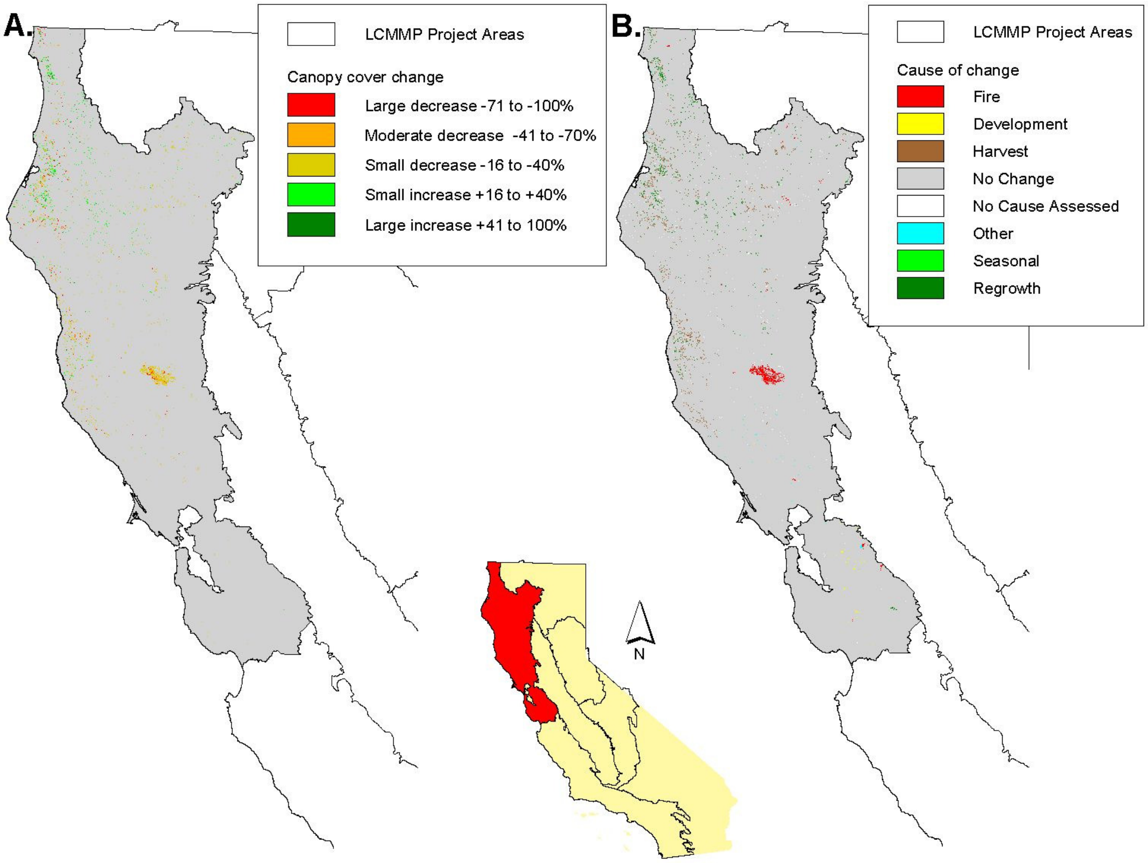


**Figure 11. Forest and rangeland areas Experiencing a Change in Canopy by Magnitude of Change (A)
and by Cause (B) for the North Coast region**

6.1.1. Rangelands

The total area of rangelands in the North Coast region affected by a canopy change (decrease and increase) was about 24,000 hectares. The greatest cause of changes for the north coast rangelands was regrowth that was responsible for 41% of the total recorded canopy crown changes (with 98% of this total in shrubs and grasses). The greatest source of decreases in canopy cover was fire with 4,063 ha affected (Table 7).

Table 7. Change in Area of North Coast Rangelands Based on Areas Affected by Canopy Cover Change (- Equals a Decrease in Canopy Cover, + Equals an Increase) between 1994–1998.

	Fire	Harvest	Development	Regrowth	Other		Unverified		SUM
					-	+	-	+	
AREA (ha)									
Woodlands	511	152	16	189	60	0	429	79	**1,436**

Grasses / Shrubs	3,552	620	1,033	9,498	889	6	2,364	4,335	**22,297**
SUM AREA	**4,063**	**772**	**1,049**	**9,687**	**949**	**6**	**2,793**	**4,414**	**23,733**

In terms of carbon stocks, carbon removals dominate, accounting for more than 700,000 tons of carbon (Table 8). Fire is the largest source of carbon emissions with a net total of about 35,000 tons emitted between 1994 and 1998. There is a net loss in the tree-covered rangelands (woodlands) of 16,000 t C and a net loss of about 60,000 t C in the shrub and grass covered rangelands mostly caused by fire. Across the rangelands in north coast California it is calculated that the net change between 1994 and 1998 was a gain of about 655,000 t C (Table 8), or about 164,000 t C per year.

Table 8. Changes in the Carbon Stock of North Coast Rangelands. (- Equals a Loss in Carbon Stocks [a Source] and + Equals a Gain in Stocks [a Sink])

EMISSIONS						**REMOVALS**		
	Fire	Harvest	Development	Other/ Unverified	**SUM EMISSIONS**	Measured Removals	Unmeasured Regrowth	**SUM REMOVALS**
GROSS – t C								
Woodlands	-6,842	-4,586	-159	-8,258	**-19,844**	2,023	643,843	**645,866**
Grasses / Shrubs	-29,717	-7,456	-1,100	-21,765	**-60,038**	85,148	-	**85,148**
SUM GROSS	**-36,559**	**-12,041**	**-1,259**	**-30,023**	**-79,883**	**87,171**	**643,843**	**731,014**
NET – t C								
Woodlands	-4,983	-2,698	-159	-8,258	**-16,098**	2,023	643,843	**645,866**
Grasses / Shrubs	-29,717	-7,456	-1,100	-21,765	**-60,038**	85,148	-	**85,148**
SUM NET	**-34,700**	**-10,154**	**-1,259**	**-30,023**	**-76,137**	**87,171**	**643,843**	**731,014**
+/- uncertainty	*13,360*	*3,825*	*471*	*11,229*	***17,872***	*32,602*	*115,892*	***118,685***

6.1.2. Forests

A total area of about 96,000 hectares of North Coast forest were affected by canopy crown change between 1994 and 1998 (Table 9). The dominant cause in terms of area is commercial harvest, accounting for 42% of the total change. Between 1994 and 1998 at least 40,000 hectares were affected by harvesting, especially in Douglas-fir and redwood forests. In contrast only 107 ha of the verified causes were altered by development.

Table 9. Change in Area of North Coast Forests Based on Areas Affected by Canopy Cover Change. (- Equals a Decrease in Canopy Cover, + Equals an Increase)

	Fire	Harvest	Development	Regrowth	Other		Unverified		SUM
					-	+	-	+	
AREA (ha)									
Douglas-fir	4,828	9,879	29	6,279	499	0	2,166	462	**24,142**
Fir-Spruce	96	777	0	689	23	7	567	67	**2,226**
Other Conifer	5,091	2,728	0	2,273	221	7	1,688	70	**12,078**
Hardwood	7,176	7,040	65	5,797	728	7	2,784	1,478	**25,075**
Redwood	17	19,553	9	6,649	172	0	1,613	978	**28,991**
Shrubs/grasses	242	100	4	1,904	90	2	209	1,232	**3,783**
SUM AREA	**17,450**	**40,077**	**107**	**23,591**	**1,733**	**23**	**9,027**	**4,287**	96,295

Total net emissions by all activities were 1.48 million t C (Table 10). Harvest was responsible for 58% of the net emissions, followed by fire for another 23% of the total. Harvest of redwood forests accounted for most of the net emission from harvest (64%). The sum of the removals was 20.7 million t C, 98% of which was from the estimated unmeasured increases in canopy coverage. Overall for the North Coast, removals exceeded emissions by 19.2 million t C (Table 10), or about 4.8 million t C/yr. Accounting for the uncertainties, the North Coast net removals could range between 17.0 to 24.3 million t C.

Table 10. Changes in the Carbon Stock of North Coast Forests. (- Equals a Loss in Carbon Stocks [a Source] and + Equals a Gain in Stocks [a Sink])

EMISSIONS						**REMOVALS**		
	Fire	Harvest	Develop-ment	Other / Unverified	**SUM EMISSIONS**	Measured Removals	Unmeasured Regrowth	**SUM REMOVALS**
GROSS – t C								
Douglas-fir	-175,410	-385,778	-686	-78,115	**-639,990**	95,893	5,329,288	**5,425,181**
Fir-Spruce	-3,053	-15,417	0	-13,141	**-31,611**	9,460	616,375	**625,835**
Other Conifer	-148,453	-66,521	0	-47,433	**-262,407**	44,587	945,949	**990,536**
Hardwood	-130,274	-171,688	-1,379	-68,823	**-372,164**	60,226	7,428,077	**7,488,303**
Redwood	0	-1,252,205	-506	-91,846	**-1,344,558**	139,668	5,990,101	**6,129,769**
Shrubs / grasses	-1,417	-607	-23	-1,764	**-3,812**	11,926	-	**11,926**
SUM GROSS	**-458,607**	**-1,892,215**	**-2,594**	**-301,125**	-2,654,541	**361,760**	**20,309,790**	20,671,550

NET – t C								
Douglas-fir	-127,146	-171,430	-460	-38,755	**-337,792**	95,893	5,329,288	**5,425,181**
Fir-Spruce	-2,211	-6,851	0	-15,552	**-24,615**	9,460	616,375	**625,835**
Other Conifer	-107,919	-29,560	0	-66,963	**-204,442**	44,587	945,949	**990,536**
Hardwood	-94,693	-101,025	-1,379	-116,180	**-313,278**	60,226	7,428,077	**7,488,303**
Redwood	0	-556,449	-339	-43,469	**-600,257**	139,668	5,990,101	**6,129,769**
Shrubs / grasses	-1,417	-607	-23	-1,764	**-3,812**	11,926	-	**11,926**
SUM NET	**-333,386**	**-865,922**	**-2,201**	**-282,686**	**-1,484,195**	**361,760**	**20,309,790**	**20,671,550**
+/- uncertainty	*128,354*	*337,474*	*823*	*105,724*	***376,220***	*-135,298*	*3,655,762*	***3,658,265***

6.2. Cascade Northeast

The area that underwent a change in canopy cover between 1994-99 (5 years) was 141,500 ha which is 1.9% of the land area of the Cascades Northeast region. In the Cascade Northeast region, development, harvest, pest-related and other causes are all in small patches of small area extent (Figure 12). Fire and regrowth occur over units of a larger area, especially fire where wide areas are affected in Modoc and Siskiyou Counties.

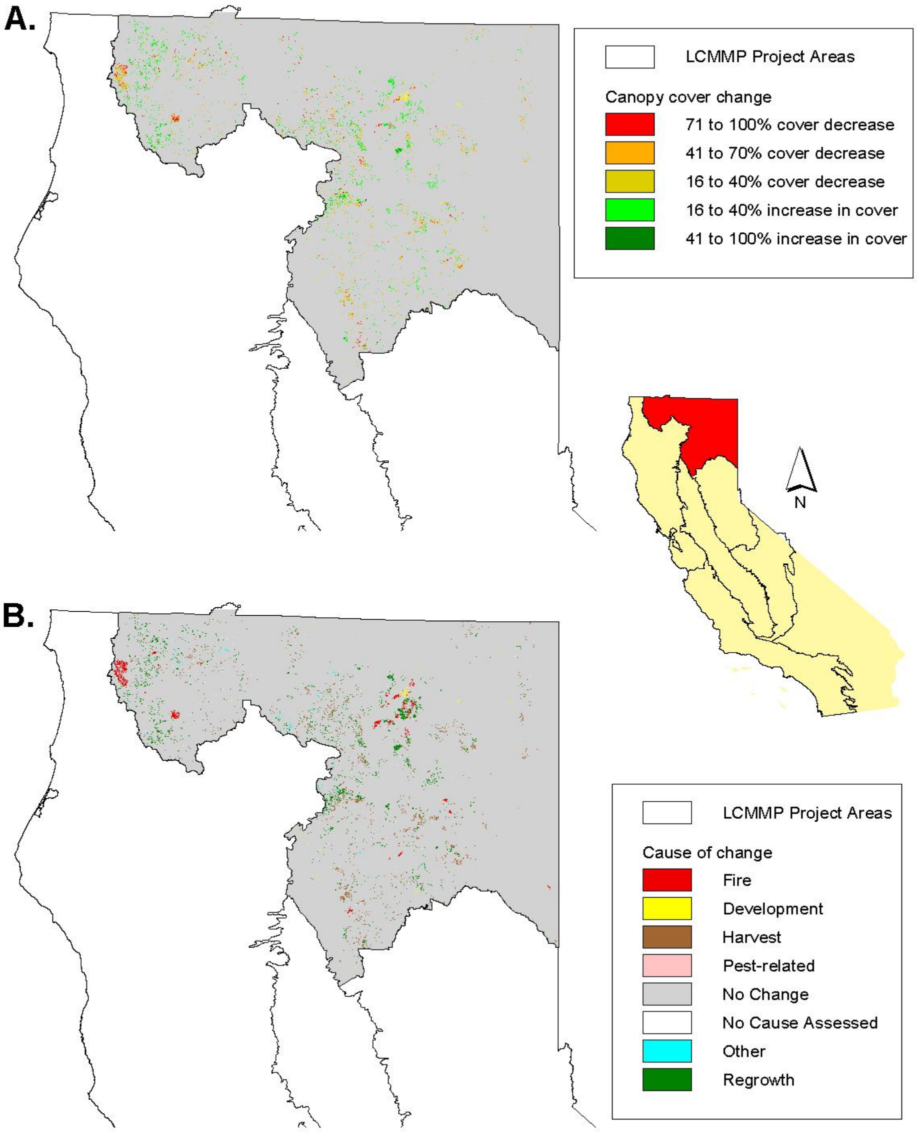


Figure 12. Illustration of Areas Experiencing a Change in Canopy by Magnitude of Change (A) and by Cause (B) in the Cascades Northeast Region

6.2.1. Rangelands

A total of 22 thousand hectares of rangelands in the Cascade Northeast region were affected by a canopy change during the census interval. Of this total about 3,000 ha were woodlands and 19,000 ha were shrub/grass lands. The dominant influences were regrowth affecting 11,676 ha and fire affecting about 5,600 ha (Table 11).

Table 11. Change in Area of Cascade Northeast Rangelands based on Areas Affected by Canopy Cover Change. (- Equals a Decrease in Canopy Cover, + Equals an Increase)

	Fire	Harvest	Development	Regrowth	Pest-related	Other		Unverified		SUM
						-	+	-	+	
AREA (ha)										
Woodlands	1272	238	0	683	7	476	1	47	172	**2,896**
Grasses / Shrubs	4,336	2056	9	10,993	140	579	96	343	751	**19,303**
SUM AREA	**5,608**	**2,294**	**9**	**11,676**	**147**	**1,055**	**97**	**390**	**923**	**22,199**

Across the Cascade Northeast, net emissions from rangelands was estimated to be about 108,000 t C, 53% of which was caused by fire (Table 12). Total removals were estimated to be about 218,600 t C. Removals exceeded emissions by 110,600 t C during the period 1994-99.

Table 12. Changes in the Carbon Stock of Cascade Northeast Rangelands. (- Equals a Loss in Carbon Stocks [a Source] and + Equals a Gain in Stocks [a Sink])

EMISSIONS							**REMOVALS**		
	Fire	Harvest	Develop-ment	Pest-related	Other/ Unverified	**SUM EMISSIONS**	Measured Removals	Unmeasured Regrowth	**SUM REMOVALS**
GROSS – t C									
Woodlands	-16,377	-4,039	0	-70	-12,612	**-33,099**	6,328	529,155	**535,483**
Grasses / Shrubs	-45,121	-21,662	-72	-1,382	-12,785	**-81,022**	79,609	-	**79,609**
SUM GROSS	**-61,499**	**-25,701**	**-72**	**-1,453**	**-25,397**	**-114,121**	**85,937**	**529,155**	**615,092**
NET – t C									
Woodlands	-11,893	-2,377	0	-70	-12,612	**-26,952**	6,328	529,155	**535,483**
Grasses / Shrubs	-45,121	-21,662	-72	-1,382	-12,785	**-81,022**	79,609	-	**79,609**
SUM NET	**-57,014**	**-24,038**	**-72**	**-1,453**	**-25,397**	**-107,974**	**85,937**	**529,155**	**615,092**
+/- *uncertainty*	*21,950*	*9,014*	*27*	*543*	*9,498*	***25,565***	*32,140*	*95,248*	***100,524***

6.2.2. Forests

About 113,000 ha of forests were affected by a canopy change in the Cascades Northeast between 1994-99, including about 49,000 hectares of regrowth, about 41,000 hectares of harvest, and about 13,000 hectares of fire damage (Table 13). Considerably more than half of the affected area occurred in the "other conifer" forests.

Table 13. Change in Area of Cascade Northeast Forests based on Areas Affected by Canopy Cover Change. (- Equals a Decrease in Canopy Cover, + Equals an Increase)

	Fire	Harvest	Development	Regrowth	Pest-related	Other		Unverified		SUM
						-	+	-	+	
AREA (ha)										
Douglas-fir	3,899	1,619	0	9,820	163	242	0	103	176	**16,022**
Fir-Spruce	340	4114	0	2683	421	424	25	107	179	**8,293**
Other Conifer	6,732	33,425	228	30,728	628	1,413	147	1,431	1,967	**76,699**
Hardwood	2,115	1,509	1	5,267	133	469	8	158	598	**10,258**
Redwood	0	0	0	0	0	0	0	0	0	**0**
Shrubs/grasses	225	257	1	889	16	70	26	24	69	**1,577**
SUM AREA	**13,311**	**40,924**	**230**	**49,387**	**1,361**	**2,618**	**206**	**1,823**	**2,989**	**112,849**

The net emissions from all activities is 1.16 million t C, with forest harvest accounting for 52% and fire for an additional 34% of the total net emissions (Table 14). The changes in carbon stocks are clearly dominated by "other conifer" forests which account for 66% of the total net emissions, particularly caused by harvest and regrowth of these forests. Total removals from all causes are estimated to be 7.95 million t C, 61% of which is caused by other conifers. The net balance for the region is a removal of 6.26 million t C (or about 1.25 million t C/yr), with a range of 5.0-7.5 million t C.

Table 14. Changes in the Carbon Stock of Cascade Northeast Forests. (- Equals a Loss in Carbon Stocks [a Source] and + Equals a Gain in Stocks [a Sink])

EMISSIONS							**REMOVALS**		
	Fire	Harvest	Develop-ment	Pest-related	Other/ Unverified	**SUM EMISSIONS**	Measured Removals	Unmeasured Regrowth	**SUM REMOVALS**
GROSS – t C									
Douglas-fir	-202,832	-66,550	0	-5,289	-12,553	**-287,224**	136,529	1,265,036	**1,401,565**
Fir-Spruce	-14,599	-164,708	0	-11,752	-17,527	**-208,586**	38,227	955,076	**993,303**
Other Conifer	-263,104	-1,066,273	-4,630	-20,031	-81,042	**-1,435,079**	565,461	3,976,765	**4,542,216**
Hardwood	-55,199	-40,197	-58	-2,658	-17,136	**-115,248**	42,895	437,943	**480,838**
Redwood	0	0	0	0	0	**0**	0	0	**0**
Shrubs / grasses	-998	-1,323	-4	-106	-429	**-2,861**	3,405	-	**3,405**
SUM GROSS	**-536,732**	**-1,339,050**	**-4,692**	**-39,836**	**-128,688**	**-2,048,998**	**786,516**	**6,634,820**	**7,417,922**
NET – t C									
Douglas-fir	-146,109	-29,573	0	-5,289	-7,675	**-188,646**	136,529	1,265,036	**1,401,565**
Fir-Spruce	-10,553	-73,192	0	-11,752	-17,527	**-113,025**	38,227	955,076	**993,303**
Other Conifer	-190,128	-473,825	-4,630	-20,031	-81,042	**-769,656**	565,461	3,976,765	**4,542,216**
Hardwood	-39,789	-23,653	-58	-2,658	-17,136	**-83,294**	42,895	437,943	**480,838**
Redwood	0	0	0	0	0	**0**	0	0	**0**
Shrubs / grasses	-998	-1,323	-4	-106	-429	**-2,861**	3,405	-	**3,405**
SUM NET	**-387,577**	**-601,566**	**-4,692**	**-39,836**	**-123,810**	**-1,157,481**	**786,516**	**6,634,820**	**7,417,922**
+/- uncertainty	*149,217*	*235,276*	*1,755*	*14,899*	*46,305*	***282,825***	*294,157*	*1,194,268*	***1,229,961***

6.3. North Sierra

The area that underwent a measured change in canopy cover between 1995-2000 (5 years) was approximately 90,200 ha, which is 2.5% of the total land area or 2.8% of the area of forests and rangelands. In the North Sierra region, fire and regrowth with moderate to large decreases in canopy are the most obvious causes of change, with scattered areas of harvest and other causes (Figure 13). Large patches of fire damage can be seen in Plumas, Yuba, Tuolumne and Butte counties.

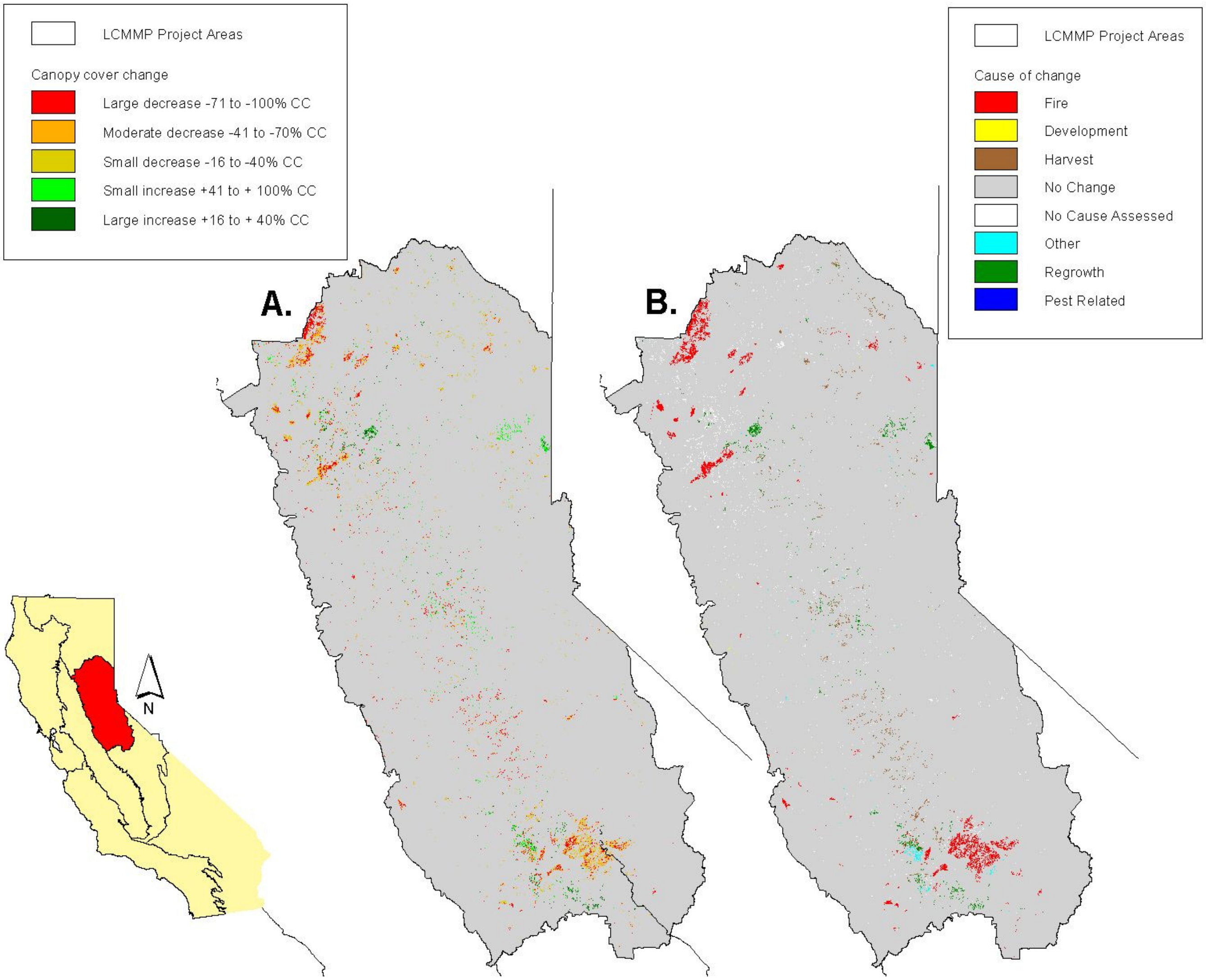


Figure 13. Illustration of Areas Experiencing a Change in Canopy by Magnitude of Change (A) and by Cause (B) in the North Sierra Region

6.3.1. Rangelands

The area of rangelands affected by canopy change between 1995-2000 (5 years) was 17.6 thousand hectares. The dominant causes were fire and regrowth each responsible for over 5 thousand hectares (Table 15). Ninety percent of the area affected was in the shrub/grass classes as opposed to woodland.

Table 15. Change in Area of North Sierra Rangelands based on Areas Affected by Canopy Cover Change. (- Equals a Decrease in Canopy Cover, + Equals an Increase)

	Fire	Harvest	Development	Regrowth	Pest-related	Other		Unverified		SUM
						-	+	-	+	
AREA (ha)										
Woodlands	883	0	47	12	0	10	0	684	93	**1,729**
Grasses / Shrubs	4,139	381	96	5,976	0	1,040	135	2,728	1,376	**15,871**
SUM AREA	**5,022**	**381**	**143**	**5,988**	**0**	**1,050**	**135**	**3,412**	**1,469**	**17,600**

Overall, the rangelands emit a net of about 153,300 t C, most of which is due to unverified causes (50%) and fire (44%) (Table 16). Total removals are estimated to be about 295,000 t C. Overall, the rangelands of this region are a net sink of carbon of about 142,000 t C (Table 16).

Table 16. Changes in the Carbon Stock of North Sierra Rangelands. (- Equals a Loss in Carbon Stocks [a Source] and + Equals a Gain in Stocks [a Sink])

EMISSIONS						**REMOVALS**		
	Fire	Harvest	Develop-ment	Other/ Unverified	SUM EMISSIONS	Measured Removals	Unmeasured Regrowth	**SUM REMOVALS**
GROSS – t C								
Woodlands	-28,706	0	-2,374	-31,363	**-62,443**	1,135	252,806	**253,941**
Grasses / Shrubs	-46,365	-5,595	-905	-45,960	**-98,825**	41,106	-	**41,106**
SUM GROSS	**-75,071**	**-5,595**	**-3,279**	**-77,323**	**-161,268**	**42,241**	**252,806**	**295,047**
NET – t C								
Woodlands	-20,701	0	-2,374	-31,363	**-54,437**	1,135	252,806	**253,941**
Grasses / Shrubs	-46,365	-5,595	-905	-45,960	**-98,825**	41,106	-	**41,106**
SUM NET	**-67,066**	**-5,595**	**-3,279**	**-77,323**	**-153,262**	**42,241**	**252,806**	**295,047**
+/- uncertainty	*25,820*	*2,093*	*1,226*	*28,919*	***38,844***	*15,798*	*45,055*	***49,988***

6.3.2. Forests

The total area of measured change in forests is about 72,600 hectares (Table 17). Fire is the dominant cause of change in canopy cover in the forests of the North Sierra region, accounting for 47% of the total measured change. This differs from the North Coast and the Cascade Northeast where harvest and regrowth dominated. This could be expected from the dry fire-prone conditions in the Sierras. The "other conifer" class is the dominant forest type reflecting the coverage by ponderosa pine and lodgepole pine.

Table 17. Change in Area of North Sierra Forests based on Areas Affected by Canopy Cover Change. (- Equals a Decrease in Canopy Cover, + Equals an Increase)

	Fire	Harvest	Development	Regrowth	Pest-related	Other		Unverified		SUM
						-	+	-	+	
AREA (ha)										
Douglas-fir	2,379	409	0	955	0	40	0	1,428	626	**5,837**
Fir-Spruce	4661	528	36	145	0	183	0	671	207	**6,431**
Other Conifer	16,006	10,401	37	5,004	0	659	166	7,981	2,925	**43,179**
Hardwood	10,928	502	64	798	0	93	0	3,346	1,331	**17,062**
Redwood	0	0	0	0	0	0	0	0	0	**0**
Shrubs/grasses	17	7	1	10	0	0	0	31	27	**93**
SUM AREA	**33,991**	**11,847**	**138**	**6,912**	**0**	**975**	**166**	**13,457**	**5,116**	**72,602**

In terms of carbon in the North Sierra region, the net emissions from all measured changes is 1.90 million t C, of which is 58% is caused by fire (Table 18). The North Sierras produce a greater source of CO_2 than either the North Coast (Table 10) or the Cascade Northeast (Table 14). Total removals by forests in the North Sierra region are 6.46 million t C. Overall, the region is a net remover (sink) of carbon of about 5.3 million t C (or 1.1 million t C/yr), with a range of 3.3 – 5.8 million t C.

Table 18. Changes in the Carbon Stock of North Sierra Forests. (- Equals a Loss in Carbon Stocks [a Source] and + Equals a Gain in Stocks [a Sink])

EMISSIONS						**REMOVALS**		
	Fire	Harvest	Development	Other/ Unverified	**SUM EMISSIONS**	Measured Removals	Unmeasured Regrowth	**SUM REMOVALS**
GROSS – t C								
Douglas-fir	-169,086	-31,997	0	-79,855	**-280,939**	29,053	1,015,486	**1,044,539**
Fir-Spruce	-288,736	-25,893	-2,249	-41,604	**-358,482**	7,086	940,676	**947,762**
Other Conifer	-706,206	-429,818	-1,117	-362,987	**-1,500,127**	166,703	3,387,965	**3,554,668**
Hardwood	-370,156	-21,032	-3,019	-122,319	**-516,526**	22,288	890,872	**913,160**

Redwood	0	0	0	0	**0**	0	0	**0**
Shrubs / grasses	-74	-27	-7	-177	**-285**	138	-	**138**
SUM GROSS	**-1,534,257**	**-508,768**	**-6,392**	**-606,942**	**-2,656,359**	**225,267**	**6,234,999**	**6,460,129**
NET – t C								
Douglas-fir	-121,514	-14,219	0	-35,845	**-171,578**	29,053	1,015,486	**1,044,539**
Fir-Spruce	-208,255	-11,506	-2,249	-41,604	**-263,614**	7,086	940,676	**947,762**
Other Conifer	-510,106	-191,000	-1,117	-362,987	**-1,065,209**	166,703	3,387,965	**3,554,668**
Hardwood	-266,521	-12,376	-3,019	-122,319	**-404,235**	22,288	890,872	**913,160**
Redwood	0	0	0	0	**0**	0	0	**0**
Shrubs / grasses	-74	-27	-7	-177	**-285**	138	-	**138**
SUM NET	**-1,106,470**	**-229,128**	**-6,392**	**-562,932**	**-1,904,923**	**225,267**	**6,234,999**	**6,460,129**
+/- uncertainty	*425,991*	*89,302*	*2,391*	*210,537*	***483,502***	*84,250*	*1,122,300*	***1,125,458***

6.4. South Sierra

The area that underwent a measured change in canopy cover between 1995-2001 (6 years) was approximately 28,335 ha, which is 0.7% of the total land area or 0.8% of the area of forests and rangelands. In the South Sierra region, fire with moderate to large decreases in canopy is the most obvious causes of change (Figure 14). A single large patch of fire damage can be seen in Tulare County.

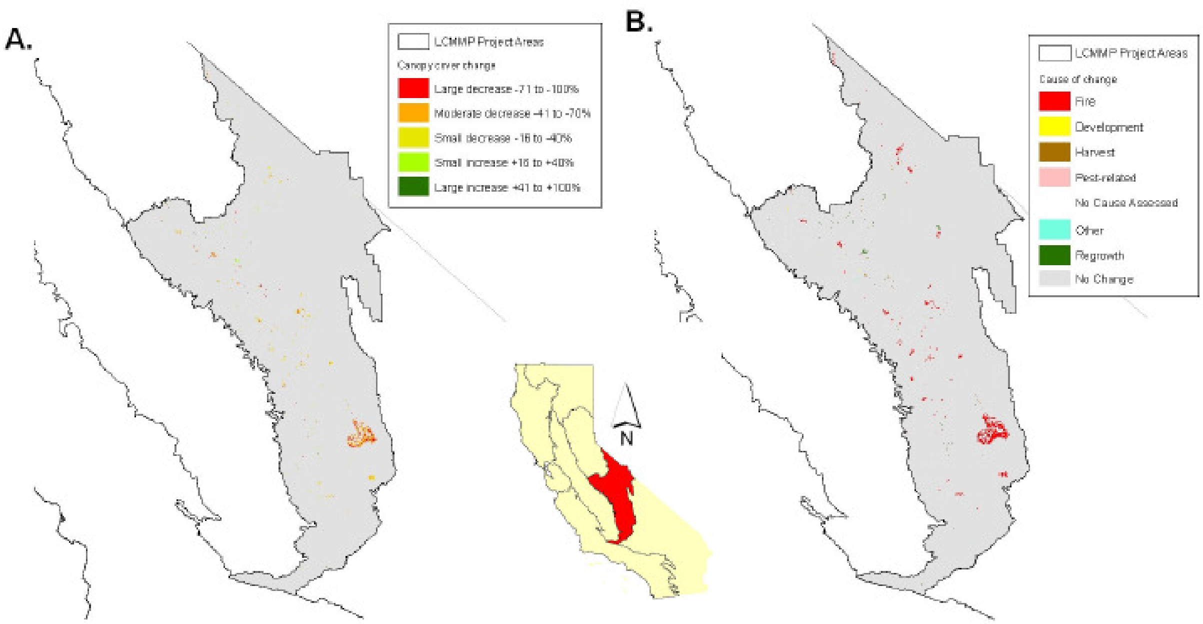


Figure 14. Illustration of Areas Experiencing a Change in Canopy by Magnitude of Change (A) and by Cause (B) in the South Sierra Region

6.4.1. Rangelands

The area of rangelands affected by canopy change between 1995-2001 was 13.1 thousand hectares. The dominant cause was fire which was responsible for 76% of the canopy change (Table 19). Eighty-five percent of the area affected was in the shrub/grass classes as opposed to woodland.

Table 19. Change in Area of South Sierra Rangelands based on Areas Affected by Canopy Cover Change. (- Equals a Decrease in Canopy Cover, + Equals an Increase)

	Fire	Harvest	Development	Regrowth	Pest-related	Other		Unverified		SUM
						-	+	-	+	
AREA (ha)										
Woodlands	1,521	35	43	48	0	27	0	264	74	**2,012**
Grasses /	8,370	103	27	1,048	24	171	8	631	703	**11,085**
SUM AREA	**9,891**	**138**	**70**	**1,096**	**24**	**198**	**8**	**895**	**777**	**13,097**

Overall, the rangelands emit a net of about 75,319 t C, most of which is due to fire (77%) (Table 20). Total removals are estimated to be about 629,995 t C. Overall, the rangelands of this region are a net sink of carbon of 566,261 t C (Table 20).

Table 20. Changes in the Carbon Stock of South Sierra Rangelands. (- Equals a Loss in Carbon Stocks [a Source] and + Equals a Gain in Stocks [a Sink])

EMISSIONS						REMOVALS		
	Fire	Harvest	Develop-ment	Other/ Unverified	SUM EMISSIONS	Measured Removals	Unmeasured Regrowth	SUM REMOVALS
GROSS – t C								
Woodlands	-31,477	-1,071	-752	-9,693	**-42,993**	970	629,995	**630,965**
Grasses /	-35,385	-1,064	-143	-4,836	**-41,428**	10,615	-	**10,615**
SUM GROSS	**-66,861**	**-2,135**	**-894**	**-14,529**	**-84,420**	**11,585**	**629,995**	**641,580**
NET – t C								
Woodlands	-22,816	-630	-752	-9,693	**-33,891**	970	629,995	**630,965**
Grasses /	-35,385	-1,064	-143	-4,836	**-41,428**	10,615	-	**10,615**
SUM NET	**-58,201**	**-1,695**	**-894**	**-14,529**	**-75,319**	**11,585**	**629,995**	**641,580**
+/- uncertainty	*22,407*	*640*	*335*	*5,434*	***23,068***	*4,333*	*113,399*	***113,443***

6.4.2. Forests

The total area of measured change in forests is 15,238 hectares (Table 21). As in the North Sierra region fire is the dominant cause of change in canopy cover in the forests of the South Sierra region, accounting for 76% of the total measured change. The higher percentage in the South Sierra region is caused by a lower area of harvest in this region. The “other conifer” class is again the dominant forest type reflecting the coverage by ponderosa pine and lodgepole pine.

Table 21. Change in Area of South Sierra Forests based on Areas Affected by Canopy Cover Change. (- Equals a Decrease in Canopy Cover, + Equals an Increase)

	Fire	Harvest	Development	Regrowth	Pest-related	Other		Unverified		SUM
						-	+	-	+	
AREA (ha)										
Douglas-fir	2	0	0	0	0	0	0	0	0	**2**
Fir-Spruce	182	128	0	100	4	0	0	25	20	**459**
Other Conifer	8,900	848	28	1,129	52	24	0	139	204	**11,324**
Hardwood	1,925	211	58	169	6	69	0	192	69	**2,699**
Redwood	0	0	0	0	0	0	0	0	0	**0**
Shrubs/grasses	527	14	0	73	4	63	0	54	19	**754**

SUM AREA	**11,536**	**1,201**		**86**	**1,471**	**66**	**156**	**0**	**410**	**312**	**15,238**

In terms of carbon in the South Sierra region, the net emissions from all measured changes is 323,408 t C, of which is 88% is caused by fire (Table 22). This total emission is just 17% of the total emission of the North Sierra region (Table 18). Total removals by forests in the South Sierra region are 1.50 million t C. Overall, the region is a net remover (sink) of carbon of about 1.18 million t C (0.20 million t C/yr), with a range of 0.89 – 1.47 million t C.

Table 22. Changes in the Carbon Stock of South Sierra Forests. (- Equals a Loss in Carbon Stocks [a Source] and + Equals a Gain in Stocks [a Sink])

EMISSIONS						**REMOVALS**		
	Fire	Harvest	Develop- ment	Other/ Unverified	**SUM EMISSIONS**	Measured Removals	Unmeasured Regrowth	**SUM REMOVALS**
GROSS – t C								
Douglas-fir	-38	0	0	0	**-38**	0	255	**255**
Fir-Spruce	-10,589	-8,501	0	-1,248	**-20,338**	1,896	296,283	**298,179**
Other Conifer	-326,692	-31,694	-919	-5,431	**-364,736**	24,157	881,063	**905,220**
Hardwood	-51,969	-6,697	-2,237	-7,105	**-68,007**	2,135	297,818	**299,952**
Redwood	0	0	0	0	**0**	0	0	**0**
Shrubs /	-2,487	-60	0	-692	**-3,239**	320	-	**320**
SUM GROSS	**-391,774**	**-46,951**	**-3,155**	**-14,476**	**-456,357**	**28,508**	**1,475,419**	**1,503,927**
NET – t C								
Douglas-fir	-27	0	0	0	**-27**	0	255	**255**
Fir-Spruce	-7,633	-3,778	0	-1,248	**-12,658**	1,896	296,283	**298,179**
Other Conifer	-236,287	-14,084	-919	-5,431	**-256,721**	24,157	881,063	**905,220**
Hardwood	-37,481	-3,940	-2,237	-7,105	**-50,763**	2,135	297,818	**299,952**
Redwood	0	0	0	0	**0**	0	0	**0**
Shrubs /	-2,487	-60	0	-692	**-3,239**	320	-	**320**
SUM NET	**-283,915**	**-21,862**	**-3,155**	**-14,476**	**-323,408**	**28,508**	**1,475,419**	**1,503,927**
+/- uncertainty	*109,307*	*8,539*	*1,180*	*5,414*	***109,780***	*10,662*	*265,575*	***265,789***

6.5. South Coast

The area that underwent a measured change in canopy cover between 1995/7-2002 (6 years) was approximately 88,536 ha, which is 1.3% of the total land area or 1.6% of the area of forests and rangelands. In the South Coast region, fire and regrowth with small to moderate decreases in canopy are the most obvious causes of change, with scattered areas of other causes and an area of large decrease due to fire in San Bernardino County (Figure 15).

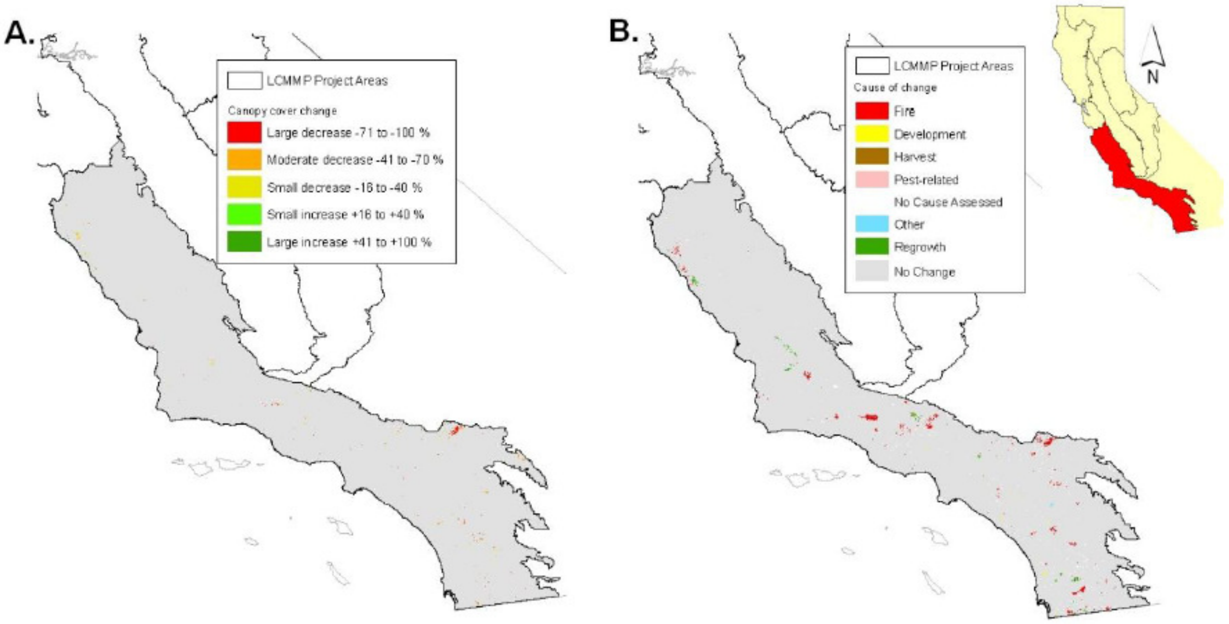


Figure 15. Illustration of Areas Experiencing a Change in Canopy by Magnitude of Change (A) and by Cause (B) in the South Coast Region

6.5.1. Rangelands

The area of rangelands affected by canopy change between 1997-2002 was 79.5 thousand hectares. The dominant cause was fire which was responsible for 47% of the canopy change and the unverified class which was responsible for 30% of the total area of canopy change (Table 23). Ninety-three percent of the area affected was in the shrub/grass classes as opposed to woodland.

Table 23. Change in Area of South Coast Rangelands based on Areas Affected by Canopy Cover Change. (- Equals a Decrease in Canopy Cover, + Equals an Increase)

	Fire	Harvest	Development	Regrowth	Pest-related	Other		Unverified		SUM
						-	+	-	+	
AREA (ha)										
Woodlands	2115	0	9	212	0	0	0	2,889	141	**5,366**
Grasses / Shrubs	35,208	0	3,551	13,449	11	1,168	13	18,541	2,201	**74,142**

SUM AREA	**37,323**	**0**	**3,560**	**13,661**	**11**	**1,168**	**13**	**21,430**	**2,342**	**79,508**

Overall, the rangelands emit a net of about 467,437 t C, most of which is due to fire (52%) and unverified causes (44%) (Table 1-24). Total removals are estimated to be about 1,127,317 t C. Overall, the rangelands of this region are a net sink of carbon of 750,856 t C (Table 24).

Table 24. Changes in the Carbon Stock of South Coast Rangelands. (- Equals a Loss in Carbon Stocks [a Source] and + Equals a Gain in Stocks [a Sink])

EMISSIONS	Fire	Harvest	Develop-ment	Other/ Unverified	SUM EMISSIONS	**REMOVALS** Measured Removals	Unmeasured Regrowth	**SUM REMOVALS**
GROSS – t C								
Woodlands	-40,004	0	-336	-80,759	**-121,099**	2,980	1,127,317	**1,130,297**
Grasses /	-215,629	0	-15,907	-125,845	**-357,381**	87,996	-	**87,996**
SUM GROSS	**-255,633**	**0**	**-16,243**	**-206,604**	**-478,481**	**90,975**	**1,127,317**	**1,218,293**
NET – t C								
Woodlands	-28,960	0	-336	-80,759	**-110,056**	2,980	1,127,317	**1,130,297**
Grasses /	-215,629	0	-15,907	-125,845	**-357,381**	87,996	-	**87,996**
SUM NET	**-244,589**	**0**	**-16,243**	**-206,604**	**-467,437**	**90,975**	**1,127,317**	**1,218,293**
+/- uncertainty	*94,167*	*0*	*6,075*	*77,270*	***121,963***	*34,025*	*202,917*	***214,684***

6.5.2. Forests

The total area of measured change in forests is just 9,038 hectares (Table 25). Fire is once again the dominant cause of change in canopy cover in the forests of the South Coast region, accounting for 69% of the total measured change. Harvest is entirely absent as a cause of canopy cover change in the region. In contrast to all the other regions, the "hardwood" class is again the dominant forest type.

Table 25. Change in Area of South Coast Forests based on Areas Affected by Canopy Cover Change. (- Equals a Decrease in Canopy Cover, + Equals an Increase)

	Fire	Harvest	Development	Regrowth	Pest-related	Other -	Other +	Unverified -	Unverified +	**SUM**
AREA (ha)										
Douglas-fir	4	0	0	0	0	0	0	0	0	**4**

Fir-Spruce	0	0	0	0	0	0	0	2	0	**2**
Other Conifer	1,718	0	0	15	55	2	0	210	4	**2,004**
Hardwood	3,747	0	5	236	49	0	0	1,422	323	**5,782**
Redwood	8	0	0	8	1	0	0	1	0	**18**
Shrubs/grasses	803	0	19	169	0	1	0	165	71	**1,228**
SUM AREA	**6,280**	**0**	**24**	**428**	**105**	**3**	**0**	**1,800**	**398**	**9,038**

In terms of carbon in the South Coast region, the net emissions from all measured changes is 165,270 t C, of which is 72% is caused by fire (Table 26). This total emission is overwhelmingly the lowest for the forests of the five California regions reflecting the fact that the region has just 4% of the forests in the state. Total removals by forests in the South Coast region are 0.89 million t C. Overall, the region is a net remover (sink) of carbon of about 0.73 million t C (0.12 million t C/year), with a range of 0.56 – 0.90 million t C.

Table 26. Changes in the Carbon Stock of South Coast Forests. (- Equals a Loss in Carbon Stocks [a Source] and + Equals a Gain in Stocks [a Sink])

EMISSIONS						**REMOVALS**		
	Fire	Harvest	Develop-ment	Other/ Unverified	**SUM EMISSIONS**	Measured Removals	Unmeasured Regrowth	**SUM REMOVALS**
GROSS – t C								
Douglas-fir	-102	0	0	0	**-102**	0	3,276	**3,276**
Fir-Spruce	0	0	0	-35	**-35**	0	1,133	**1,133**
Other Conifer	-60,566	0	0	-6,741	**-67,308**	212	127,354	**127,567**
Hardwood	-98,253	0	-214	-38,959	**-137,426**	5,212	647,723	**652,934**
Redwood	-127	0	0	0	**-127**	0	109,192	**109,192**
Shrubs /	-3,793	0	-74	-732	**-4,599**	834	-	**834**
SUM GROSS	**-162,841**	**0**	**-288**	**-46,466**	**-209,596**	**6,257**	888,678	894,935
NET – t C								
Douglas-fir	-74	0	0	0	**-74**	0	3,276	**3,276**
Fir-Spruce	0	0	0	-35	**-35**	0	1,133	**1,133**
Other Conifer	-43,661	0	0	-6,741	**-50,402**	212	127,354	**127,567**
Hardwood	-70,895	0	-214	-38,959	**-110,067**	5,212	647,723	**652,934**
Redwood	-93	0	0	0	**-93**	0	109,192	**109,192**
Shrubs /	-3,793	0	-74	-732	**-4,599**	834	-	**834**
SUM NET	**-118,516**	**0**	**-288**	**-46,466**	**-165,270**	**6,257**	888,678	894,935

+/- uncertainty	*45,629*	*0*	*108*	*17,378*	***48,826***	*2,340*	*159,962*	***159,979***

7.0 Non-CO_2 Gases for California Forests and Rangelands

Fire

Although 333,386 t C (1,222,415 t CO_2 eq) were emitted through fire in the North Coast forests during the inter census period the simultaneous release of N_2O is estimated as just 37 tons. However, N_2O has 296 times the global warming potential of CO_2 so the 37 tons of N_2O translates to almost 11,000 tons of CO_2 equivalents. Yet nitrous oxide even when converted to CO_2 equivalents never exceeds 1% of the release of CO_2 (Table 27).

Methane emissions through the actions of fire are more significant. Methane release approximates 10% of the CO_2 release in an average fire or 8% for a fire that burns rapidly (flaming). This is equal to more than 100 thousand tons of CO_2 equivalents for the inter census period for the cascades northeast (simultaneous CO_2 releases = 1,421,115 tons) (Table 27).

Table 27. Estimated Forest and Rangelands Non-CO_2 Gases (Methane and Nitrous Oxide) Resulting from Fire. a) Results for Average Fires, b) Results for Flaming Fires which may be more Typical of Fires in California.

a) Average Fire

Region	**Vegetation**	**Carbon emitted t C**	**Methane**			**Nitrous Oxide**		
			t emitted	**t CO_2 eq**	**% of C released**	**t emitted**	**t CO_2 eq**	**% of C released**
North	rangelands	34,700	555	12,769	10	4	1,130	0.9
Coast	forests	333,386	5,334	122,686	10	37	10,855	0.9
Northeast	rangelands	57,014	912	20,981	10	6	1,856	0.9
Cascades	forests	387,577	6,201	142,628	10	43	12,620	0.9
North	rangelands	67,066	1,073	24,680	10	7	2,184	0.9
Sierra	forests	1,106,470	17,704	407,181	10	122	36,027	0.9
South	rangelands	58,201	931	21,418	10	6	1,895	0.9
Sierra	forests	283,915	4,543	104,481	10	31	9,244	0.9
South	rangelands	244,589	3,913	90,009	10	27	7,964	0.9
Coast	forests	118,516	1,896	43,614	10	13	3,859	0.9

b) Flaming Fire

Region	**Vegetation**	**Carbon emitted t C**	**Methane**			**Nitrous Oxide**		
			t emitted	**t CO_2 eq**	**% of C released**	**t emitted**	**t CO_2 eq**	**% of C released**
North	rangelands	34,700	416	9,577	8	3	807	0.6
Coast	forests	333,386	4,001	92,015	8	26	7,754	0.6

Northeast	rangelands	57,014	684	15,736	8	4	1,326	0.6
Cascades	forests	387,577	4,651	106,971	8	30	9,014	0.6
North	rangelands	67,066	805	18,510	8	5	1,560	0.6
Sierra	forests	1,106,470	13,278	305,386	8	87	25,733	0.6
South	rangelands	58,201	698	16,063	8	5	1,354	0.6
Sierra	forests	283,915	3,407	78,361	8	22	6,603	0.6
South	rangelands	244,589	2,935	67,507	8	19	5,688	0.6
Coast	forests	118,516	1,422	32,710	8	9	2,756	0.6

Harvest

The reduction in methane sequestration caused by the disturbance of harvesting is very low relative to the net losses of CO_2. Here we estimate the increase in atmospheric CH_4 CO_2 equivalents as less than one tenth of a percent of the actual increase in carbon dioxide (Table 28).

Table 28. Estimated Forest and Rangelands Methane Emissions Resulting from Harvest

Region	Vegetation	Carbon emitted	Methane		
		t C	t emitted	t CO_2 eq	% of C released
North	rangelands	10,154	1	33	0.09
Coast	forests	865,922	75	1,733	0.05
Northeast	rangelands	24,038	4	99	0.11
Cascades	forests	601,566	77	1,770	0.08
North	rangelands	5,595	1	16	0.08
Sierra	forests	229,128	22	512	0.06
South	rangelands	1,695	0	6	0.10
Sierra	forests	21,862	2	52	0.06
South	rangelands	0	0	0	0.00
Coast	forests	0	0	0	0.00

8.0 Forests and Rangelands of California as Sources and Sinks of Greenhouse Gases

Across the 423,970 km^2 of California, there are an estimated 95,694 km^2 of forest and 126,751 km^2 of rangelands. Of this area 4,622 km^2 of forests and rangelands had a change in canopy cover between the measurement periods (equal to 2.0% of the total area). Of this area of change 83% had a verified cause. Sixty-six percent of the changes were on forestland and 33% on rangeland.

On forestland, 31% of the area with a canopy change was caused by commercial harvest, 27% by forest regrowth and 27% by fire. Development was only responsible for 0.2% of the verified change, but it could be higher when and if the cause of the unverified changes was confirmed. The distribution of causes, however, varied by region. In the North Coast 42% of the change area was caused by commercial harvest, in the Cascade Northeast 44% of the change area was undergoing forest regrowth, and fire was the cause of 47% of the change area in the North Sierras, 69% in the South Coast and 76% in the South Sierra region.

On rangeland, fire was the dominant cause of change in canopy cover accounting for 40%. Next in significance was measured regrowth with 27%. However, 60% of the total rangeland area affected by fire was in the South Coast region alone.

In terms of carbon, 5.03 million t C were emitted from forestland in California (Table 29). On forestland, fires emitted as much as 2.2 million t C, however, 50% of this total came from the North Sierra alone. During the same period, approximately 36.9 million t C were removed.

On rangelands, 0.88 million t C were emitted between the regional time intervals across California, included in this total are 0.46 million t C emitted through fire (Table 29). During the same period it is estimated that 3.5 million t C were removed through rangeland regrowth and natural tree growth.

Table 29. Summary of the Carbon Emitted and Removed in Forests and Rangelands of Five Regions of California between a 4-6-year Interval during 1994-2002 (Actual Periods Vary by Region)

Forests	**Net t C**					
	North Coast	**Cascades Northeast**	**North Sierra**	**South Sierra**	**South Coast**	**TOTAL**
EMISSIONS						
Fire	-333,386	-387,577	-1,106,470	-283,915	-118,516	**-2,229,864**
Harvest	-865,922	-601,566	-229,128	-21,862	0	**-1,718,479**
Development	-2,201	-4,692	-6,392	-3,155	-288	**-16,728**
Other/Unverified	-282,686	-163,646	-562,932	-14,476	-46,466	**-1,070,206**
EMISSIONS TOTAL	**-1,484,195**	**-1,157,481**	**-1,904,923**	**-323,408**	**-165,270**	**-5,035,277**
Estimated error	*376,220*	*282,825*	*483,502*	*109,780*	*48,826*	***685,377***
REMOVALS TOTAL	**20,671,550**	**7,417,922**	**6,460,129**	**1,503,927**	**894,935**	**36,948,463**
Estimated error +/-	*3,658,265*	*1,229,961*	*1,125,458*	*265,789*	*159,979*	***4,032,195***

Rangelands	**Net t C**					
	North Coast	**Cascades Northeast**	**North Sierra**	**South Sierra**	**South Coast**	**TOTAL**
EMISSIONS						
Fire	-34,700	-57,014	-67,066	-58,201	-244,589	**-461,570**
Harvest	-10,154	-24,038	-5,595	-1,695	0	**-41,483**
Development	-1,259	-72	-3,279	-894	-16,243	**-21,747**
Other/Unverified	-30,023	-26,850	-77,323	-14,529	-206,604	**-355,329**
EMISSIONS TOTAL	**-76,137**	**-107,974**	**-153,262**	**-75,319**	**-467,437**	**-880,129**
Estimated error	*17,872*	*25,565*	*38,844*	*23,068*	*121,963*	***133,750***
REMOVALS TOTAL	**731,014**	**615,092**	**295,047**	**641,580**	**1,218,293**	**3,501,026**
Estimated error +/-	*118,685*	*100,524*	*49,988*	*113,443*	*214,684*	***292,657***

Uncertainty in the estimated carbon totals is high. Confidence can be had in the pattern of change but the precise carbon values attained should be viewed as plus or minus 38% due to the limitations mentioned above (principally in the imagery).

8.1. Summary at the County Level

In general the areas with the largest emissions are not necessarily those with the largest removals, either due to a disconnection between the factors leading to the high values of each (e.g., fire principally in the Sierras and South Coast and fast forest growth rates principally in the North Coast), or due to a lag in the regrowth response (Figures 16, 17, 18, 19). The areas with low emissions and low removals do coincide with the more highly developed areas along the coast and in the Sierras.

The counties with the highest emissions are Siskiyou, Plumas and Tuolumne each affected by fire damage during the investigation period. Counties with high removals include Humboldt and Mendocino where the fast growing, high biomass Douglas fir and redwood forests are located (Figure 16 and 17).

When emissions and removals are summed the high sequestration rates in the northwestern counties dominate, but on a per unit area basis the low rates of removals leave the highest net emissions in the southern counties of San Diego, Riverside, Orange, San Bernardino and Ventura and the far western counties of Mono and Inyo (Figures 18 and 19).

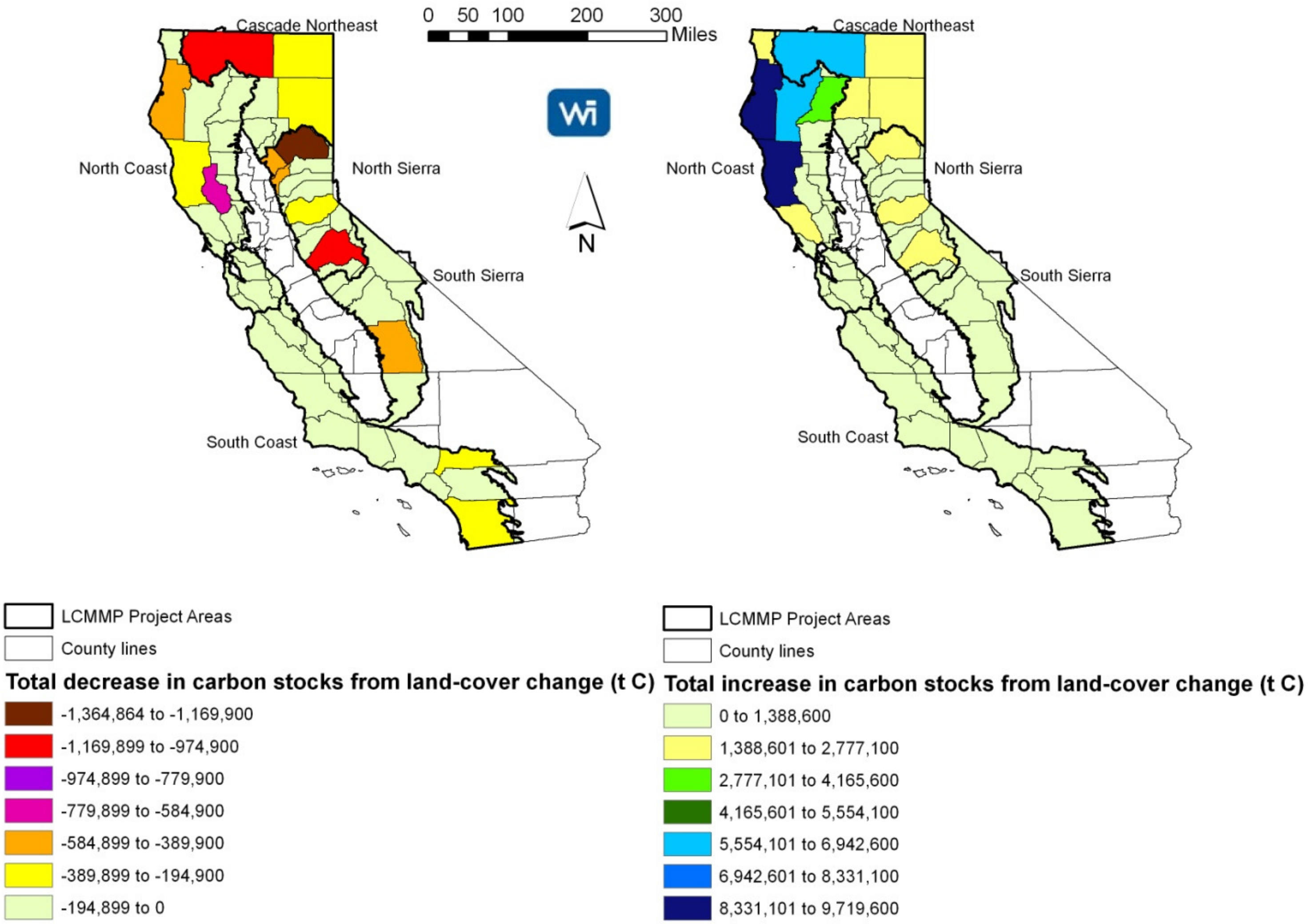


Figure 16. County Level Summary of the Decreases (left), and Increases (right) in Carbon Stocks in the North Coast (1994-1998), the Cascades Northeast (1994-1999), the North Sierra (1995-2000), the South Sierra (1995-2001) and the South Coast (1995/7-2002)

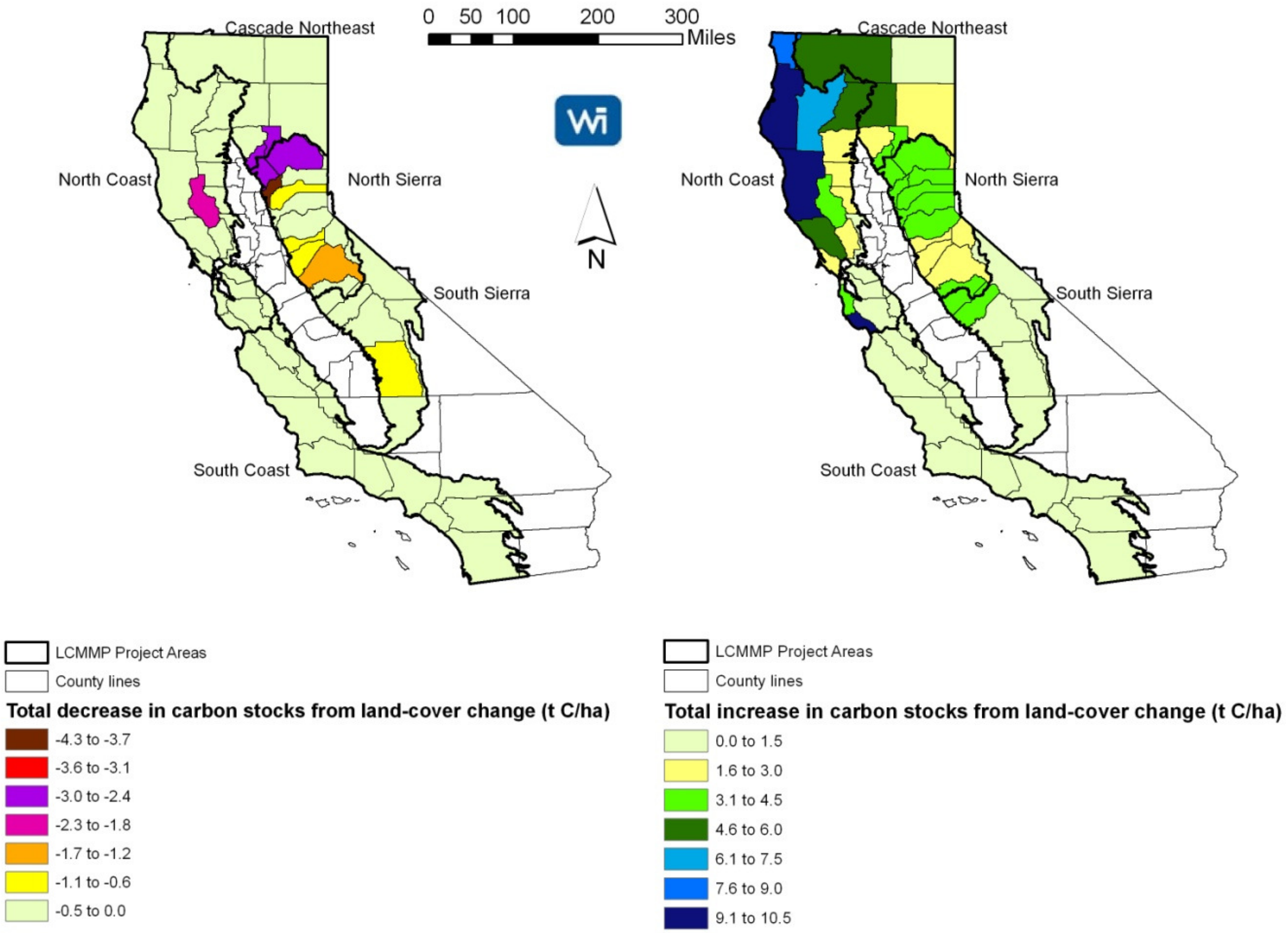


Figure 17. County Level Summary of the Decreases (left), and Increases (right) in Carbon Stocks Normalized by County Area in the North Coast (1994-1998), the Cascades Northeast (1994-1999), the North Sierra (1995-2000), the South Sierra (1995-2001) and the South Coast (1995/7-2002)

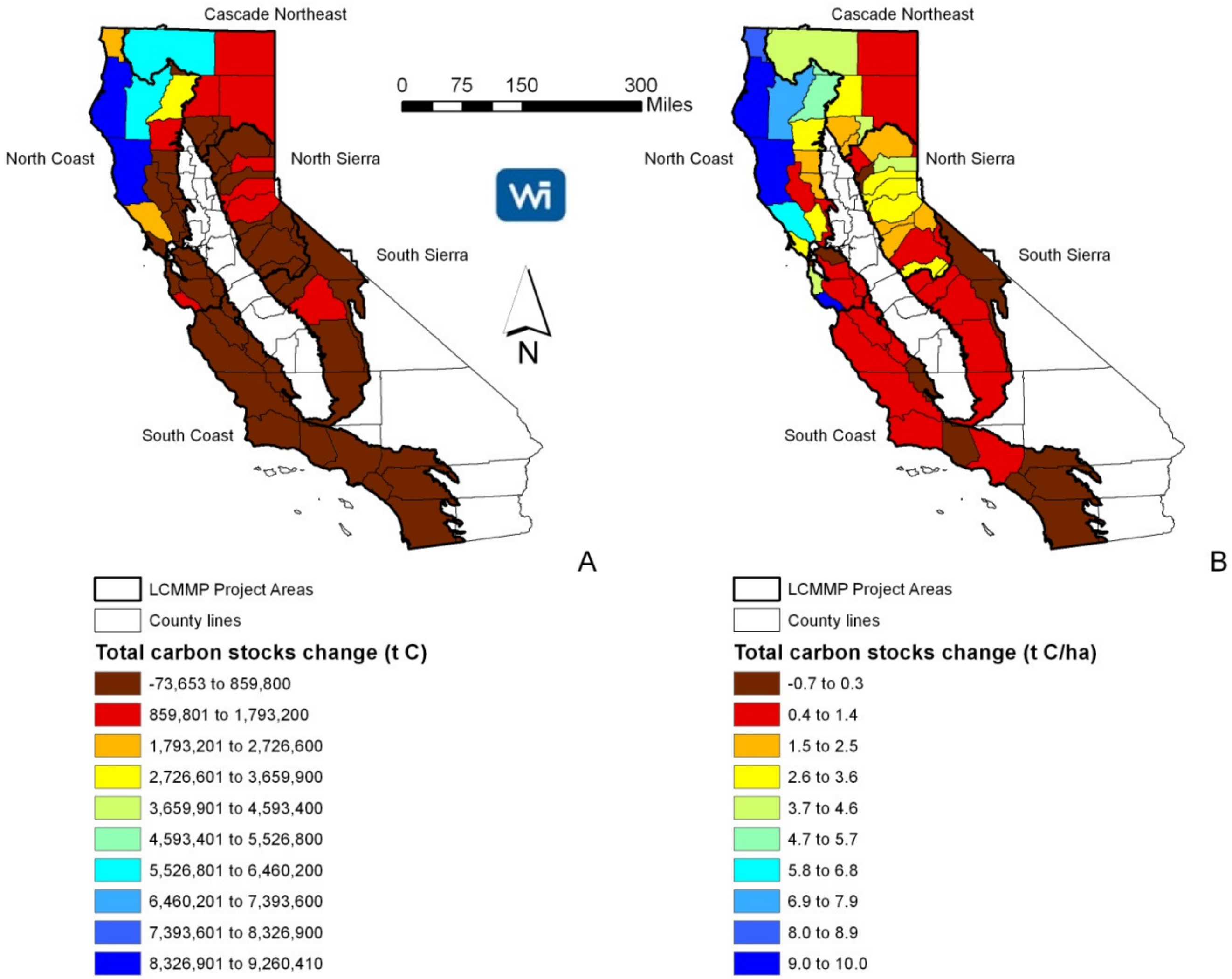


Figure 18. County Level Summary of the Summed Decreases and Increases in Carbon Stocks in the North Coast (1994-1998), the Cascades Northeast (1994-1999), the North Sierra (1995-2000), the South Sierra (1995-2001) and the South Coast (1995/7-2002) (A displays total change and B displays change normalized by County area)

8.2. Carbon Dioxide Equivalents

If the non-CO_2 gases are included and all values are converted to carbon dioxide equivalents, across California 19.36 million metric tons of carbon dioxide equivalents (MMTCO_2eq) were emitted between the census dates from forest land and 3.41 MMTCO_2eq from rangelands. This converts to an annual emission of 3.90 MMTCO_2eq from forests and 0.59 MMTCO_2eq from rangelands (Table 30).

During the same periods 135.48 MMTCO_2eq were estimated to have been removed by forestland and 12.84 MMTCO_2eq on rangeland. This is equal to an annual rate of removals of 27.10 MMTCO_2eq in forests and 2.57 MMTCO_2eq on rangelands (Table 30).

Table 30. Summary of the Emissions and Removals both over the Analysis Period and on a Per Year Basis

	Forests				**Rangelands**			
	C	*N_2O†*	*CH_4**	**TOTAL**	*C*	*N_2O†*	*CH_4**	**TOTAL**
MMTCO_2eq								
Emissions	18.46	0.07	0.82	**19.36**	3.23	0.02	0.17	**3.41**
Removals	135.48	-	-	**135.48**	12.84	-	-	**12.84**
MMTCO_2eq/year								
Emissions	3.90	0.01	0.16	**4.09**	0.59	0.003	0.03	**0.63**
Removals	27.10	-	-	**27.10**	2.57	-	-	**2.57**

*†N_2O only calculated for fire. *CH_4 only calculated for fire and harvest.*

8.3. Comparison with Other Studies for California

The California Energy Commission published a report in 2002 summarizing all estimated emissions and removals of CO_2 and CO_2 equivalents in California during the 1990s. For the forest sector, the data come directly from the publication of Birdsey and Lewis (2001). In turn Birdsey and Lewis (2001) based their reporting on the U.S. Forest Service's FIA data. It is significant that the last re-measurement of the FIA plots for California for this report was completed in 1994. The data reported by Birdsey and Lewis are modeled net emissions or removals through 1997 from the 1994 inventory. The Energy Commission report then makes a further extrapolation to include values through 1999. The reported data for the forest sector represent net changes with no separate consideration of emissions and removals and no consideration of non-CO_2 gases nor non-woody rangeland vegetation.

In contrast, the values reported in our analyses are based on measured changes in canopy cover for emissions and removals, and estimates of undetectable changes. It must be acknowledged that the flux from undetectable changes greatly exceeded that from measured changes.

The Energy Commission (2002) reports a net removal from Californian forestland of 17.3 MMTCO_2eq/yr for each of the years examined in the study. In contrast, here the annual removal is reported as 27.10 MMTCO_2eq/yr and if emissions are included, the net removals are 23.01 MMTCO_2eq/yr for forestland. No measure of uncertainty is included in the Energy Commission report in contrast to our analyses.

The estimates from the Energy Commission report are different from those that we report on here. Reasons for the differences may include errors implicit in the modeling and extrapolation approach employed by Birdsey and Lewis (2001)/CEC (2002). The results reported by the Energy Commission (2002) are also at a scale whereby individual emissions are overlooked. Instead species-group growth rates are applied across extents including areas that rather than accumulating biomass actually had a net emission due, for example, to fire.

Errors are also likely in the methods employed here, especially given the predominance of the growth estimated without a change in canopy cover. However, the detail in the calculation of emissions and precision on area of background growth gives additional credence to the approach employed here.

The results presented here also differ from the results reported in Brown et al. (2004) – the earlier version of this baseline assessment. This difference goes beyond just the inclusion of two additional Californian regions – South Sierra and South Coast. Analysis differences arise from the standardization in estimating the time interval for each region (4-6 years) and a new more detailed region-specific calculation of carbon accumulation rates for forests with no detectable change in canopy cover.

We conclude that, despite the relatively high uncertainty associated with our analyses, because of the finer detail and inclusion of areas with measured changes in canopy, and thus carbon stocks, our estimate should be considered to be representative of the real changes occurring on forest and range lands during the period of 1994/5-2002.

9.0 Conclusions

- Data on change in vegetation coverage from the California Land Cover Mapping and Monitoring Program (LCMMP) was combined with carbon estimates derived principally from Forest Inventory and Analysis (FIA) data. The baseline includes all changes in carbon stocks, including detectable and undetectable changes in canopy coverage in the remote sensing products. .
- A change in canopy cover was measured on 4,622 km^2 of forests and rangelands across California. This is approximately 1.8% of the total area of forests and rangeland in the regions. For 83% of the changed area, the cause of change was verified.
- For forests, a net removal of 27.1 MMTCO$_2$eq/yr and a net emission of 4.1 MMTCO$_2$eq/yr were estimated (Table 1-30). The greatest emissions were found in the North Sierra region with its dry conditions and resultant fires. The greatest removal was found in the forests of the North Coast with its dominance by fast-growing redwoods and Douglas-fir.
- Rangelands were a net sink of carbon with a net removal of 2.57 MMTCO$_2$eq/yr exceeding a net emission of 0.63 MMTCO$_2$eq/yr (Table 1-30).
- Fire and harvest were the dominant causes of emissions on forestlands; these causes were responsible for 1.83 MMTCO$_2$eq/yr and 1.42 MMTCO$_2$eq/yr respectively. On rangeland, harvest was less important, accounting for only 5% of the total emissions as opposed to 54% for fire on rangelands. Development appears to be a minor cause of carbon emissions through land-use change in both forest- and range-land in California.

However, much of the unverified change could include development that tends to occur in smaller patches and goes undetected in the remote sensing imagery.

- The counties with the largest decrease in carbon stocks (largest emissions) were located in areas affected by fire especially in North Sierra and parts of Cascade Northeast. The largest increases in carbon stocks (detectable and undetectable canopy change) are in the high volume fast-growing conifer forests of the North Coast and Cascades Northeast. Despite a high fire incidence the lower carbon stocks of the forests in the southern regions leads to emissions levels that are not greatly elevated.
- The calculated removals of 27.10 MMTCO$_2$eq/yr and emissions of 4.09 MMTCO$_2$eq/yr with a net removal of 23.0 MMTCO2eq/yr, for the forest sector differs from the reported removal of 17.3 MMTCO$_2$eq/yr in the California Energy Commission's report (CEC, 2002). We conclude that despite the relatively high uncertainty, the finer detail, and inclusion of areas with measured changes in canopy, and thus carbon stocks, our estimate should be considered to be representative of the real changes occurring on forest and range lands during the period of 1994/1995–2002.

10.0 References

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FINAL FUELS MANAGEMENT REPORT ON WESTCARB MANAGEMENT PILOT ACTIVITIES IN SHASTA COUNTY, CALIFORNIA

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Winrock International

DOE Contract No.: DE-FC26-05NT42593

Contract Period: October 1, 2005 - May 11, 2011

Arnold Schwarzenegger
Governor

FINAL REPORT ON WESTCARB FUELS MANAGEMENT PILOT ACTIVITIES IN SHASTA COUNTY, CALIFORNIA

PIER PROJECT REPORT

Prepared For:

California Energy Commission
Public Interest Energy Research Program

Prepared By:

Winrock International

July 2010
CEC-XXX-XXX-XXX

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Commission Contract No. 500-02-004
Commission Work Authorization No. MR-045

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Acknowledgements

Nick Martin was instrumental in initiating this research. The Western Shasta RCD assisted in finding project sites and collecting data, in particular, Leslie Bryan and Gretchen Garwood. Bob Rynearson of Beaty and Associates offered critical assistance in locating project sites, and provided important background information on the HH and Davis Biomass sites. Dan McCall of PG&E provided key background information on the Berry Timber project, and assistance in allowing Winrock to install research plots ion the property

Legal Notice

Please cite this report as follows:

Goslee, K., T. Pearson, S. Grimland, S. Petrova, and S. Brown. 2010. *Final Report on WESTCARB Fuels Management Pilot Activities in Shasta County, California.* California Energy Commission, PIER. CEC-500-XXXX-XXX.

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission) conducts public interest research, development, and demonstration (RD&D) projects to benefit the electricity and natural gas ratepayers in California. The Energy Commission awards up to $62 million annually in electricity-related RD&D, and up to $12 million annually for natural gas RD&D.

The PIER program strives to conduct the most promising public interest energy research by partnering with RD&D organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally Preferred Advanced Generation
- Energy-Related Environmental Research

This *Final Report on WESTCARB Fuels Management Pilot Activities in Shasta County, California* is a report for the West Coast Regional Carbon Sequestration Partnership – Phase II (contract number MR-06-03L, work authorization number MR-045), conducted by Winrock International. The information from this project contributes to PIER's Energy-Related Environmental Research program.

For more information on the PIER Program, please visit the Energy Commission's Web site at www.energy.ca.gov/pier or contact the Energy Commission at (916) 654-5164.

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Abstract

This report summarizes efforts by Winrock International, WM Beaty and Associates, and other Shasta County, California partners to implement hazardous fuel reduction/biomass energy pilot activities in WESTCARB Phase II (2006-10). Wildfire is a significant source of GHG emissions in California and throughout the WESTCARB region. WESTCARB developed methodologies to evaluate, validate and demonstrate the potential of reducing hazardous biomass for biomass energy to contribute to GHG mitigation and adaptation. The report describes hazardous fuel reduction pilot activities on private lands in Shasta County; pre- and post-treatment measurements to quantify forest carbon impacted by treatment and/or fire; and analysis of data from these pilots to determine the net GHG impact of the fuel reduction treatments.

Keywords: *Carbon, sequestration, hazardous fuel reduction, forest, Shasta County*

Executive Summary

Introduction

The West Coast Regional Carbon Sequestration Partnership (WESTCARB), led by the California Energy Commission, is one of seven US Department of Energy regional partnerships working to evaluate, validate and demonstrate ways to sequester carbon dioxide and reduce emissions of greenhouse gases linked to global warming.

Earlier analyses by Winrock showed wildland fire to be a substantial source of greenhouse gas (GHG) emissions throughout the region. Actions to reduce hazardous fuel loads, so as to reduce the probability, areal extent, or severity of wildfires, could result in lower net GHG emissions when compared to a baseline scenario without such treatments. Fuel reduction may also contribute to carbon sequestration by enhancing forest health or growth rates in post-treatment stands. Finally, for treatments where fuel removal to a biomass energy facility is feasible, additional GHG benefits may be created by substituting the biomass for fossil fuel rather than leaving the biomass in the forest to decompose.

Hazardous fuel reduction/biomass energy pilot activities were implemented in the two WESTCARB terrestrial pilot locations, Shasta County, California and Lake County, Oregon. These projects provide real-world data on carbon impacts of treatments, costs, and project-specific inputs to a related WESTCARB task, in which Winrock International and the WESTCARB Fire Panel are working to investigate whether the development of a rigorous methodology to estimate GHG benefits of activities to reduce emissions from wildland fires is feasible.

Purpose

This report provides results from the WESTCARB Phase II hazardous fuel reduction pilot activities in Shasta County, California.

Project Objectives

The overall goal of WESTCARB Phase II is to demonstrate the region's key carbon sequestration opportunities through pilot projects, methodology development, reporting, and market validation. WESTCARB research will inform policymakers, communities, and businesses on how to invest in carbon capture and storage technology development and deployment to achieve climate change mitigation objectives.

The specific objectives of the Phase II Shasta County fuel reduction pilots are to investigate the feasibility of fuels-treatment-based terrestrial sequestration by conducting pilot projects in a representative West Coast forest; compile information on site conditions, fuel treatment prescriptions, and costs; and inform and field-test the WESTCARB fire GHG emissions methodology.

Methodology for measuring impacts of hazardous fuels treatments

Pre- and post-treatment measurements were made on three fuels treatment projects in Shasta County, California: Berry Timber, Davis, and HH Biomass. The fuel reduction activities were located in the southeast corner of the county; all three projects were located on privately owned land. These projects involved removal of non-commercial biomass and sawtimber with the overall objective of reducing fuel loading and risk of catastrophic wildfire. Treatments also included chipping and removal of biomass fuel to a biomass energy plant. The actual fuels treatments were not initiated under WESTCARB support, but they provided an opportunity to conduct on-the-ground measurements of actual hazardous fuel reduction efforts.

Data were collected in a total of 35 plots (15 on Davis, 9 on HH, and 11 on Berry Timber). Pre- and post-treatment measurements on these plots addressed live trees greater than 5 cm diameter at breast height, canopy density, standing and lying dead wood, understory vegetation, forest floor litter and duff. These represent the forest carbon pools that are likely to be affected by fire, treatment, or both, and so are critical to the accounting of hazardous fuel reduction treatment impacts and potential wildfire impacts on forest carbon.

These measurements were used to determine the carbon stocks before and after treatment and before and after a potential wildfire, for each project area. Growth modeling was conducted with the Forest Vegetation Simulator for both with and without treatment stands. Emissions from a potential fire were modeled in both with- and without-fuels treatment scenarios using both the Fuel Characteristic Classification System and the Forest Vegetation Simulator fire and Fuels Extension (FVS-FFE). FVS was also used to project growth on burned stands, incorporating the impacts of fire on the future stand.

The substitution of harvested biomass for existing energy sources was taken into account where fuels were extracted to a biomass energy plant. Board feet of timber harvested was converted to metric tons of carbon, with retirement rates applied.

Project Outcomes

Berry Timber

Treated stands without wildfire have total stocks of 51.2 tons of carbon per acre, with 44.2 t C/ac in the same stands following a wildfire, including carbon stored in long term wood products and energy offsets.

Incorporating the risk of fire of 0.64% to calculate net emissions or removals, the fuels treatment on the Berry Timber project resulted in an effective immediate net carbon emission of 69.2 t CO_2-e/ac (18.9 tons of carbon per acre).

In the absence of a wildfire, the fuels treatments and commercial harvest result in short term emissions of 83.2 t CO_2/ac and emissions of 116.2 t CO_2/ac over 60 years (Table A1).

Table A1. Net short and long term emissions from fuels treatment without fire on Berry Timber in tons of carbon dioxide per acre (+ = removals; - = emission)

	Short term 10 years	Long term 60 years
Biomass energy	-4.5	-4.5
Commercial timber	3.7	2.6
Treatment emissions	-86.9	-118.8
NET	-83.2	-116.2

For the treatment to yield benefits to the atmosphere, the emissions from treatments will need to be offset by reductions in emissions from a potential wildfire hitting the area. In order for the treatment to have an impact, such a fire would have to occur before fuels have returned to hazardous conditions, at which point it will be necessary to re-treat the forest. According to the FVS-modeled results, if a wildfire were to occur in the year of treatment, after 10 years the net emissions from treatment would be 31.5 t CO_2/ac.

<u>Davis</u>

Including carbon stored in long term wood products and energy offsets, treated stands without wildfire have total stocks of 47.9 tons of carbon per acre compared to stocks of 38.7 t C/ac in treated stands following a wildfire.

Incorporating the risk of fire of 0.64% to calculate net emissions or sequestration (section 2.2.6), the fuels treatment on the Davis project resulted in a net carbon emission in year one of 11.0 t CO_2-e/ac (3.0 t C/ac).

In the absence of a wildfire, the fuels treatments and commercial harvest result in short term emissions of 39.2 t CO_2/ac and emissions of 60.1 t CO_2/ac over 60 years (Table A2).

Table A2. Net short and long term emissions from fuels treatment without fire on Davis in tons of carbon dioxide per acre (+ = removals; - = emission)

	Short term 10 years	Long term 60 years
Biomass energy	-15.4	-15.4
Treatment emissions	-23.8	-44.7
NET	-39.2	-60.1

For the treatment to yield benefits to the atmosphere, the emissions from treatments will need to be offset by reductions in emissions from a potential wildfire hitting the area. In order for the treatment to have an impact, such a fire would have to occur before fuels have returned to hazardous conditions, at which point it will be necessary to re-treat the forest. According to the FVS-modeled results, if a wildfire were to occur in the year of treatment, after 10 years the net emissions from treatment would be 20.2 t CO_2/ac.

HH biomass

Including carbon stored in long term wood products and energy offsets, treated stands without wildfire have total stocks of 55 tons of carbon per acre compared to a stock of 45.3 t C/ac in treated stands following a wildfire.

Incorporating the risk of fire of 0.64% to calculate net emissions or sequestration (section 2.2.6), the fuels treatment on the HH Biomass project resulted in a net carbon emission in year one of 32.3 t CO_2-e/ac (8.8 t C/ac).

In the absence of a wildfire, the fuels treatments and commercial harvest result in short term emissions of 83.6 t CO_2/ac and emissions of 90.5 t CO_2/ac over 60 years (Table A3).

Table A3. Net short and long term emissions from fuels treatment without fire on HH biomass in tons of carbon dioxide per acre (+ = removals; - = emission)

	Short term 10 years	Long term 60 years
Biomass energy	-23.8	-23.8
Treatment emissions	-59.8	-66.7
NET	-83.6	-90.5

For the treatment to yield benefits to the atmosphere, the emissions from treatments will need to be offset by reductions in emissions from a potential wildfire hitting the area. In order for the treatment to have an impact, such a fire would have to occur before fuels have returned to hazardous conditions, at which point it will be necessary to re-treat the forest.

According to the FVS-modeled results, if a wildfire were to occur in the year of treatment, after 10 years the net emissions from treatment would be 41.4 t CO_2/ac.

Conclusions and Recommendations

In all three projects, the treatments resulted in overall carbon emissions. This result clearly has negative implications for the future potential of fuels treatments as a carbon projects offset category. Within the treated areas, all three projects had significant net emissions when considering treatment and the risk of a potential wildfire. Davis experienced the lowest emissions, but the treatment on Davis did not decrease fire intensity. If a fire were to occur in the year of treatment, all projects would still experience net emissions, though the impact of treatment emissions would be approximately halved in all cases.

All three of the pilots led to a projected decrease in crown fire potential, which decreases fire severity and size. While treatments lead to net carbon emissions in both the short and long term in all three projects, there are, of course, additional benefits to fuels treatments, such as increased ability to successfully fight fires and decreased cost of fire fighting; reduced loss of life and property; and reduced potential damage to wildlife habitat.

The results from this study in combination with the paired study in Lake County and the allied study in Mendocino National Forest underlie the unsuitability of fuels treatment as a potential greenhouse gas offset generating activity. Instead we argue the shift should be made to policies minimizing greenhouse gas emissions from wildfires and from fuel treatments while minimizing wildfire risks to lives, homes, wildlife habitat, and livelihoods in the WESTCARB region.

1.0 Introduction

1.1 Background and overview

The West Coast Regional Carbon Sequestration Partnership (WESTCARB), led by the California Energy Commission, is one of seven US Department of Energy regional partnerships working to evaluate, validate and demonstrate ways to sequester carbon dioxide and reduce emissions of greenhouse gases linked to global warming. Terrestrial (forestry and land use) sequestration options being investigated include afforestation, improved management of hazardous fuels to reduce GHG emissions from wildfires, biomass energy, and forest management. Shasta County, California and Lake County, Oregon were chosen for Phase II terrestrial sequestration pilot projects because of the diversity of land cover types present, opportunities to implement the most attractive terrestrial carbon activities identified in Phase I, and replication potential elsewhere in the WESTCARB region.

Earlier reports identified fire as a significant source of GHG emissions throughout the WESTCARB region. Estimated emissions from fires for the 1990-96 analysis period were: 1.03 $MMTCO_2e$ per year on average for Oregon (Pearson et al 2007a); 1.83 $MMTCO_2e$ per year for California (Pearson et al 2009); 0.18 $MMTCO_2e/yr$ for Washington (Pearson et al. 2007b); and 0.47 $MMTCO_2e/yr$ for Arizona (Pearson et al. 2007c).

The estimated baseline GHG emissions helped focus attention in Phase II on the questions: can actions by landowners to manage forest fuel loads be shown to produce measurable GHG reductions by decreasing the risk, severity, or extent of catastrophic wildfires? If so, can scientifically rigorous methods for measuring, monitoring, and verifying these GHG reductions serve as the basis for new protocols and market transactions, ultimately allowing landowners who reduce hazardous fuels to receive “carbon credit” revenues and improving the cost-effectiveness of fuel reduction? To explore these questions, hazardous fuel reduction (and where possible, removal of fuel for biomass energy generation) was chosen as a WESTCARB Phase II pilot activity in Shasta and Lake counties, and the WESTCARB Fire Panel was formed to develop fire GHG methodologies and protocols as needed.

1.2 Project Objectives

The overall goal of WESTCARB Phase II is to validate and demonstrate the region’s key carbon sequestration opportunities through pilot projects, methodology development, reporting, and market validation. WESTCARB research will inform policymakers, communities, and businesses on how to invest in carbon capture and storage technology development and deployment to achieve climate change mitigation objectives.

The specific objectives of the Phase II Shasta County fuel reduction pilots are to:

- Verify the feasibility of fuels-treatment-based terrestrial sequestration by conducting pilot projects in representative West Coast forests;
- Compile information on site conditions, fuel treatment prescriptions, and costs;
- Inform and field-test the WESTCARB fire GHG emissions methodology by:

- Collecting measurements of real-world fuel treatments to quantify:
    - the carbon stocks available to be burned before and after treatment,
    - the direct impacts of fuel treatments on carbon stocks in different carbon pools (e.g. increases in dead wood, decreases in dense growth), and
    - the fuel removed from the forest for potential biomass energy applications;
- Providing input data for fire models used to simulate fire behavior and emissions in the baseline (without-treatment) and with-treatment scenarios.

1.3 Report Organization

The report is organized into four sections: 1. Introduction; 2. project approach; 3. results; and 4. conclusions/ recommendations. Section 2 summarizes the private- and federal-lands fuel treatments chosen for study as WESTCARB pilot activities, and methods used for pre- and post-treatment measurements and data analysis. Section 3 provides results of those measurements and analyses. Section 4 discusses the findings and provides recommendations based on this research.

2.0 Project Approach

2.1 Fuel reduction project locations and descriptions

Pre- and post-treatment measurements were made on three fuels treatment projects in Shasta County, California. These projects all involved removal of non-commercial biomass and/or sawtimber with the overall objective of reducing fuel loading and risk of catastrophic wildfire. All also involved chipping and removal of biomass fuel to the Wheelabrator Shasta biomass energy plant in Anderson, California. The actual fuels treatments were not initiated under WESTCARB support, but they provided an opportunity to conduct on-the-ground measurements of actual hazardous fuel reduction efforts.

2.1.1 Fuel reduction on Berry Timber project (PG&E)

Location

The project area encompassed 845 acres and is shown in the map in Figure 1. It is located just southeast of the town of Shingletown in Shasta County, CA. The legal description is portions of Sections 25, 34, 35 & 36 Township 31 North, Range 1 East, M.D.B.&M. The forest type of the project area is Sierra Nevada Mixed Conifer, (Ponderosa Pine, Sugar Pine, White Fir, Douglas-fir and Incense Cedar.) Minor amounts of California Black Oak reside on the project area as well.

Treatment

The PG&E Berry timber harvest operation was conducted in the summer of 2007.

The area was treated under an individual tree selection silivicultural prescription focusing on the merchantable trees 10 inches diameter at breast height (dbh) and greater. Trees identified for harvest were trees showing signs of distress, mechanical defect, evidence of insects/disease and trees growing too close together. Biomass thinning of trees between 4 and 9 inches (dbh) was conducted on a small portion of the project area. Trees were extracted intact and tops and branches of commercial trees chipped and hauled to the Wheelabrator biomass energy facility along with the pre-commercial trees. A total of 3.461 million board feet of sawlogs were harvested from the project. A total of 173 loads of biomass were shipped to Wheelabrator Biomass Energy Plant in Anderson, comprised of 4,357 green tons of biomass with 39.3% moisture content (2,644 bone dry tons). The logging method was mechanical ground based, utilizing whole tree harvesting. All tree tops, limbs and biomass were chipped on the landing and sent to Wheelabrator Shasta Energy.

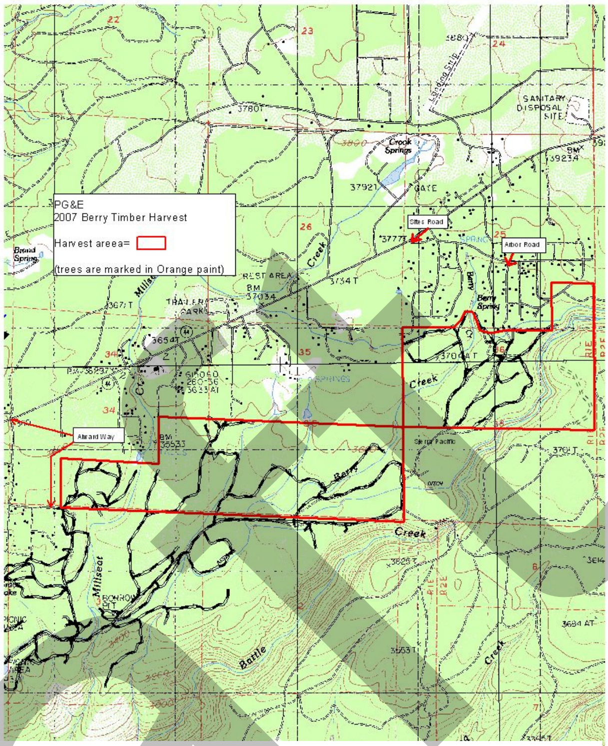

Figure 1. Map of harvest area for PG&E Berry Timber project

2.1.2 Fuel reduction on Davis Biomass project (W.M. Beaty & Associates, Inc. / Brooks Walker et al)

Location

The Davis Biomass project is located approximately three miles east of Whitmore, CA at approximately 3,000 foot elevation on the west slope of the Southern Cascades on forestlands managed by W.M. Beaty & Associates, Inc. The project area consists of 2,200 acres of uneven-age natural stands of mixed conifer and ponderosa pine along with a portion of a 30 year old ponderosa pine plantation that was established after the 1977 Whitmore Fire.

Figure 2: Loading thinned trees for delivery to biomass energy plant

Treatment

The objectives of the project were to thin small overcrowded trees in the understory of the conifer forest to improve the health and vigor of the remaining trees and reduce hazardous fuel ladders and fuel loading. Trees targeted for removal included suppressed trees between 4 and 12 inches (dbh) with poor live crown ratios. Vigorous trees of this size class with good live crown ratios were retained along with all live trees of larger size classes (12 inch dbh and greater). Although the logging contractor was not required to cut trees less than 3 inches dbh, some were thinned out to facilitate removal of the target trees.

The treatment was completed over three years (2007 – 2009) with the removal of 1,804 chip van loads totaling 24,998 bone dry tons (BDTs) that were delivered to Wheelabrator Shasta Energy Co., Inc. in Anderson for electricity generation. While this treatment might have been completed in one long operating season, the following factors contributed to extending the treatment over three operating seasons:

- the onset of early fire seasons,
- operators being called away to other jobs, and
- the inability to operate in this area during the winter.

As fire hazards increased with the onset of each summer, each year the humidity levels dropped below 20% by 9 or 10 o'clock in the morning and fire hazard restrictions forced operational shutdowns. However, the objectives of the project were accomplished by thinning the understory to promote residual stand health and vigor and reduce the risk of catastrophic loss by reducing fuel loads and ladder fuels which will aid fire suppression efforts should a wildfire occur.

2.1.3 Fuel reduction on HH Biomass project (W.M. Beaty & Associates, Inc. / Red River Forests Partnership and Bank of the West, Trustee)

Location

The HH Biomass project is located approximately two miles north of Shingletown, CA at approximately 3,500 foot elevation on mixed conifer forestlands managed by W.M. Beaty & Associates, Inc.

Figure 3. Stand in HH Biomass project after thinning

Treatment

Objectives of the 1,445-acre biomass thin project were to increase stand health and vigor, reallocate the species composition to mimic a more "natural" historic forest and to reduce the risk of loss from catastrophic wildfire by reducing ladder fuels and total fuel loading. Trees targeted for removal included suppressed trees between 4 and 12 inch dbh with poor live crown ratios. Except for a special "Shaded Fuel Break" prescription within 100 feet of the main roads, vigorous trees of this size class with good live crown ratios were retained along with all live trees of larger size classes (12 inch dbh to 36+ inches dbh). Within 100 feet of some main roads almost all understory trees were thinned out and the re-sprouting brush was then treated to create a "Shaded Fuel Break". Although the logging contractor was not required to cut trees less than 3 inches dbh, some were thinned out to facilitate removal of the target trees.

The treatment was completed over three years (2007 – 2009) with the removal of 1,917 chip van loads totaling 26,104 bone dry tons (BDTs) that were delivered to Wheelabrator Shasta Energy Co., Inc. in Anderson for electricity generation. The objectives of the project were accomplished by thinning the understory to promote residual stand health and vigor and to reduce the risk of catastrophic loss by decreasing fuel loads and ladder fuels which will aid fire suppression efforts should a wildfire occur.

2.2 Methods

2.2.1 Field measurements before and after fuel treatments

The location of field sampling plots was pre-assigned in a geographical information system (GIS) prior to fieldwork (Figures 4a, b, c). Data were collected in a total of 35 measurement plots[1] (15 on Davis, 9 on HH, and 11 on Berry Timber). Plot coordinates were generated randomly in advance of the field work. The field team navigated to the pre-assigned points. Plot measurements were taken in accordance with USFS General Technical Report NRS-18 (Pearson et al. 2007d), and included the following measurements at each plot location within fuel treatment units:

- All trees >5 cm diameter at breast height, measured in nested plots and marked for post-treatment measurements;
- Canopy density, tree heights, and height to live crown, as inputs to fire behavior models;
- Standing dead wood;
- Lying dead wood, measured along transects (plus dead wood density from collected samples).
- Understory vegetation, forest floor litter and duff, measured in clip plots;

These represent forest dimensions that will influence fire severity and the forest carbon pools that may be affected by fire, treatment, or both. The protocols used for these measurements are described in Annex A.

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[1] The number of plots was the result of available resources and field time rather than being statistically calculated.

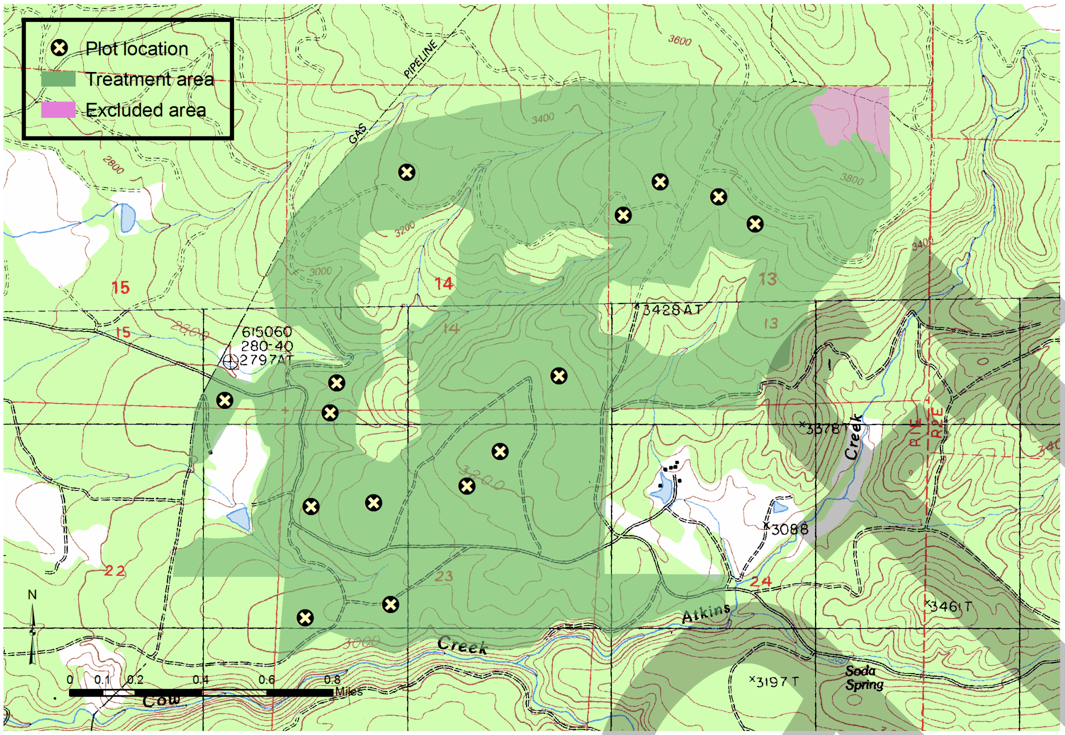

Figure 4a. Davis Mountain treatment area and plots

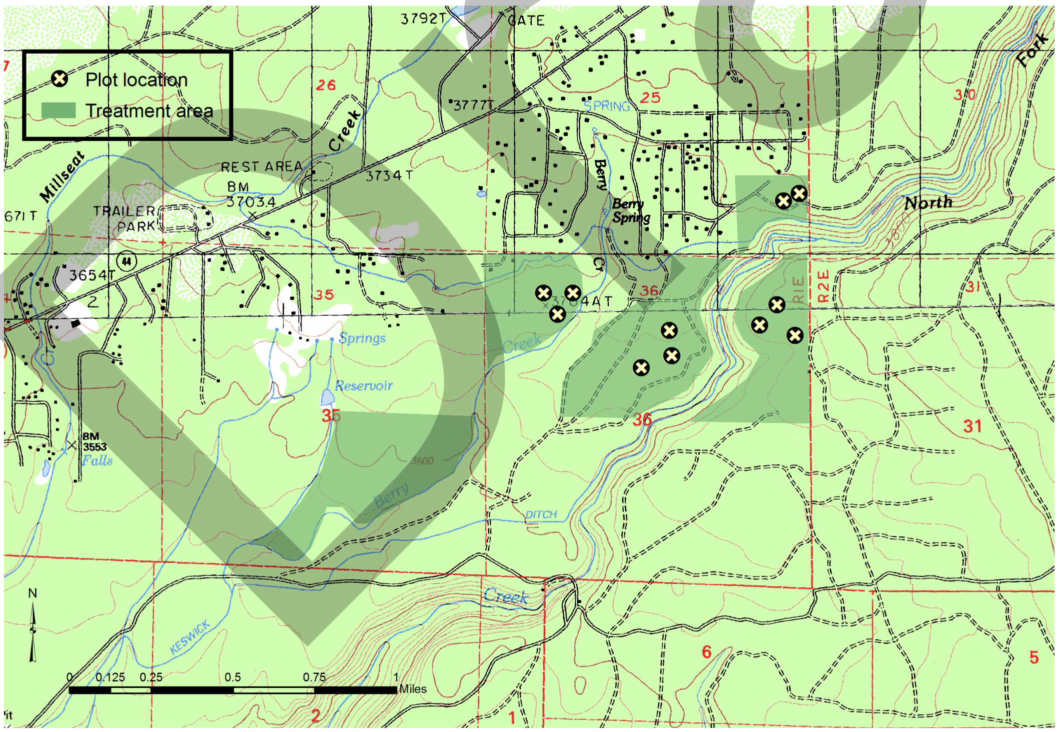

Figure 4b. Berry Treatment area and plots

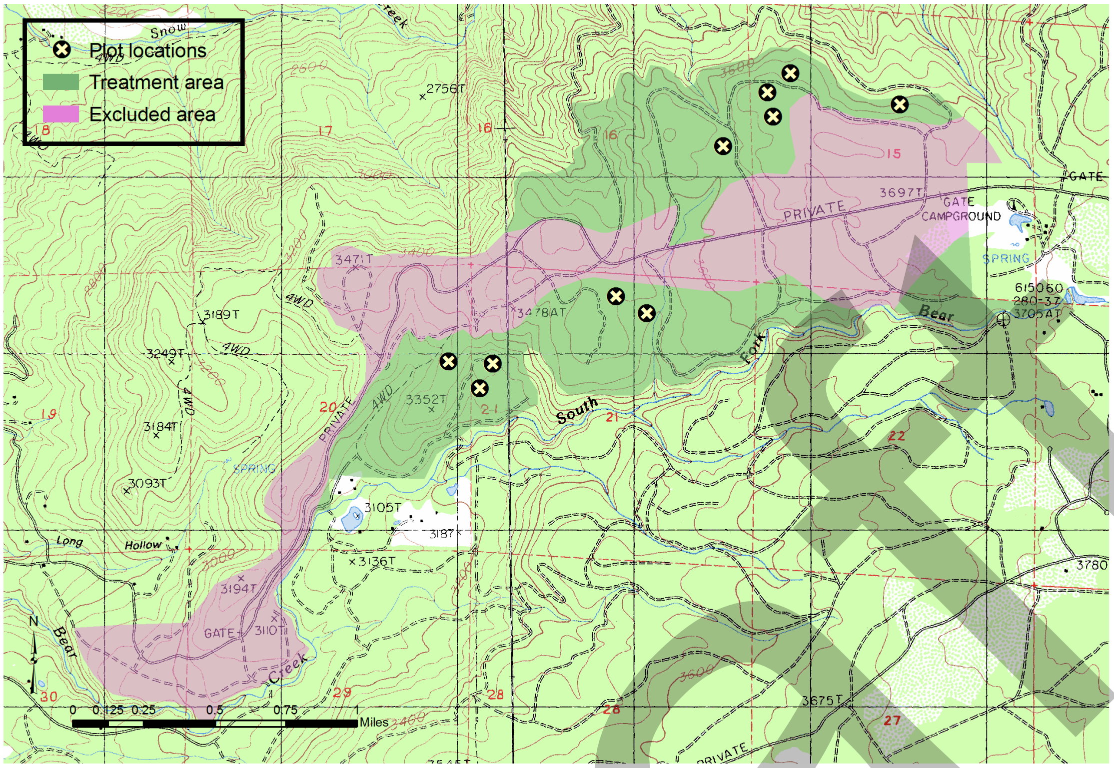

Figure 4c. HH treatment area and plots

The date of treatment at each site and the dates of pre- and post-treatment measurements by Winrock/Western Shasta RCD crews are shown in Table 1. In order to quantify the effects of treatment on the same carbon pools, the post-treatment measurements were conducted shortly after treatments were completed, on the same plots used for pre-treatment measurements, following a measurement protocol similar to pre-treatment fieldwork. The one difference in the post-treatment measurements was that tree diameters were not measured; instead, trees marked during pre-treatment measurements were counted and assumed to have the same diameter.

Table 1. Dates of fuel treatment and pre- and post-treatment measurements for the three Shasta County fuel treatment sites

Location	Date		
	Pre-Treatment Measurement	Treatment	Post-Treatment Measurement
Davis Mountain	June 2007	2007-2009	June 2009
HH Biomass	June 2007	2007-2009	June 2009
Berry Timber	June 2007	July – August 2007	September 2007

The purpose of the measurements was to identify, in real as opposed to modeled forests, the carbon stocks available to be burned before and after treatment, the direct impacts of fuel treatments on carbon stocks in different carbon pools (e.g. increases in dead wood, decreases in dense growth), and the fuel removed from the forest for biomass energy during treatment. Measurements also provided input data for fire models used to simulate fire behavior and emissions in the baseline (without-treatment) and with-treatment scenarios.

The total carbon stocks were determined using the standard allometric equations of Forest Vegetation Simulator Fire and Fuels Extension Inland California and Southern Cascades variant[2].

2.2.2 Fire Modeling

Based on the field data disaggregated by carbon pool, emissions from a potential fire were modeled in both with- and without-fuels treatment scenarios. The modeling was conducted using two separate approaches.

1. The FCCS program (**Fuel Characteristic Classification System**) was developed by the Pacific Northwest Research Station to capture the structural complexity and geographical diversity of fuel components across landscapes and to provide the ability to assess elements of human and natural change. FCCS is a software program that allows users to access a nationwide library of fuelbeds or create customized fuelbeds. The fuelbeds are organized into six strata: canopy (trees), shrubs, nonwoody vegetation, woody fuels (lying deadwood and stumps), litter-lichen-moss, and ground fuels (duff and basal accumulations). FCCS calculates the relative fire hazard of each fuelbed, including crown fire, surface fire behavior, and available fuel potentials. It also reports carbon storage by fuelbed category and predicts the amount of combustible carbon in each category.[3]

2. In addition to the FCCS modeling, fire effects were modeled using the **Forest Vegetation Simulator Fire and Fuels Extension** (FVS-FFE). FVS provides different output to FCCS and FVS can be used to project growth, incorporating the impacts of fire on the future stand.

The two models produced slightly different results, as they use different modeling methodologies and different biomass equations. They also produce somewhat different output. Reported outputs from FCCS include flame length in feet; crown fire potential as a scaled index from 0-9; rate of spread in feet per minute; and carbon consumed for live canopy, dead wood, and total. Reported results from FVS-FFE include flame length in feet; the crowning index in miles/hour; and total carbon consumed. Results for both prescribed fire and wildfire are reported from FCCS, while only wildfire is reported from the FVS-FFE results.

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[2] More information, including the FVS User's Guide and variant descriptions, are available at http://www.fs.fed.us/fmsc/fvs/index.shtml.

[3] More information is available at the FCCS website: http://www.fs.fed.us/pnw/fera/fccs/. The modeling was conducted by Dr. David "Sam" Sandberg – Emeritus of the PNW Research Station Fire and Environmental Application Team.

Although FVS uses a somewhat simpler methodology than FCCS for projecting fire impacts, it is based on established fire models and allows for growth projections. In order to address growth over time, FVS projections are used throughout the results, but FCCS output is presented to demonstrate the range of potential fire emissions.

2.2.3 Fire Risk

Annual burn probability is difficult to project accurately, as it is a factor of the likelihood of ignition and the conditions on the ground at the time of ignition, including fuels, climate, temperature, and topography (see Finney, 2005). Saah *et al.* (2010) determined the relative fire probability and observed annual burn probability for Shasta County, which were used to identify a potential annual burn probability of 0.64% (Eric Waller, 2010, UCB CFRO, pers. comm.). It is important to note that this is a generalized probability and is not based specifically on pre- and post-treatment conditions for these projects, but rather for Shasta County as a whole.

2.2.4 Growth Modeling

Stand growth, both with- and without-treatment and considering all pools, was modeled with the US Forest Service's Forest Vegetation Simulator (FVS), using the Inland California and Southern Cascades variant. The standard allometric equations in the Fire and Fuels Extension (FFE) of FVS were used to produce biomass and carbon reports in conjunction with forest growth. Data from both the 2007 and 2009 inventories were used, with the pre-treatment inventory year counted as year zero to compare with and without treatment scenarios. Growth was projected over a 60 year period, and did not include any additional future treatments. To incorporate the effects of wildfire on growth, FVS-FFE was also used to model wildfire behavior.

2.2.5 Modeled Scenarios

For both fire and growth modeling, four different scenarios were modeled for all three projects. Each scenario includes the following carbon pools: aboveground live, belowground live, standing dead, and lying dead. The treated scenarios also include carbon stored in merchantable timber after 100 years. To simplify calculations, the emissions arising from wood product conversion and subsequent retirement are included at the beginning of the project. The treatment scenarios also incorporate average emissions from equipment use.

	Untreated	Treated
No Wildfire	1.Untreated, no fire	3.Treated, no fire
Wildfire	2.Untreated, wildfire	4.Treated, wildfire

- *Scenario 1* gives the situation where there is no treatment or fire. At time zero it represents simply the carbon stocks (tons of carbon per acre) prior to treatment.
- *Scenario 2* is the carbon emissions and remaining stocks following a wildfire on untreated lands.
- *Scenario 3* is the carbon stocks remaining after the treatment, incorporating any emissions that were a result of treatment activities but in the absence of any fire.
- *Scenario 4* is the carbon emissions and remaining stocks following a wildfire on treated lands.

2.2.6 Biomass Accounting

We assumed that biomass harvested from project areas and burned to produce energy offsets energy that would otherwise be derived from fossil fuels. In California power generation is dominated by natural gas with small contributions from clean energy/nuclear and coal. In January 2007 the California Public Utilities Commission established a performance standard that all new long-term baseload generation must meet (http://docs.cpuc.ca.gov/Published/NEWS_RELEASE/63997.htm). As this performance standard is equivalent to the minimum standard required for any new power generation in California it is considered to be a conservative comparison for this analysis. The CPUC performance standard is equal to 1,100 pounds of carbon dioxide emitted for each Megawatt hour of electricity produced, an amount equivalent to 0.499 metric tons of carbon dioxide.

Literature[4] and our partners at Wheelabrator indicate that one bone dry ton of biomass produces one MWh of electricity. One bone dry ton is 0.5 bone dry ton of carbon or 1.833 tons of carbon dioxide. Each ton of biomass extracted for biomass energy therefore effectively emits:

$$1.833 - 0.499 = 1.334 \text{ t } CO_2$$[5]

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[4] cf. http://bioenergy.ornl.gov/papers/misc/energy_conv.html, http://groups.ucanr.org/WoodyBiomass/documents/InfoGuides12929.pdf

[5] The assumption of many (including the IPCC) is that biomass burned to produce electricity is carbon neutral. The argument is that all biomass that is burned was once grown, and so one MWh of electricity derived from biomass leads to a positive emissions avoidance of 0.499 t CO_2 (i.e., avoiding natural gas emissions). This would be true if the biomass were grown as part of the project in a plantation, where in the absence of the project the biomass being burned would never have been sequestered from the atmosphere. However, natural forests in California are not plantations. In the absence of the project, CO_2 *was* sequestered out of the atmosphere by the forest biomass. In the project case, this biomass is burned and released into the atmosphere. In the baseline the biomass remains sequestered in the forest. Thus what the atmosphere "sees" is a net increase in carbon dioxide because of the project. However, because of the project some amount of natural gas does not need to be burned to produce electricity. Specifically, as shown above, for each 1.833 t CO_2 released to produce 1 MWh of electricity through biomass from hazardous fuels, 0.499 t CO_2 are saved due to natural gas not having to be burned. Therefore, burning hazardous fuels rather than natural gas results in a net emission of 1.334 t CO_2.

This subject often leads to confusion. Many interpret the fact that biomass is replaceable in the way that fossil fuels are not to mean that all biomass burned has no net impact on the atmosphere. But as the paragraph above demonstrates, burning biomass does increase the greenhouse gases resident in the atmosphere. Burning biomass might prevent emissions from fossil fuels, but this is by no means permanent. What is being achieved is a delay in the date at which all fossil fuels will be used. It is critical to focus on the atmosphere, i.e. does the project cause an increase or decrease in the concentration of carbon dioxide in the atmosphere? In this case, burning biomass

Because of the biomass removal treatment some amount of natural gas does not need to be burned to produce electricity. Specifically, as shown above, for each 1.833 t CO_2 released to produce 1 MWh of electricity through biomass from hazardous fuels, 0.499 t CO_2 are saved due to natural gas not having to be burned. This is equivalent to 27.2% of the net emission being offset.

2.2.7 Timber Accounting

Of the three projects, only Berry Timber included removal of sawtimber. Board feet of timber harvested is converted to metric tons of carbon according to Smith *et al.* (2006), that provides a factor of 0.44 per thousand board feet to convert softwood lumber to metric tons of carbon. The fraction of carbon in primary wood products remaining over time in end uses and stored in land fill, as described in Smith *et al.* (2006), are then applied: after 10 years, 42.4% of carbon will remain in use as long-term wood products, and 11.6% will be sequestered in landfills; after 60 years, 17.3% of carbon will remain in long-term wood products, and 21.8% in landfills; after 100 years, 11.2% will remain in wood products and 24.3% in landfills.

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rather than natural gas leads to an increase in CO_2 in the atmosphere because natural gas burns more cleanly than biomass. If coal were displaced instead of natural gas the savings would be greater while if the displacement is of electricity generated by nuclear power, solar, wind or hydro power then the result is an emission with no net saving.

If the stand is not treated the fuels are available in the forest to be emitted to the atmosphere through wildfires. However, this should not be considered under the biomass energy calculations. If it is then we are double-counting. The baseline fire risk multiplied by the stock gives the baseline emission from wildfires, which is the emission from fuels in the absence of fuel treatment.

2.2.8 Net Impact Calculations

Net project benefits following a treatment must incorporate

- *carbon stocks in the forest;*
- *carbon emissions in a wildfire, accounting for the probability of fire;*
- *growth;*
- *carbon stored as long-term wood products;*
- *emissions offset through energy production.*

The net emissions or removals in year one are calculated as

$$[(Ct + Cw + Ce - Cb) * (1 - risk)] + [(Ctf + Cw + Ce - Cbf) * (risk)]$$

Where

Ct	carbon stocks remaining in the forest after treatment and without a wildfire
Cw	carbon stored as wood products
Ce	reduced emissions from using biomass for energy generation
Cb	carbon stocks in the forest before treatment and without a wildfire
risk	probability of fire
Ctf	carbon stocks remaining in the forest after treatment and with a wildfire
Cbf	carbon stocks remaining in the forest before treatment and with a wildfire

This equation states that the net emissions in year 1 are equal to:

The high probability that there will **be no fire** multiplied by the difference between stored carbon before and after treatment

Plus

The low probability that there will **be a fire** multiplied by the difference in total carbon storage after a fire in the treated stand and in the baseline stand.

3.0 Project Results

3.1 Berry Timber Results

3.1.1 Field results

Prior to treatment, the Berry Timber project had a stock of 70.1 tons of carbon per acre across all pools. Following the treatment, the average carbon stock was 49.4 t C/ac. Treatment therefore resulted in a decrease in carbon stocks of 20.7 tons per acre, 30% of pretreatment stocks. The breakdown by pool is shown in Table 2, and the confidence limits at a 90% confidence interval for the aboveground live carbon pool are shown in Table 2a.

Table 2. Berry Timber carbon stocks (metric t C/ac) before and after fuels treatments

Carbon pool	Pre-treatment	Post-treatment	Difference
Trees	39.7	27.1	*-12.6*
Roots	10.6	7.6	*-3.0*
TOTAL TREES	50.3	34.7	*-15.6*
Standing dead	0.5	0.3	*-0.2*
Down dead wood	12.0	9.3	*-2.7*
TOTAL DEAD WOOD	12.5	9.6	*-2.9*
Forest Floor	7.2	4.6	*-2.6*
Shrubs/herbaceous	0.2	0.4	*0.2*
TOTAL	70.1	49.4	*-20.7*

Table 2a. Upper and lower confidence limits at 90% CI for Berry Timber aboveground live carbon stocks (metric t C/ac) before and after fuels treatments

Aboveground live carbon	Pre-treatment	Post-treatment
LCL	32.3	20.4
mean	39.7	27.1
UCL	47.1	33.8
CI as a % of mean	18.6 %	24.7 %

3.1.2 Potential fire emissions

Using FCCS-created fuel beds, a wildfire in the untreated stands would yield 46.6 tons of CO_2 per acre of emissions, while a wildfire in the treated stands would yield 31.7 t CO_2 / ac (Table 3). Using the FVS Fire and Fuels Extension, a wildfire in the untreated stands would yield 42.5 t CO_2 / ac of emissions, while a wildfire in the treated stands would yield 26.4 t CO_2 / ac (Table 4).

Table 3. FCCS fire modeling results for Berry Timber

	Prescribed Fire		Wildfire	
	Pre-treatment	Post-treatment	Pre-treatment	Post-treatment
Flame Length (ft)	2.5	2.2	6.1	5.0
Crown Fire Potential (scaled index 0-9)	3.6	2.3	4.2	3.0
Rate of Spread (ft/min)	3.6	4.5	18.3	19.4
CO_2 emissions (t/ac)				
Canopy	-4.6	-1.8	-14.3	-6.2
Dead Wood	-22.4	-18.2	-28.2	-23.1
Litter	-2.9	-1.8	-3.5	-2.2
Total	-29.9	-21.8	-46.0	-31.5

Table 4. FVS fire modeling results for Berry Timber

	Wildfire	
	Pre-treatment	Post-treatment
Flame Length (ft)	6.5	5.7
Crowning index (miles/hr)[6]	31.4	49.8
CO_2 emissions (t/ac)	-42.5	-26.4
Total stand carbon remaining	58.1	42.4

3.1.3 Timber and biomass

The commercial harvest on Berry Timber yielded 4,096 board feet of timber per acre. According to the conversion factor in Smith *et al.* (2006), this equals 1.8 t C/ac. Based on carbon disposition rates, a total of 1.0 t/ac will remain stored in either long-term wood products or landfill after 10 years; 0.7 t/ac will remain stored in either long-term wood products or landfill after 60 years; and 0.6 t/ac will remain stored in either long-term wood products or landfill after 100 years.

Wheelabrator received 3.3 bone dry tons of biomass per acre from the Berry Timber project, which represents 1.7 t C/ac. Because this biomass was used to generate energy, it offset 1.7 t C/ac * 27.2% = 0.5 t C/ac, resulting in reduced total emissions of 4.5 t CO_2-e/ac (1.2 t C/ac).

3.1.4 Growth modeling

Based on FVS modeling (Table 5), in the absence of fire, the treatment resulted in an initial decrease in carbon stocks of 20.7 t C/ac (compare columns 1 and 2), and a reduced increase in carbon stocks of 11.7

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[6] The 20-foot windspeed required to cause an active crown fire.

t C/ac after 60 years, for a total decrease in live stocks of 32.4 t C/ac over a 60 year period relative to no treatment.

In the event of a wildfire in year zero, the treated stands contain 15.7 t C/ac less than the untreated stands (difference between columns 3 and 4), but carbon stocks in the treated stands increase more than those in untreated stands over 60 years (25.5 t C/ac), for a total increase of 9.8 t C/ac relative to the untreated stand.

Table 5. Modeled total stand carbon pre and post treatment and with and without fire on Berry Timber project. Modeling conducting using the Fuels and Fire Extension of FVS. Data in metric tons of carbon per acre

Year	Untreated, no fire (1)	Treated, no fire (2)	Untreated, wildfire (3)	Treated, wildfire (4)
0	70.1	49.4	58.1	42.4
10	76.6	52.9	55.2	45.6
20	86.0	58.3	53.6	49.6
30	94.8	64.3	53.0	54.1
40	103.1	70.6	54.1	59.0
50	110.6	77.3	56.3	64.0
60	116.9	84.5	59.6	69.4
Total change	*46.8*	*35.1*	*1.5*	*27*
Total % change	*167%*	*171%*	*103%*	*164%*

FVS growth modeling (Table 6) indicates that after 60 years in the absence of wildfire, treated stands continue to have fewer trees per acre, lower basal area, and fewer cubic feet and board feet than untreated stands, while the quadratic mean diameter[7] (QMD) is greater in the treated stands. However, the rate of change (Table 7) is greater in the treated stands for all measurements except QMD. This indicates that while the treated stands did not catch up to the untreated stands in absolute numbers, they had a lower mortality rate and a higher per tree growth rate overall. In addition, the trees remaining in the treated stands remained larger, on average, than those in the untreated stands.

In the event of a wildfire, treated stands have fewer trees per acre after 60 years, but increased basal area, QMD, cubic feet, and board feet, and they have a higher rate of change in all categories than do untreated stands.

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[7] The diameter corresponding to the mean basal area of a stand.

Table 6. Projected Growth on Berry Timber project, modeled in FVS

	Untreated			Treated		
	Year 0	Year 60 – no fire	Year 60 - wildfire	0	Year 60 – no fire	Year 60 – wildfire
Trees per acre	282	160	73	132	118	64
Basal area	173	251	113	121	213	172
QMD	10.6	17.0	16.8	13.0	18.2	22.3
Cubic feet	4,873	8,799	3,828	3,541	7,383	6,270
Board feet	22,683	47,077	20,509	16,450	38,703	34,334

Table 7. Percent change within each scenario after 60 years of growth on Berry Timber project

	Untreated		Treated	
	No fire	Wildfire	No fire	Wildfire
Trees per acre	57%	26%	89%	48%
Basal area	145%	65%	176%	142%
QMD	160%	158%	140%	172%
Cubic feet	181%	79%	209%	177%
Board feet	208%	90%	235%	209%

3.1.5 Net GHG emissions/sequestration

Including carbon stored in long term wood products and energy offsets, for treated stands without wildfire, the total stock is 51.2 tons of carbon per acre and 44.2 t C/ac in the same stands following a wildfire. Figure 5 shows the tons of carbon per acre sequestered on Berry Timber in each of the four scenarios, the total carbon stored following treatment when wood products and biomass energy are included, and the percent change from untreated to treated and unburned to burned lands.

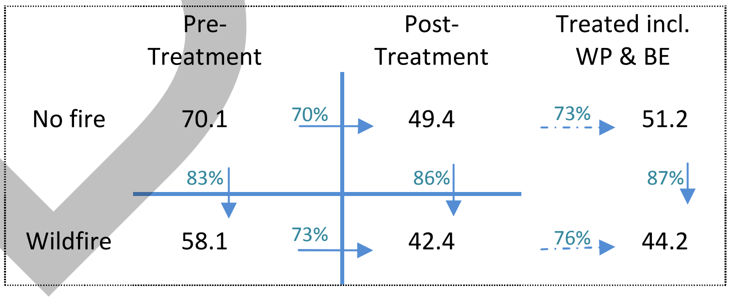

Figure 5. Tons of carbon per acre stored on Berry Timber project lands in each scenario, and included carbon stored in wood products and reduced emissions from biomass used to produce energy. Percentages show change from untreated lands to treated or from unburned to burned. BE = biomass energy. WP = storage in long term wood products and landfill after 5 years

Incorporating the risk of fire of 0.64% and utilizing the equation described above for net emissions or sequestration (section 2.2.6), [(Ct+Cw +Ce-Cb)*(1-risk)]+[(Ctf+Cw+Ce-Cbf)*(risk)], the fuels treatment on the Berry Timber project resulted in an effective immediate net carbon emission of 69.2 t CO_2-e/ac (18.9 tons of carbon per acre).

In the absence of a wildfire, the fuels treatments and commercial harvest result in short term emissions of 83.2 t CO_2/ac and emissions of 116.2 t CO_2/ac over 60 years (Table 8).

Table 8. Net short and long term emissions from fuels treatment, without fire, on Berry Timber in tons of carbon dioxide per acre (+ = removals; - = emission)

	Short term 10 years	Long term 60 years
Biomass energy	-4.5	-4.5
Commercial timber	3.7	2.6
Treatment emissions	-86.9	-118.8
NET	-83.2	-116.2

For the treatment to yield benefits to the atmosphere, the emissions from treatments will need to be offset by reductions in emissions from a potential wildfire hitting the area. In order for the treatment to have an impact, such a fire would have to occur before fuels have returned to hazardous conditions, at which point it will be necessary to re-treat the forest. According to the FVS-modeled results, if a wildfire were to occur in the year of treatment, after 10 years the net emissions from treatment would be 36.0 t CO_2/ac.

3.2 Davis Results

3.2.1 Field results

Prior to treatment, the Davis project had a stock of 50.9 tons of carbon per acre across all pools. Following the treatment, the average carbon stock was 46.4 t C/ac. Treatment therefore resulted in a decrease in carbon stocks of 4.5 tons per acre, 8% of pretreatment stocks. The breakdown by pool is shown in Table 9, and the confidence limits at a 90% confidence interval for the aboveground live carbon pool are shown in Table 9a.

Table 9. Davis carbon stocks (metric t C/ac) before and after fuels treatments

Carbon pool	Pre-treatment	Post-treatment	Difference
Trees	26.7	22.4	*-4.3*
Roots	7.8	6.3	*-1.5*
TOTAL TREES	34.5	28.7	*-5.8*
Standing dead	0.6	1.1	*0.5*
Down dead wood	9.0	11.1	*2.1*
TOTAL DEAD WOOD	9.6	12.2	*2.6*
Forest Floor	6.6	5.1	*-1.5*
Shrubs/herbaceous	0.2	0.4	*0.2*
TOTAL	50.9	46.4	*-4.5*

Table 9a. Upper and lower confidence limits at 90% CI for Davis above ground live carbon stocks (metric t C/ac) before and after fuels treatments

Aboveground live carbon	Pre-treatment	Post-treatment
LCL	22.0	18.1
mean	26.7	22.4
UCL	31.4	26.7
CI as a % of the mean	17.6 %	19.2 %

3.2.2 Potential fire emissions

Using FCCS-created fuel beds, a wildfire in the untreated stands would yield 35.2 tons of CO_2 per acre of emissions, while a wildfire in the treated stands would yield 39.2 tons of CO_2 per acre (Table 10). Using the FVS Fire and Fuels Extension, a wildfire in the untreated stands would yield 37.0 tons of CO_2 per acre of emissions, while a wildfire in the treated stands would yield 34.1 tons of CO_2 per acre (Table 11).

Table 10. FCCS fire modeling results for Davis

	Prescribed Fire		Wildfire	
	Pre-treatment	Post-treatment	Pre-treatment	Post-treatment
Flame Length (ft)	3.4	3.5	8.2	8.3
Crown Fire Potential (scaled index 0-9)	3.7	3.2	4.4	3.8
Rate of Spread (ft/min)	5.2	7.0	27.4	34.6
CO_2 emissions (t/ac)				
Canopy	-2.4	-2.4	-7.5	-7.5
Dead Wood	-18.9	-22.2	-23.7	-28.2
Litter	-2.8	-2.6	-3.5	-3.1
Total	-24.1	-27.2	-34.7	-38.8

Table 11. FVS fire modeling results for Davis

	Wildfire	
	Pre-treatment	Post-treatment
Flame Length (ft)	5.8	6.8
Crowning index (miles/hr)[8]	25.1	36.8
CO_2 emissions (t/ac)	-37.0	-34.1
Total stand carbon remaining	40.5	37.2

3.2.3 Biomass

Wheelabrator received 11.4 bone dry tons of biomass per acre from the Davis project, which represents 5.7 tons of carbon per acre. Because this biomass was used to generate energy, it offset 5.7 t C/ac * 27.2% = 1.5 t C/ac, resulting in reduced total emissions of 15.4 t CO_2-e/ac (4.2 t C/ac).

3.2.4 Growth modeling

Based on FVS modeling (Table 12), in the absence of fire, the treatment resulted in an initial decrease in carbon stocks of 4.5 t C/ac (compare columns 1 and 2), and a reduced increase in carbon stocks of 7.7 t C/ac after 60 years, for a total decrease in live stocks of 12.2 t C/ac over a 60 year period relative to an untreated stand. In the event of a wildfire in year zero, the treated stands sequester 3.3 t C/ac less than the untreated stands (difference between columns 3 and 4), but carbon stocks in the treated stands

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[8] The 20-foot windspeed required to cause an active crown fire.

increase more than those in untreated stands over 60 years (3.6 t C/ac), for a total increase of 0.3 t C/ac relative to an untreated stand.

Table12. Modeled total stand carbon pre and post treatment and with and without fire on Davis project. Modeling conducting using the Fuels and Fire Extension of FVS. Data in metric tons of carbon per acre

Year	Untreated, no fire (1)	Treated, no fire (2)	Untreated, wildfire (3)	Treated, wildfire (4)
0	50.9	46.4	40.5	37.2
10	59.1	52.6	39.6	38.3
20	70.2	61.4	40.6	41.0
30	80.9	70.2	42.6	43.8
40	91.1	79.4	46.0	47.2
50	100.5	88.2	50.4	51.2
60	108.7	96.5	55.6	55.9
Total change	*57.8*	*50.1*	*15.1*	*18.7*
Total % change	*214%*	*208%*	*137%*	*150%*

FVS growth modeling (Table 13) indicates that after 60 years in the absence of wildfire, treated stands continue to have fewer trees per acre, lower basal area, and fewer cubic feet than untreated stands, while QMD is greater in the treated stands and the board feet is slightly higher.

Table 13. Projected Growth on Davis, modeled in FVS

	Untreated			Treated		
	Year 0	Year 60 – no fire	Year 60 - wildfire	0	Year 60 – no fire	Year 60 – wildfire
Trees per acre	405	205	98	164	128	46
Basal area	140	251	126	106	233	124
QMD	8.0	15.0	15.4	10.9	18.3	22.1
Cubic feet	3,141	8,246	4,181	2,730	8,072	4,612
Board feet	12,780	43,022	22,163	12,154	43,657	26,592

However, the rate of change (Table 14) is greater in the treated stands for all measurements except QMD. This indicates that while the treated stands did not catch up to the untreated stands in absolute numbers, they had a lower mortality rate and a higher growth rate overall. In addition, the trees remaining in the treated stands remained larger, on average, than those in the untreated stands.

In the event of a wildfire, treated stands have fewer trees per acre after 60 years and slightly lower basal area, but increased cubic feet, and board feet, and they have a higher rate of change in all categories than do untreated stands.

Table 14. Percent change after 60 years of growth on Davis project

	Untreated		Treated	
	No fire	Wildfire	No fire	Wildfire
Trees per acre	51%	24%	78%	28%
Basal area	179%	90%	220%	117%
QMD	188%	193%	168%	203%
Cubic feet	263%	133%	296%	169%
Board feet	337%	173%	359%	219%

3.2.5 Net GHG emissions/sequestration

Including carbon stored in long term wood products and energy offsets, treated stands without wildfirehave an estimated total stock of 47.9 tons of carbon per acre compared to a stock of 38.7 t C/ac in treated stands following a wildfire. Figure 6 shows the tons of carbon per acre sequestered on Davis in each of the four scenarios, the total carbon stored following treatment when wood products and biomass energy are included, and the percent change from untreated to treated and unburned to burned lands.

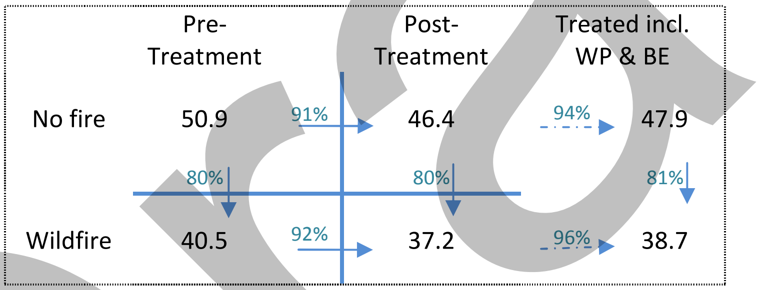

Figure 6. Tons of carbon per acre stored on Davis project lands in each scenario, and included carbon stored in wood products and reduced emissions from biomass used to produce energy. Percentages show change from untreated lands to treated or from unburned to burned.

Incorporating the risk of fire of 0.64% and utilizing the equation described above for net emissions or sequestration (section 2.2.6), [(Ct+Cw +Ce-Cb)*(1-risk)]+[(Ctf+Cw+Ce-Cbf)*(risk)], the fuels treatment on the Davis project resulted in a net carbon emission in year one of 11.0 t CO_2-e/ac (3.0 t C/ac).

In the absence of a wildfire, the fuels treatments and commercial harvest result in short term emissions of 39.2 t CO_2/ac and emissions of 60.1 t CO_2/ac over 60 years (Table 15).

Table 15. Net short and long term emissions from fuels treatment, without fire, on Davis in tons of carbon dioxide per acre (+ = removals; - = emission)

	Short term 10 years	Long term 60 years
Biomass energy	-15.4	-15.4
Treatment emissions	-23.8	-44.7
NET	-39.2	-60.1

For the treatment to yield benefits to the atmosphere, the emissions from treatments will need to be offset by reductions in emissions from a potential wildfire hitting the area. In order for the treatment to have an impact, such a fire would have to occur before fuels have returned to hazardous conditions, at which point it will be necessary to re-treat the forest. According to the FVS-modeled results, if a wildfire were to occur in the year of treatment, after 10 years the net emissions from treatment would be 20.2 t CO_2/ac.

3.3 HH Biomass Results

3.3.1 Field results

Prior to treatment, the HH Biomass project had 63.9 tons of carbon per acre across all pools. Following the treatment, the average carbon stock was 52.5 t C/ac. Treatment therefore resulted in a decrease in carbon stocks of 11.4 tons per acre, 18% of pretreatment stocks. The breakdown by pool is shown in Table 16, and the confidence limits at a 90% confidence interval for the aboveground live carbon pool are shown in Table 16a.

Table 16. HH Biomass carbon stocks (metric t C/ac) before and after fuels treatments

Carbon pool	Pre-treatment	Post-treatment	Difference
Trees	36.5	27.3	*-9.2*
Roots	10.7	7.7	*-3.0*
TOTAL TREES	47.2	35.0	*-12.2*
Standing dead	0.9	0.2	*-0.7*
Down dead wood	9.0	11.1	*2.1*
TOTAL DEAD WOOD	9.9	11.3	*1.4*
Forest Floor	6.5	5.9	*-0.6*
Shrubs/herbaceous	0.2	0.3	*0.1*
TOTAL	63.9	52.5	*-11.4*

Table 16a. Upper and lower confidence limits at 90% CI for HH Biomass carbon stocks (metric t C/ac) before and after fuels treatments

Aboveground live carbon	Pre-treatment	Post-treatment
LCL	30.1	22.1
mean	36.5	27.3
UCL	42.9	32.5
CI as a % of the mean	17.5%	19.0%

3.3.2 Potential fire emissions

Using FCCS-created fuel beds, a wildfire in the untreated stands would yield 39.2 t CO_2 /ac of emissions, while a wildfire in the treated stands would yield 38.3 t CO_2 /ac (Table 17). Using the FVS Fire and Fuels Extension, a wildfire in the untreated stands would yield 39.6 tons per acre of emissions, while a wildfire in the treated stands would yield 35.2 tons per acre (Table 18).

Table 17. FCCS fire modeling results for HH Biomass

	Prescribed Fire		Wildfire	
	Pre-treatment	Post-treatment	Pre-treatment	Post-treatment
Flame Length (ft)	3.2	2.4	7.7	5.3
Crown Fire Potential (scaled index 0-9)	4.1	3.2	4.7	3.7
Rate of Spread (ft/min)	6.3	5.0	32.3	21.2
CO_2 emissions (t/ac)				
Canopy	-3.7	-2.8	-11.0	-8.4
Dead Wood	-19.3	-20.7	-24.0	-26.6
Litter	-3.3	-2.9	-4.0	-3.5
Total	-26.3	-26.4	-39.0	-38.5

Table 18. FVS fire modeling results for HH Biomass

	Wildfire	
	Pre-treatment	Post-treatment
Flame Length (ft)	4.9	6.6
Crowning index (miles/hr)[9]	18.2	36.5
CO_2 emissions (t/ac)	-39.6	-35.2
Total stand carbon remaining	52.7	42.8

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[9] The 20-foot windspeed required to cause an active crown fire.

3.3.3 Biomass

Wheelabrator received 18.1 bone dry tons of biomass per acre from the HH Biomass project, which represents 9.0 tons of carbon per acre. Because this biomass was used to generate energy, it offset 9.0 t C/ac * 27.2% = 2.5 tC/ac, resulting in reduced total emissions of23.8 t CO_2-e/ac (6.5 t C/ac).

3.3.4 Growth modeling

Based on FVS modeling (Table 19), in the absence of fire, the treatment resulted in an initial decrease in carbon stocks of 11.4 t C/ac (compare columns 1 and 2), and a reduced increase in carbon stocks of 6.8 t C/ac after 60 years, for a total decrease in live stocks of 18.2 t C/ac over a 60 year period. In the event of a wildfire in year zero, the treated stands sequester 9.9 t C/ac less than the untreated stands (difference between columns 3 and 4), but carbon stocks in the treated stands increase more than those in untreated stands over 60 years (9.9 t C/ac), resulting in no net change in carbon sequestered after 60 years.

Table 20. Modeled total stand carbon pre and post treatment and with and without fire on HH Biomass project. Modeling conducted using the Fuels and Fire Extension of FVS. Data in metric tons of carbon per acre

Year	Untreated, no fire (10	Treated, no fire (2)	Untreated, wildfire (3)	Treated, wildfire (4)
0	63.9	52.5	52.7	42.8
10	75.4	59.1	49.7	44.9
20	88.9	68.5	49.5	48.9
30	100.0	77.7	51.7	52.8
40	108.2	86.1	55.7	57.5
50	114.6	94.1	61..5	62.7
60	119.9	101.7	68.3	68.3
Total change	*56.0*	*49.2*	*15.6*	*25.5*
Total % change	*188%*	*194%*	*130%*	*160%*

FVS growth modeling (Table 21) indicates that after 60 years in the absence of wildfire, treated stands continue to have fewer trees per acre, but the basal area is nearly the same, and they have greater cubic feet, board feet, and QMD than untreated stands.

Table 21. Projected Growth on HH Biomass, modeled in FVS

	Untreated			Treated		
	Year 0	Year 60 – no fire	Year 60 - wildfire	0	Year 60 – no fire	Year 60 – wildfire
Trees per acre	629	197	122	208	147	70
Basal area	197	251	156	132	247	166
QMD	7.6	15.3	15.3	10.8	17.6	20.8
Cubic feet	4,313	8,329	4,911	3,439	8,541	5,968
Board feet	16,521	42,748	24,613	14,849	45,528	33,357

The rate of change (Table 22) is greater in the treated stands for all measurements except QMD. This indicates that after 60 years, treated stands have a higher growth rate and have surpassed untreated stands in overall volume.

Table 22. Percent change after 60 years of growth on HH Biomass project

	Untreated		Treated	
	No fire	Wildfire	No fire	Wildfire
Trees per acre	31%	19%	71%	34%
Basal area	127%	79%	187%	126%
QMD	201%	201%	163%	193%
Cubic feet	193%	114%	248%	174%
Board feet	259%	149%	307%	225%

In the event of a wildfire, treated stands have fewer trees per acre after 60 years, but have higher basal area, and increased cubic feet and board feet, and they have a higher rate of change in all categories except QMD than do untreated stands.

3.3.5 Net GHG emissions/sequestration

Including carbon stored in long term wood products and energy offsets, treated stands without wildfire have a total of 55.0 tons of carbon per acre compared to a stock of 45.3 t C/ac in treated stands following a wildfire. Figure 7 shows the tons of carbon per acre sequestered on Davis in each of the four scenarios, the total carbon stored following treatment when wood products and biomass energy are included, and the percent change from untreated to treated and unburned to burned lands.

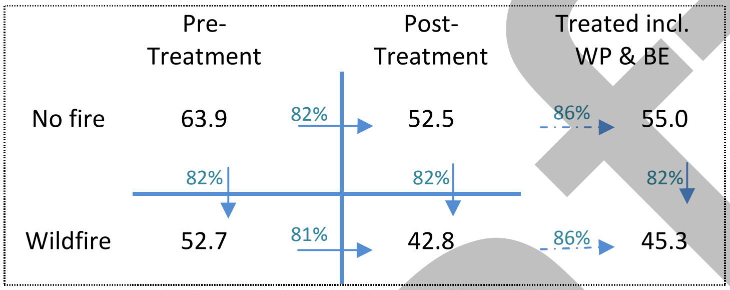

Figure 7. Tons of carbon per acre stored on HH Biomass project lands in each scenario, and included carbon stored in wood products and reduced emissions from biomass used to produce energy. Percentages show change from untreated lands to treated or from unburned to burned.

Incorporating the risk of fire of 0.64% and utilizing the equation described above for net emissions or sequestration (section 2.2.6), [(Ct+Cw +Ce-Cb)*(1-risk)]+[(Ctf+Cw+Ce-Cbf)*(risk)], the fuels treatment on the HH Biomass project resulted in a net carbon emission in year one of 32.3 t CO_2-e/ac (8.8 t C/ac).

In the absence of a wildfire, the fuels treatments and commercial harvest result in short term emissions of 83.6 t CO_2/ac and emissions of 90.5 t CO_2/ac over 60 years (Table 23).

Table 23. Net short and long term emissions from fuels treatment, without fire, on HH biomass in tons of carbon dioxide per acre (+ = removals; - = emission)

	Short term 10 years	Long term 60 years
Biomass energy	-23.8	-23.8
Treatment emissions	-59.8	-66.7
NET	-83.6	-90.5

For the treatment to yield benefits to the atmosphere, the emissions from treatments will need to be offset by reductions in emissions from a potential wildfire hitting the area. In order for the treatment to have an impact, such a fire would have to occur before fuels have returned to hazardous conditions, at which point it will be necessary to re-treat the forest. According to the FVS-modeled results, if a wildfire were to occur in the year of treatment, after 10 years the net emissions from treatment would be 41.4 t CO_2/ac.

4.0 Discussion

In all three projects, the treatments resulted in significant net carbon emissions[10]. This result clearly has implications for the future potential of fuels treatments as a carbon projects offset category.

The reasons for the net emission from hazardous fuel reductions are multiple. In the case of the Davis and HH projects, deadwood stocks increased following the treatment. This may be due to these projects' focus on removal of pre-commercial trees and a corresponding increase in the amount of limbs and branches left following the treatment. Because the Berry project included sawtimber removal, the live standing carbon removed was far greater than for the other sites. However, due to milling inefficiencies and the retirement of wood over time, only a fraction of the carbon removed as sawtimber is stored in wood products over the long term. The use of biomass for electricity generation also does not compensate for the loss of carbon stored as standing timber, especially given the common use of natural gas and the minimum performance standards required in California.

Both the Berry and the HH treatments led to a decrease fire intensity and in potential CO_2 emissions from fire. There was a greater decrease on the Berry project, likely due to sawtimber removal and the subsequent reduction in the forest crown. Despite the decrease in emissions from fire, both projects continue to have lower standing carbon stocks after a fire in the year of treatment. The treatment on the Davis project led to increased fire intensity. According to FCCS modeling, the treated stand also yielded slightly higher CO_2 emissions from fire, while FVS modeling indicated slightly lower CO_2 emissions after a fire in the treated stand[11]. The significant increase in both standing and lying deadwood on the Davis project explains the increase in fire intensity in the year following treatment. However, in subsequent years, as the deadwood continues to break down, the intensity of a potential fire is likely to decrease. In addition, the reduction in live ladder fuels improves the ability to control a fire.

The rate of growth on both Berry and HH increased following the treatment, but in the absence of a wildfire, total carbon stocks in the treated areas still had not surpassed those in untreated areas after 60 years. Growth rates on the Davis project were slightly lower following treatment. The treatment in the Davis project removed a smaller percentage of basal area than did the other two treatments, and may not have increased resources for residual trees enough to allow increased growth. However, when growth is projected following a fire in the year of treatment, all three projects experienced higher

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[10] A complete accounting of emissions would have also incorporated equipment use. Though this project did not address equipment emissions, a similar project in Shasta County found emissions ranging from 0.8 to 1.8 tons CO_2/ac. While this is not an insignificant amount, it is a small fraction of the emissions which result from the removal of biomass from the forest.

[11] The difference between the two models is likely based on the specificity required of input data for each model. FCCS requires certain input data which is not required by FVS and which was not collected in the field. In order to run FCCS, base fuelbed data was used in cases where empirical data was not available.

growth rates with treatment. Treated stands in all three projects also have greater overall carbon stocks by year 30, though it's important to note that there is an annual risk of fire and subsequent wildfires were not modeled. Additionally, with each year following a hazardous fuels treatment, the benefits of the treatment are reduced and the maximum shelf life is probably less than 20 years.

Within the treated areas, all three projects had significant net emissions when considering treatment and the risk of a potential wildfire. Davis experienced the lowest emissions, but as discussed above, the treatment on Davis did not decrease fire intensity. If a fire were to occur in the year of treatment, all projects would still experience net emissions, though the impact of treatment emissions would be approximately halved in all cases.

One critical factor not addressed in this study is the impact of fuels treatment on fire intensity and emissions outside the treated area itself. In many cases, the reduced intensity of fire in a treated area decreases the intensity of fire in the surrounding untreated areas, increasing the beneficial aspects of the treatment without removing additional biomass. This is often referred to as a fire shadow. The size of a fire shadow along with the level of reduced emissions varies based on a number of factors, including topography, location of treatment, climatic conditions, and fire intensity. Incorporating the fire shadow in the overall emission calculations would decrease the net emissions in most cases, but given the extent of emissions for all three projects, it is likely that inclusion of a fire shadow would yield lower emissions but significant emissions would still result from treatment.

All three of the pilots led to a decrease in crown fire potential, which decreases fire severity and size. While treatments lead to net carbon emissions in both the short and long term in all three projects, there are, of course, additional benefits to fuels treatments, such as increased ability to successfully fight fires and decreased cost of fire fighting; reduced loss of life and property; and reduced potential damage to wildlife habitat.

These results are mirrored well in the results from the Alder Springs treatment in Mendocino National Forest conducted under funding from the US Forest Service. In Alder Springs, net emissions of 26.3 tons of carbon dioxide per acre were recorded immediately after treatment climbing to a total of 86.9 t CO_2-e/ac after 60 years.

The results from this study in combination with the paired study in Lake County and the allied study in Mendocino National Forest underlie the unsuitability of fuels treatment as a potential greenhouse gas offset generating activity. Instead we argue the shift should be made to policies minimizing greenhouse gas emissions from wildfires and from fuel treatments while minimizing wildfire risks to lives, homes and livelihoods in the WESTCARB region.

5.0 References

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Annex A: Standard Operating Procedures for Fuels Measurements in 2007

See separate attachment.

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DEMONSTRATION OF CONSERVATION-BASED FOREST MANAGEMENT TO SEQUESTER CARBON ON THE BASCOM PACIFIC FOREST

Jonathan Remucal, C. Best, L. Wayburn, M. Fehrenbacher, and M. Passero.

Pacific Forest Trust

DOE Contract No.: DE-FC26-05NT42593
Contract Period: October 1, 2005 - May 11, 2011

Arnold Schwarzenegger
Governor

Demonstration of Conservation-Based Forest Management to Sequester Carbon on the Bascom Pacific Forest

PIER PROJECT REPORT

Prepared For:

California Energy Commission
Public Interest Energy Research Program

Prepared By:

PACIFIC FOREST TRUST

October 2010
CEC-500-XXX-XXX

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Commission Work Authorization No. MR-045

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Jonathan Remucal, C. Best, L. Wayburn, M. Fehrenbacher, M. Passero. 2010. *Demonstration of Conservation-Based Forest Management to Sequester Carbon on the Bascom Pacific Forest.* California Energy Commission, PIER. Publication number.

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission) conducts public interest research, development, and demonstration (RD&D) projects to benefit the electricity and natural gas ratepayers in California. The Energy Commission awards up to $62 million annually in electricity-related RD&D, and up to $12 million annually for natural gas RD&D.

The PIER program strives to conduct the most promising public interest energy research by partnering with RD&D organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration

Demonstration of Conservation-Based Forest Management to Sequester Carbon on the Bascom Pacific Forest is a final report for the West Coast Regional Carbon Sequestration Partnership – Phase II (contract number 500-02-004, work authorization number MR-06-03L. The information from this project contributes to PIER's Energy-Related Environmental Research program.

For more information on the PIER Program, please visit the Energy Commission's Web site at www.energy.ca.gov/pier or contact the Energy Commission at (916) 654-5164.

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Abstract

The Bascom Pacific Conservation Forestry Project was initiated as part of the West Coast Regional Carbon Sequestration Partnersthip (WESTCARB) in order to demonstrate how the baseline and project activities associated with the conservation-based management of a commercially productive forestland site in northern California would be interpreted and projected if a carbon dioxide emissions reductions project were undertaken in accordance with version 2.1 of the Forest Project Protocol of the California Climate Action Registry (now the Climate Action Reserve). After measuring the initial forest carbon stocks on the Bascom Pacific Forest, project activities based on the forest management guidelines outlined in the conservation easement on the property were identified that would create emissions reductions on the project site relative to a baseline scenario based on harvesting the greatest amount of timber feasible and practicable under applicable forest laws. The costs and benefits of undertaking a forest management project for the purpose of registering forest carbon stock changes with the Climate Action Reserve were evaluated, including an assessment of ways the Forest Project Protocol may be improved to increase its practicality and effectiveness. Since the Forest Project Protocol was updated from version 2.1 to version 3.1 near the completion of this study, a number of changes made in the updated version were referenced throughout the report, including a brief discussion of how these changes may affect the subject project.

Executive Summary

Introduction

The following report summarizes the Bascom Pacific Conservation Forestry Project as part of the West Coast Regional Carbon Sequestration Partnership (WESTCARB) – Phase II. The project was initiated with the intent to achieve the following:

- Demonstrate how baselines and project activities associated with the conservation-based management of a commercially productive forestland site in northern California would be interpreted and projected on this site if a carbon dioxide (CO_2) emissions reduction project were undertaken in accordance with the California Climate Action Registry Forest Project Protocol (Version 2.1) (which, together with the associated general reporting and verification protocols are referred to herein as the "Forest Protocols")
- Identify specific management activities that would create carbon reductions on this site
- Evaluate the costs and benefits of the Forest Protocols with respect to undertaking a forest management project for the purpose of registering forest carbon stock changes with the Climate Action Reserve ("Reserve").

Purpose

The initial conditions on the Bascom Pacific project site (hereafter Bascom Pacific Forest) were defined as the amount of forest carbon stocks on site prior to the start of project activities. Initial conditions were established by directly sampling carbon stocks. This was done by performing both a conventional timber inventory, as is typically used in commercial timber applications, and a lying dead wood inventory. Methodologies for both the conventional commercial timber inventory and the lying dead wood inventory are provided below. Conventional inventory measurements are summarized by stand, whereas lying dead wood measurements are summarized by Public Land Survey System section. Summary information from each inventory includes conversions of data to carbon values.

Project Objectives

The direct sampling efforts on the Bascom Pacific Forest were designed to generate inventory data that achieve the following:

1. Provide current estimates of the standing timber volume and biomass.
2. Provide current estimates of biomass in lying dead wood.
3. Support timber and habitat management activities.
4. In the case of the 2006 inventory, support projections of future timber resources and carbon stocks using the CACTOS growth model (Wensel *et al*. 1986; http://www.cnr.berkeley.edu/~wensel/cactos/cactoss.htm).
5. In the case of the 2008 inventory update, monitor project activities and resulting changes to carbon stocks.

Project Outcomes

Once initial conditions for the Bascom Pacific Forest were established, changes to future carbon stocks were modeled pursuant to the requirements of the Forest Protocols to evaluate the difference between projected carbon stocks under two distinct management scenarios: *baseline activities* and *project activities*. The baseline management scenario under version 2.1 of the Forest Protocols is based on how the forest would be managed if the landowner were to realize timber harvest volumes to the greatest extent feasible and practicable as allowed under applicable forest management laws, in this case the California Forest Practice Act/Rules. The project activity scenario for the Bascom Pacific Forest is based on management that follows the conservation easement on the property and is intended to sequester and store more carbon stocks over time than the baseline activity scenario. Those project activity carbon stocks that are stored above and beyond baseline activity stocks are considered *additional* carbon stocks, representing net gains due to sequestration and avoided depletion in reference to the "business as usual" baseline. Based on the baseline and project activities modeled, this study shows that over 1 million tons of additional metric tons of CO_2, or 118 metric tons of CO_2 per acre, would be generated by the end of the 100-year project lifetime.

Conclusions

Over the life of the project, 447,877 thousand board feet (MBF) of timber are harvested under the baseline activity scenario, whereas 417,563 MBF are harvested under the project activity scenario (Tables 14 and 15). The amount of timber harvested in any given period of time varies considerably under the baseline activity scenario, with significant pulses during the periods in which clearcutting occurs, more modest harvest volumes when intermediate thinning takes place, and no volume harvested in some periods as standing timber volume is allowed to accumulate on clearcut sites. Although the baseline activity scenario exhibits an average harvest rate of about 4,475 MBF per year, as much as 7,413 MBF per year are harvested per year during the initial clearcut phase and up to 14,820 MBF per year in the second clearcut phase, but only between about 1,000 and 3,000 MBF per year during intermediate thinnings and 0 MBF during fallow years. The wood products carbon pool reflects these changes by accumulating rapidly during clearcutting phases, and more slowly during intermediate thinning phases (Figure 7). But during the periods in which no harvesting occurs, decay of existing wood products leads to a slight decrease in the overall stocks in this pool. At the end of the project lifetime, the baseline activity scenario has a total of 88,775 metric tons of carbon in the wood products pool.

Combining the wood products pool with the standing live tree, standing dead tree and lying dead wood pools increases the amount of carbon stored under both the baseline activity and project activity scenarios (Figure A1). When the baseline values are averaged over the project lifetime, inclusion of wood products increases the baseline average by 179,064 tons of CO_2. Incorporating wood products also increases the cumulative emissions reductions at the end of the project lifetime by 132,208 tons of CO_2. However, cumulative emissions reductions including wood products remains lower than emissions reductions without wood products until 2066, at which point emissions reductions including wood products is greater through the remainder of the project lifetime.

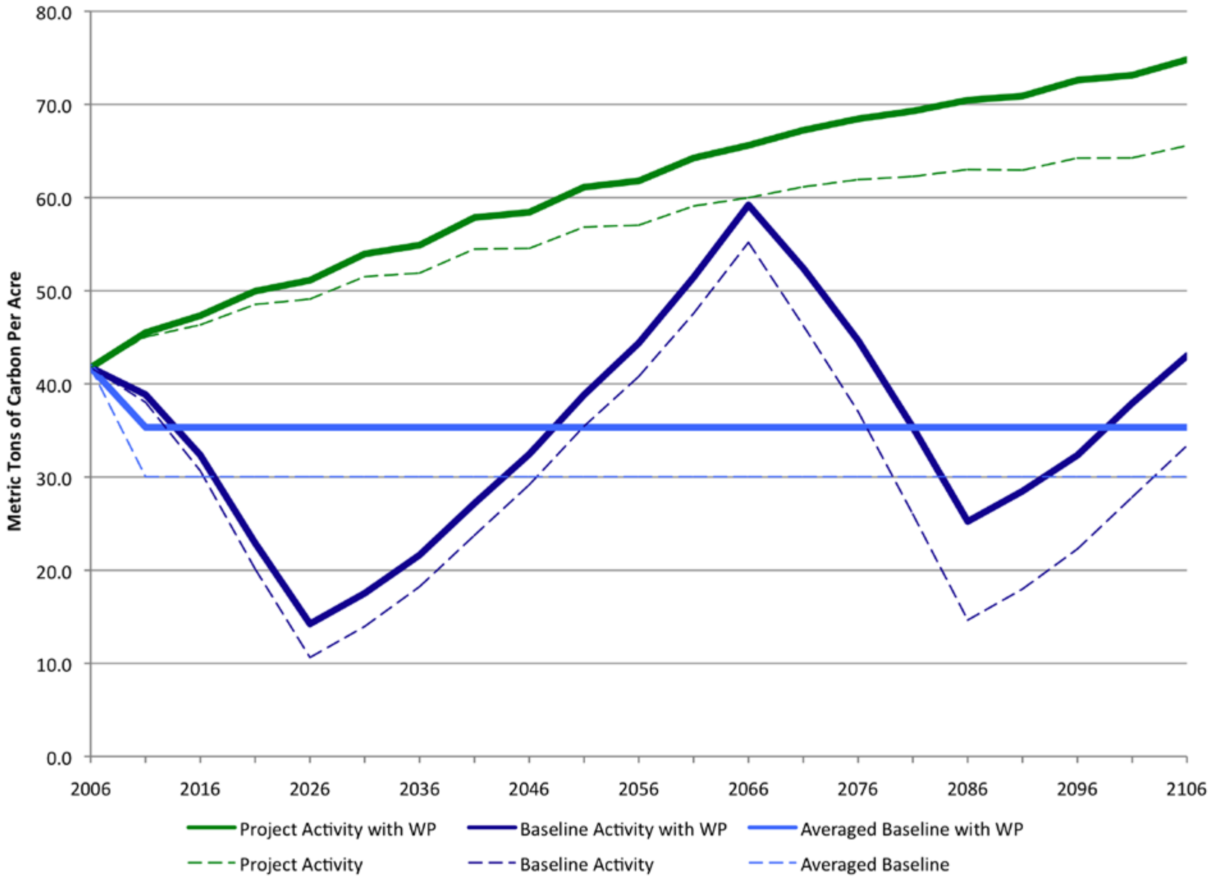

Figure A1. Baseline and project activity carbon stocks, both with and without wood products pool stocks, over the 100-year project lifetime on a per acre basis. The averaged baseline activity value is also shown. All scenarios have the same initial carbon stocks at the project start date in 2006. The averaged baseline curve begins at this same starting value, but achieves the average value by the end of the first 5-year reporting period by being reduced annually in equal increments.

Overall, the results of the application of version 2.1 of the Forest Protocols appear to provide practical but rigorous accounting of emissions reductions to internationally acceptable standards. Nonetheless, there are a number of areas were we recommend changes to provide for more efficient and accurate application, many of which have been incorporated into version 3.0. In considering the costs and returns of a project such as Bascom Pacific, under the assumptions used in a pro forma analysis, we believe the potential financial returns from an emissions reduction project provide an incentive for landowner participation, while fostering long term forest conservation and net gains from long term reduction of CO_2 emissions.

Recommendations

The initial conditions inventory, when properly specified, can be cost effectively undertaken concurrent with a conventional timber inventory but does add expense. The greater expense is due to the generally higher statistical confidence required in sampling[1] and the inclusion of additional inventory elements such as standing and down dead biomass. Further, the requirement for permanent marking of plot centers is a costly variance from the standard timber inventory practice of temporary flagging. Version 3.0 of the Forest Protocols eliminates the requirement for permanent monumenting, while still requiring temporary flagging so that verifiers can locate plot centers. In addition to the specific requirements of different project types under the Protocols, inventory costs vary with the size and heterogeneity of the property, not unlike timber inventories. Larger more homogenous properties will cost less to inventory than the mid-size, relatively diverse Bascom Pacific property.

Benefits to California

During the course of this project the Reserve initiated a stakeholder process to review, update and revise the Forest Protocols. The experience the authors gained in preparing this report helped inform the development of the revised Protocols, which are now published as version 3.0 (and subsequently updated to version 3.1). In addition, the Bascom Pacific Forest analysis provides an example for future improved forest management projects, so that project developers can have a sense of what to expect when undertaking such an endeavor and so that policymakers and the public can better understand the potential for real, lasting and verifiable emissions reductions to be achieved through changes in forest management.

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[1] Lower sampling confidence intervals (i.e., greater than +/-5% at the 90% confidence interval)

1.0 Introduction

1.1 Project Overview and Objectives

The following report summarizes the Bascom Pacific Conservation Forestry Project as part of the West Coast Regional Carbon Sequestration Partnership (WESTCARB) – Phase II. The project was initiated with the intent to achieve the following:

- Demonstrate how baselines and project activities associated with the conservation-based management of a commercially productive forestland site in northern California would be interpreted and projected on this site if a carbon dioxide (CO_2) emissions reduction project were undertaken in accordance with the California Climate Action Registry Forest Project Protocol (Version 2.1) (which, together with the associated general reporting and verification protocols are referred to herein as the "Forest Protocols")
- Identify specific management activities that would create carbon reductions on this site
- Evaluate the costs and benefits of the Forest Protocols with respect to undertaking a forest management project for the purpose of registering forest carbon stock changes with the Climate Action Reserve ("Reserve").

We note that during the course of this project the Reserve initiated a stakeholder process to review, update and revise the Forest Protocols. The experience the authors gained in preparing this report helped inform the development of the revised Protocols, which are now published as version 3.0 (and subsequently updated to version 3.1). Throughout this report we reference a number of changes made to version 3.0 in comparison to 2.1 and how these changes could affect the subject project.

The initial conditions on the Bascom Pacific project site (hereafter Bascom Pacific Forest) were defined as the amount of forest carbon stocks on site prior to the start of project activities. Initial conditions were established by directly sampling carbon stocks. This was done by performing both a conventional timber inventory, as is typically used in commercial timber applications, and a lying dead wood inventory. Methodologies for both the conventional commercial timber inventory and the lying dead wood inventory are provided below. Conventional inventory measurements are summarized by stand, whereas lying dead wood measurements are summarized by Public Land Survey System section. Summary information from each inventory includes conversions of data to carbon values.

Once initial conditions for the Bascom Pacific Forest were established, changes to future carbon stocks were modeled to evaluate the difference between baseline activities and project activities. The Forest Protocols require that an analysis be conducted to project future carbon stocks under two distinct management scenarios: *baseline activities* and *project activities*. The baseline management scenario under version 2.1 of the Forest Protocols is based on how the forest would be managed if the landowner were to realize timber harvest volumes to the greatest extent feasible and practicable as allowed under applicable forest management laws, in this case the California Forest Practice Act/Rules. The project activity scenario for the Bascom Pacific Forest is based on management that follows the conservation easement on the property and is intended to sequester and store more carbon stocks over time than the baseline activity scenario. Those project activity carbon stocks that are stored above and beyond baseline activity stocks are considered *additional* carbon stocks, representing net gains due to sequestration and avoided depletion in reference to the "business as usual" baseline. Based on the baseline and project activities modeled, this study shows that over 1 million tons of additional metric tons of CO_2, or 118 metric tons of CO_2 per acre, would be generated by the end of the 100-year project lifetime.

We found the Forest Protocols to be a useful and useable tool for measuring changes to forest carbon stocks and estimating the emissions reductions that may be generated by a forest project, providing real net gains for the atmosphere and meaningful added financial value to forest owners. However, there are a number of ways in which the practicality and effectiveness of the Protocols can be and have been improved to increase the accuracy of emissions reductions estimates, reduce costs to project developers, and increase participation in the Reserve.

1.2 Climate Action Reserve Forest Protocol and Its Key Principles

The Forest Protocols (to reference both version 2.1 and the new version 3.0, please go to http://www.climateactionreserve.org/how/protocols/adopted-protocols/forest/current/) provide guidance for the voluntary registration and certification of greenhouse gas emissions and reductions from the forest sector. The Forest Protocols consist of three related Protocols that set consistent accounting standards and provide guidance for measurement and reporting at the entity and project levels, as well as for third-party certification (or "verification" as it is also known). The Forest Sector Reporting Protocol, in conjunction with the Reserve's existing General Reporting Protocol, governs the accounting and registration of a forest entity's "entity-wide" greenhouse gas (GHG) emissions, both biological and non-biological. The Forest Project Protocol provides guidance for the accounting and registration of forest project activities that are focused on GHG reductions, specifically reductions in biological emissions. Specific project types (or activities) include conservation-based forest management, reforestation and conservation (or avoided conversion). Guidance for third-party certification of entity and project GHG emission and reduction reporting is also provided in the Certification Protocol. The Bascom Pacific Project used the forest management guidance of the Project Protocol.

The specific requirements of the Reserve's Forest Project Protocol are derived from widely accepted greenhouse gas emission reduction principles. These principles include the requirements of establishing a **baseline**, calculating the **additionality** of project carbon stores, and assuring the **permanence** or durability of emissions reductions.

Baseline: The baseline reflects a business as usual scenario, or a characterization of what can reasonably be assumed would happen on the project site in the absence of the forest project activity. The baseline for a forest management project under the Forest Protocols assumes that business as usual would be for a landowner to manage the property to realize its economic value in a way that is legal and feasible. Version 2.1 of the Forest Protocol describes a standardized performance-based approach that captures the limits imposed by prevailing regulation of the property, in particular the silvicultural prescriptions of "Option C" in sections 913.11, 933.11 and 953.11 of article 3 of the California Forest Practice Rules (14 CCR), as well as any other rule or law that affects management activities. Other potential rules and laws that affect the baseline analysis include watercourse protection rules, endangered species laws, and any county ordinances, deed restrictions or other mandatory, enforceable constraints. This baseline scenario is then modeled to create a projection of total baseline forest carbon stocks throughout the 100-year timeframe.

Version 3.0 of the Protocol amends and expands on the Baseline methodology used in version 2.1, with the same goal of characterizing what reasonably can be assumed would happen in the absence of the project. The standardized guidance for a Baseline performance standard in version 3.0 can be applied in forest types across the U.S., not only in California, and defines different rules for projects depending on the volume of the initial project carbon stocks. The methodology uses a "Common Practice" performance standard and two tests: The regulatory test requires the project developer to demonstrate that the baseline activity complies with all applicable laws, regulations and Best Management Practices; the financial feasibility test requires that the project developer demonstrate that the baseline activity, including timber harvest and other management activities are financially feasible. As with version 2.1, the baseline relies on a computer simulation to project stocks over the 100 years of the project commitment period. The first step in estimating the baseline condition is to determine if the initial project live tree carbon stocks are above or below a metric meant to quantify Common Practice, or typical live tree carbon stocking that is the result of forest management for similar lands in the forest type and jurisdiction surrounding the property. The Reserve has utilized data for private forestlands developed by the USDA Forest Inventory and Analysis (FIA) program to develop a mean live tree stocks value to represent common practice. If a project's initial stocks are above Common Practice, Baseline live tree carbon values cannot fall below Common Practice. If a project's initial stocks are below Common Practice, Baseline live tree carbon values must not fall below historical levels (as defined). Once the carbon flux of the Baseline is modeled incorporating all required carbon pools, the results are averaged for the project lifetime. If for any reason that average value is below the initial starting live carbon stock value or the historic stocking level, then the highest of the values is used to estimate the Baseline condition.

Overall, the Baseline methodology in version 3.0 is expected to produce more conservative results. The potential relative impact on the hypothetical project that serves as the basis of this study is discussed later in this paper.

Additionality: Forests store CO_2 as carbon biomass naturally, yet all CO_2 stores in a forest do not yield certifiable emissions reductions. To produce qualifying emission reductions, a forest management project must also demonstrate additionality, or that the CO_2 stores that are being reported as the basis for emissions reductions calculations are additional to what would have occurred under business as usual. In other words, the forest management practices applied to the project site must exceed the baseline projection, as described in the preceding paragraph, thus leading to additional carbon stocks over time. For example, the management of the Bascom Pacific Forest exceeds the Option C rules through both the avoided depletion of standing stocks and through changes in forest management (by harvesting at a significantly lower rate than the rules allow, by improving understocked areas, and by expanding riparian buffer strips) that lead to increased carbon stocks on the property. As with an actual project, accrual of additional forest carbon stocks, and ultimately emission reductions, are assumed to happen over time. Therefore, emission reductions for the hypothetical Project are projected based on modeled results. Under the Protocols, these anticipated emission reductions would be monitored, measured, reported and independently verified over time to account for additional carbon stocks as they accrue.

Permanence: Permanence refers to the long-term duration of emission reductions. Achieving long term emissions reductions is a key international standard for carbon projects due to the long time it takes for CO_2 to be reabsorbed from the atmosphere (i.e., in its Fourth Assessment Report, the Intergovernmental Panel on Climate Change states "about 50% of a CO_2 increase will be removed from the atmosphere within 30 years, and a further 30% will be removed within a few centuries. The remaining 20% may stay in the atmosphere for many thousands of years" (IPCC 2007). Assuming the middle 30 percent cycles out in 200 years, about 41 percent of the original emission is still in the atmosphere after 100 years. These cycle times assume current sinks continue to function as they are now. It is possible that both oceanic and terrestrial sinks could absorb less CO_2 as the impacts of climate change intensify, thus these cycling times could lengthen (IPCC 2007).

This is an especially challenging area to adequately address in forest emissions reduction projects. Forests are naturally dynamic systems, with carbon flux reflecting growth and mortality, including varying degrees of natural disturbances. Insects and fire have naturally shaped forest ecosystems since time immemorial and resulting forest mortality, with associated carbon flux. The impacts of changing climate are affecting forest dynamics in ways we are only just beginning to observe and study. Forest management brings added elements such as intentional disturbance through logging, vegetation management, and site preparation for reforestation; as well as enhancements such as management to foster faster forest growth and stand re-establishment after harvest. Finally, forest owners and forest ownerships change over time and with these changes, forest management and carbon stocks often change. Forest ownership changes include both voluntary ones (e.g., the sale of a property) and involuntary ones (e.g., through the death or bankruptcy of the owner).

Yet, in spite of these challenges, it may be possible to craft a system whereby overall forest carbon emissions reductions at the project level can be defensibly considered long term, with a minimum life-time of 100 years. This is critical if forest based emissions reductions are to be considered equal to those achieved through the avoided combustion of fossil fuels, especially if the forest emissions reductions are being used as offsets to fossil fuel emissions under a mandatory regulatory scheme. In a GHG regulatory scheme that caps GHG emissions and allows both trading of allowances and the use of offsetting emissions reductions from uncapped sources such as forests, the project developer's promise to maintain a forest-based emissions reduction ton over 100 years allows a ton of CO_2 to be emitted into the atmosphere that wouldn't otherwise have been permitted.

Such a system should require project developers to assess the various risks to permanence, both anthropogenic and natural, and seek to mitigate them through legal instruments, required loss reserves of emissions reductions and forest management activities. The newly adopted version 3.0 of the Forest Project Protocol lays out such an approach. This scheme includes a 100-year contractual agreement between the Reserve and the project developer that would form the primary commitment mechanism, and could be further buttressed through a conservation easement (described further below). We note that in this Project Implementation Agreement

(PIA) the project developer agrees to maintain each year's accrued and verified emissions reduction for 100 years, implicitly extending the project lifetime for up to 199 years in total duration, or more than the duration of the contract with the Reserve. (See http://www.climateactionreserve.org/how/protocols/adopted/forest/current/.) In addition, each project is required to undertake a standardized risk assessment and, based on the verified results, contribute a percentage of each year's verified emissions reductions into a collective loss reserve or group insurance account administered by the Reserve called the Buffer Pool. As a remedy for actual tons lost to either avoidable or unavoidable reversals, such tons would be replaced with emissions reductions from those set aside in the Buffer Pool (for unavoidable or natural reversals) or as obtained from other projects as may be necessary in an avoidable reversal (due to, for instance, breach of the PIA or early project termination).

Version 2.1 of the Forest Protocols seek to address permanence by requiring all forest projects be secured with a perpetual conservation easement. While not as comprehensive, the approach outlined under version 3.0 of the Project Protocols, a conservation easement binds current and future landowners, and can be drafted to restrict land uses in such a fashion as to better secure the emissions reductions against losses from changes in ownership and management not only over 100 years, but in perpetuity. Given that around 40% of emitted CO_2 remains in the atmosphere 100 years later, there is considerable atmospheric benefit in a landowner's permanent commitment to maintaining additional carbon stores beyond the 100-year project lifetime required by the Reserve. As the PIA with the Reserve terminates at 100 years, and as the landowner may actually have on-going obligations to maintain emissions reductions beyond the 100-year project lifetime (i.e., for any ton accrued after year 1), a conservation easement provides added assurances. Further, conservation easements are enforceable against all future owners without advance assignment and, with proper drafting, can survive transfers at death or through bankruptcy or other forms of default, mitigating the risk of financial failure to lead to an emissions reductions reversal.

In the case studied here, the Bascom Pacific Forest is bound by a perpetual working forest conservation easement, which protects the forest project area from conversion to non-forest use and guides management practices to enhance overall forest carbon stocks. The easement is a voluntary legal instrument that was executed by the landowner and Pacific Forest Trust. The Trust, as easement grantee, is obligated to monitor and enforce the terms of the conservation easement, adding a layer of third party supervision and legally well-grounded enforcement rights to the Protocol specific but novel ones required in the PIA with the Reserve. In the event the landowner sells the property, the conservation easement will remain valid, as it is legally a part of the deed. Thus, no matter who owns the land, it will not be converted to non-forest use and the management impacts to it will be limited, as specified by the easement. Indeed, under the terms of the Bascom Pacific easement, the carbon stocks on the property are expected to increase to a certain minimum level and remain at (or exceed) that level. This is due to the requirement that management activities, in general, foster a significant increase in timber stocks from current levels to at least a specified stocking level. Once achieved, the landowner is committed to managing the forest in such as way as to help assure that at least this stocking level is sustained in perpetuity. As a result, the forest, and the climate benefits of the forest are permanently protected from risks associated with land use changes.

1.3 Application of Conservation Easements in the Context of Forest Carbon Projects

As noted above, under version 2.1 of the Forest Project Protocol, a conservation easement is required to mitigate risks to the permanence of emissions reductions generated by a project. While a new system has been established under version 3.0, conservation easements are optional for use associated with Improved Forest Management Projects (and still mandatory for Avoided Conversion projects). In calculating a project's Buffer Pool allocation, conservation easements are recognized as a valuable risk mitigation tool that results in a reduced allocation. As we expect that conservation easements will continue to be used in many of the Reserve's projects, this section examines their application in this context generally, with particular reference to the Bascom Pacific Forest project as an example.

Conservation easements have been in use in one form or another for about 100 years; although the modern era of conservation easement use began with formal recognition in the federal Internal Revenue Code in 1980 and a subsequent wave of conservation easement enabling statutes in states around the U.S. A conservation easement is a legal restriction that a landowner places on his or her property to define and limit the types of activities (e.g., development, forest management) that may take place there. It is drafted between the landowner (the "grantor") and the recipient organization (the "grantee") and must conform to enabling state legislation (e.g., see California Civ. Code § 815) and federal laws.

A conservation easement, generally speaking, is based on the principle of separating out one or more of various ownership rights (development, mineral, timber, etc.) and selling or giving those rights to a qualified third party (i.e., an appropriately constituted land trust or government agency). The underlying property and all the retained property rights are unaffected. As with a right of way or powerline easement or timber deed, a conservation easement becomes part of the title to the property and all future owners are subject to the easement's restrictions, even if the land is thereafter mortgaged, sold, transferred to heirs or subdivided; and existing mortgages or deeds of trust need to be subjected to the easement terms. In this way, the easement is permanently established for that property. Generally, conservation easements are donated or sold to the grantee entity, which then carries the responsibility to inspect the land periodically and enforce the restrictions. Enforcement provisions and remedies for breach are typically embedded in statute, and include the use of restraining orders or injunctive relief to stop damaging actions for requirement as well as the opportunity to require restoration of impaired conservation values, such as, for instance, lost carbon stores.

The specific rights that a property owner is restricting or retaining are spelled out in each easement document according to the agreement reached between the landowner and the recipient organization. Typically, with conservation easements certain development rights, such as construction, subdivision, timber harvesting or mining, are restricted to some degree so as to limit impacts on the land that may harm the conservation values that have been identified for protection. The grantee organization, such as the Pacific Forest Trust, receives these rights on the basis that they will ensure these rights are not exercised by the grantor through time.

A conservation easement drafted for the purposes of helping secure GHG emissions reductions needs to have certain key terms, including:

1. A specific recital identifying that the property is or will be enrolled in an emissions reduction project pursuant to the relevant standard (i.e., the Forest Protocol) and any relevant statutes.
2. Identification that the ability of the property to be conserved and managed to avoid emissions and/or reduce and store atmospheric CO_2 is a "conservation value" that provides significant public benefit consistent referenced public policy.
3. Inclusion of the same as one of the governing purposes of the conservation easement.
4. Specific restrictions on land use to achieve the purpose, depending on the property and the project activity, but which may include, for example, the prevention of the conversion of forest area to other cover types or uses; limitations on other forest disturbance, such as road building; limitations on the rate and extent of timber harvest over time; etc.

While conservation easements are of a perpetual term, they are not inflexible. Conservation easements can be amended with the consent of both parties to correct, clarify or change terms to reflect advances in knowledge or other changes in condition, provided that the overall conservation purposes are still achieved and the changes are consistent with public grant agreements and/or Internal Revenue Sservice regulations that may pertain. Conservation easements may also be extinguished under a court proceeding if the purpose for which the easement was created can no longer be achieved; or through government condemnation of the property as a whole.

1.3.1. Comparison of Conservation Easements to Other Deed Restrictions

A conservation easement is a form of deed restriction and some commentators have suggested other deed restrictions could be just as effective in securing carbon reductions on forest projects. Attorney Matthew Zinn of Shute Mihaly & Weinberger, LLP, considered this question for PFT and responded with a legal opinion dated April 15, 2009, arguing that conservation easements are superior to ordinary deed restrictions in their enduring enforceability through time, making them an appropriate instrument to buttress the permanence requirements of a forest carbon project:

> *"Deed restriction" is a generic term for a covenant or other servitude that limits the allowable uses of a property. For example, a deed restriction might limit future construction on the property to a single family home or specify portions of the property that cannot be developed.*
>
> *Deed restrictions will "run with the land," that is, they will automatically bind future owners of the restricted property, if they comply with a variety of formal legal requirements for the creation of servitudes. Most important in the present context is the requirement that the restrictions benefit a specific parcel or parcels of real property. As an example, consider a restriction that prohibits construction of any structure that would cast shade onto an adjoining property. The adjoining property owner could enforce the restriction against future owners of the restricted property because the restriction provides a clear benefit—access to sunlight—to the plaintiff's property. By contrast, restrictions with benefits "in gross"—benefits that do not accrue to a*

> *specific parcel or parcels—will not run with the land.* See*, e.g.,* Marra v. Aetna Constr. Co.*, 15 Cal. 2d 375 (1940);* Chandler v. Smith*, 170 Cal. App. 2d 118 (1959);* Martin v. Ray*, 76 Cal. App. 2d 471 (1946); Cal. Civ. Code § 1468. For instance, in* Greater Middleton Ass'n v. Holmes Lumber Co.*, 222 Cal. App. 3d 980 (1990), the court held that a deed restriction prohibiting logging was enforceable by neighboring property owners against a subsequent owner because the restrictions identified "dominant and servient tenements," i.e., properties respectively benefited and burdened by the restriction.* Id. *at 992-94. The court rejected the defendants' argument that the restriction failed to benefit any property.* Id. *at 994.*
>
> *In response to this traditional limitation on the enforceability of deed restrictions, California and some other states legislatively established special categories of deed restrictions that will run with the land though they do not benefit identifiable parcels. Conservation easements are one category of such restrictions.* See *Cal. Civ. Code § 815.1 (Conservation easement "means any limitation in a deed, will, or other instrument in the form of an easement, restriction, covenant, or condition, which is or has been executed by or on behalf of the owner of the land subject to such easement and is binding upon successive owners of such land."). The benefits of a conservation easement are almost always "in gross": they benefit the entity that holds the easement and the public generally, rather than a specific parcel of property.*
>
> *"Environmental covenants" represent another legislative exception to the rule. They are restrictions on the use of property contaminated with hazardous materials, such as a restriction that the property will not be used for residential or other uses that could bring people into contact with residual contamination.* See *Cal. Civ. Code § 1471.*
>
> *Accordingly, one of the primary differences between a conservation easement and a run-of-the-mill deed restriction is the power of the former to bind successor landowners without a connection to a benefited property. Conservation easements are nevertheless subject to their own limitations, such as perpetual duration, the existence of a "purpose . . . to retain land predominantly in its natural, scenic, historical, agricultural, forested, or open-space condition," and the limited group of entities that may hold the easements.* See *Cal. Civ. Code §§ 815.1, 815.2(b), 815.3. These limitations would prevent most ordinary deed restrictions from being considered de facto conservation easements.*

1.3.2. The Added Value of Easements to Landowners, Forest Ecosystems and Society

Conservation easements not only provide added insurance against the loss of GHG emissions reductions from the risks of changes in ownership or forest management; they also protect and enhance the important environmental co-benefits that forest projects can provide, such as habitat for rare or threatened species or natural communities, watershed values, and sustainable forestry. Further, they generally provide a means for individuals, families and businesses in rural communities to protect their natural resources and traditional land uses from depletion, urbanization, and wholesale development, while retaining private ownership and productive uses.

For the landowner, a conservation easement offers a means to protect the special attributes of a property without the need to relinquish the ownership and the use and enjoyment of the land.

In addition, the landowner gains the satisfaction of knowing that the land he or she values will be protected and preserved in perpetuity.

Moreover, conservation easements can bring financial returns to landowners, above and beyond those from the sale of emissions reductions. The conservation easement can provide near-term financial benefits, often gained in the year it is granted, while the sale of emissions reductions would typically provide an annual earnings stream that can defray on-going land stewardship costs associated with a landowner's conservation-based management commitments. A conservation easement that meets the standards of the Internal Revenue Code is deductible as a charitable contribution. Even easements not meeting the Internal Revenue Service standards may still provide tax benefits. For example, by reducing the size of a taxable estate a conservation easement may enable land to pass intact to future generations when it might otherwise have to be sold to pay estate taxes. On the other hand, a grantor may choose to sell a conservation easement and be paid with public funds, receiving immediate cash benefits as a result.

In either instance, the value of the easement is determined by comparing the value of the property prior to the easement grant and then again what it would be after factoring in the limitations set by the conservation easement. The easement value is then calculated as the difference between the "before" and "after" valuations. The primary driver to the value of a conservation easement on productive forestland is the degree to which development and timber harvest are restricted. Such appraisals must meet standards established for state and federal programs, as well as for charitable donations, the full description of which is beyond the scope of this paper. We note that interactions between conservation easement projects and emissions reductions projects and associated implications for their financial returns are only now emerging, as are the implications of the emerging carbon market for forestland valuation overall. As emissions reductions transactions and market data accumulate, appraisals will be required to analyze the impacts on conservation easement values.

With respect to the Bascom Pacific Forest, commercial timber owners in the state are at an increasing disadvantage as high cost producers in a global forest products market. As a response, many large owners are seeking to generally improve their company's financial performance or are leaving the state altogether. Combined with the often higher value of forest properties as rural residential and recreational real estate, this trend puts California's privately owned forests and their biological resources at risk. Conservation easements are a tool increasingly used in California and across the U.S. to bring added returns for landowners' sustainable forestry investments.

Conservation easements can be an effective, private, and low-cost means for the public to benefit from the protection of forestland for open space, wildlife habitat, ecological significance, responsible resource production and scenic enjoyment—all of which would be lost through unrestricted development. Conservation easements can both aid significantly in the protection of sensitive resources while supporting sustainable timber management that benefits the local and state economy. Unlike fee title acquisition by a governmental agency, the forestland stays on the property tax rolls and on-going land management costs remain with the landowner.

The conservation easement on the Bascom Pacific property provides numerous ecological and societal benefits that are cited in the document and form the argument for its public benefit conservation purposes. The conservation easement is written to help assure that:

- Productive timberland will be protected as such and stay in production.
- The land will stay in private ownership and current zoning, with no impact on property tax receipts.
- Wood will flow from the property to provide supplies to local mills and associated forest products businesses, helping sustain the local and regional timber economy in a time of decline.
- Scenic and recreational resources will be protected and enhanced, contributing to the growing tourism economy of northeastern California.
- Fish and wildlife resources will be protected and enhanced, contributing to the local economy through consumptive and non-consumptive enjoyment and to the ecological viability of the area.
- Current hunting and fishing access will be protected and improved.
- The detrimental environmental impacts of more development in the timberlands of McCloud region will be avoided, protecting resources and underpinning a more sustainable, mixed use economy.

Greater carbon sequestration will occur than the without-project scenario due to required changes to forest management that promote increases in biomass, on average, across the property and that such gains will be maintained in perpetuity, certainly well beyond the 100-year Reserve project lifetime.

1.3.3. Monitoring Requirements Associated with Conservation Easements

One means by which the permanence of the climate benefits associated with a project is ensured is through the easement grantee’s monitoring of activities on or related to the project property and enforcing the terms of the conservation easement. By receiving an easement from the grantor, the grantee is authorized to enforce the specific terms of the easement on future use of the property. The grantee periodically monitors the property for compliance with the easement's restrictions and takes corrective action if its terms are violated. Enforcement can include legal action and restoration of the property. Procedures for correcting violations and rectifying damages are specified in the easement document itself.

In the case of the Bascom Pacific Conservation Easements, the properties are subject to both office-based and field-based monitoring activities. These activities include but are not limited to:

- Annual meeting to discuss plans for the coming year
- Office review of long term management plans and timber harvest plans, as well as site visits as needed to better understand such plans
- Confirmation with pertinent permitting agencies that the grantor has not submitted permit applications, unbeknownst to PFT, for activities that are prohibited or restricted by the conservation easement

- Review of Board of Equalization reports or similar documentation of timber harvest volumes
- Site inspection(s) to observe conditions and monitor for compliance with the easement restrictions. At least one site inspection will be made each year. However, during years in which active management is occurring, several site inspections may be required to ensure compliance is maintained.
- Annual review of aerial/satellite imagery (subject to availability of imagery) to remotely monitor portions of the property that were not directly visited during site inspection(s).

PFT produces monitoring reports following each site inspection. Such reports detail how the property was monitored, what observations were made during the visit, how such observations are related to the restrictions of the easement, and whether the grantor is in compliance with the easement. PFT also maintains records of correspondence related to the monitoring of the property, such as letters of approval for management plans that require review by PFT.

The monitoring and enforcement activities that a conservation easement holder is obligated to undertake help to secure the permanence of the climate benefits of a forest project and complement the landowner's measurement, reporting and verification requirements under the Protocols. In the case of Bascom Pacific Project, the monitoring and enforcement of the conservation easement, particularly the terms requiring forest management activities to achieve higher timber stocking levels than would be required under the Forest Practice Rules, ensure that the additional carbon stocks produced will be maintained in perpetuity, barring any natural catastrophic events.

2.0 Project Approach, or Methods

2.1 Description of Study Site

The Bascom Pacific Forest includes two tracts of commercial forestland in Siskiyou and Shasta Counties that are a subset of a larger ownership in area known as the Pondosa Timberlands. The River Tract consists of 4,859 acres and the Bear Tract consists of 4,344 acres. Both tracts are zoned for timber production and are composed primarily of mixed conifer forests. The average timber productivity rating on each tract is Site Class III. According to GIS data maintained by the landowner, approximately 8,326 acres of the property is in managed timberland, with about 480 acres in even-aged plantations; 282 acres are in areas managed for sensitive habitat, while approximately 500 acres are in watercourse or lake protection zones. Another 92 acres are in brushfields capable of supporting coniferous forest cover, while the remaining 31 acres are in non-forest cover types (Table 1). The closest community is McCloud. US Forest Service roads leading from Highway 89 provide access to both tracts. A map of the tracts is included below (Figure 1).

Table 1. Distribution of cover types on the Bascom Pacific Forest Project Site.

Cover Type	Acres
Managed Timberland	8,326
Uneven-aged	*7,846*
Even-aged	*480*
Sensitive Habitat	282

Watercourse/Lake Protection Zone	500
Brushfield	92
Non-Forest Cover	31

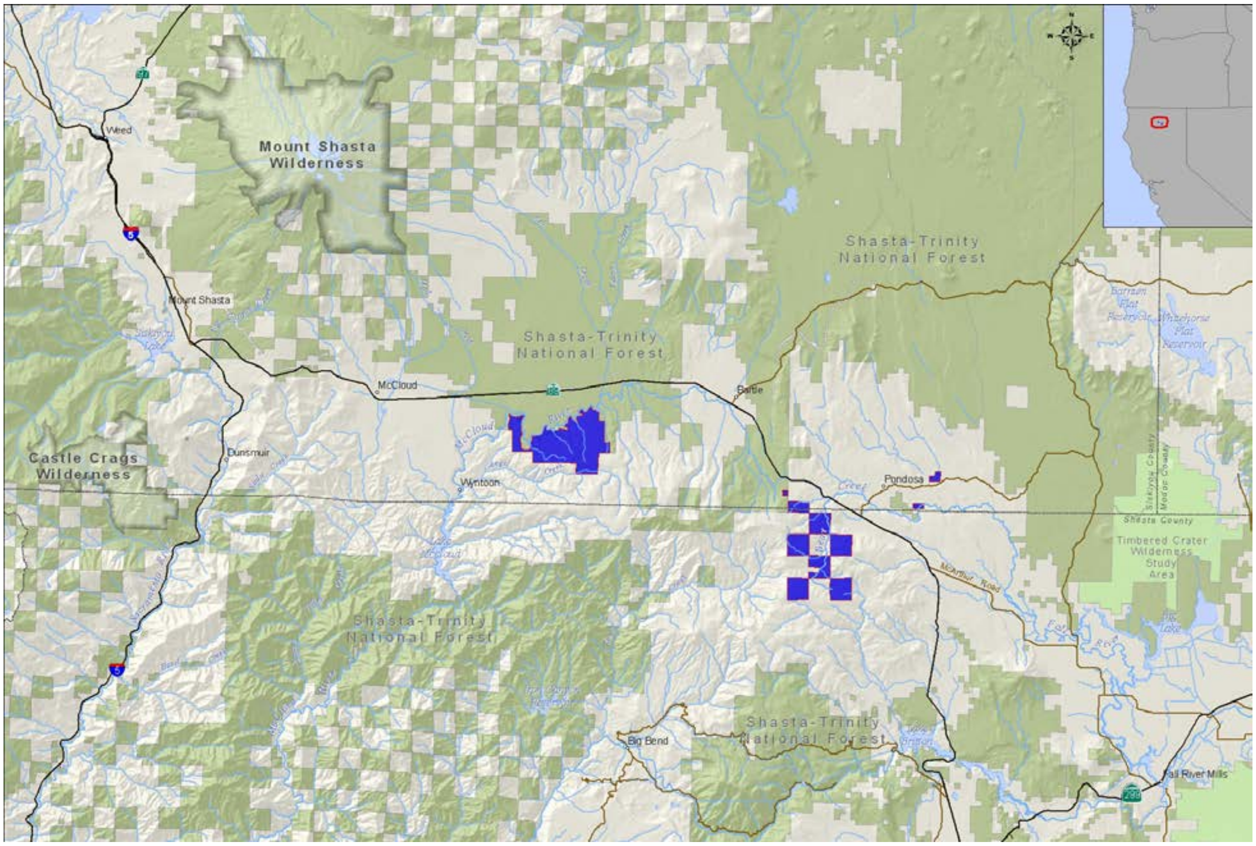


Figure 1. Bascom Pacific Forest project site (in dark blue).

2.2 Carbon Stocks Measurement Methodology

Initial carbon stocking was determined on the Bascom Pacific Forest at the initiation of project activities in 2006. A conventional commercial timber inventory performed prior to project initiation serves as the primary basis for evaluating baseline carbon stocks on the project site. Although performed prior to the development of this project, the timber inventory was nonetheless compliant with the measurement standards specified by the Forest Protocols for live trees and standing dead trees. A separate lying dead wood inventory was performed in 2007 in order to fulfill the requirement of the Forest Protocols to report carbon stocks in lying dead wood. Although lying dead wood data was gathered after the project initiation date, this pool is assumed to remain constant throughout the project lifetime. As such, the 2007 lying dead wood inventory was assumed to represent the same level of carbon stocks as were present at project initiation in 2006.

In 2007, the project site was sold to a new owner. Given the new landowner's interest in participating in the project, the change in ownership provided an opportunity to update the carbon inventory on the property. With the inventory update, improvements were made to the measurement methodology in order to increase efficiency and correct an error in the measurement standards applied to the sampling of lying dead wood in the initial inventory. All sampling for the inventory update was conducted during the fall of 2008. Determining the carbon stocks on the project site two years after the project was initiated provides the opportunity to analyze how well conditions on the ground match the conditions that were anticipated as a result of modeling performed under this study (see "Planned Activities to Increase Carbon Stores" below). Furthermore, the 2008 inventory update fulfills project monitoring obligations, ensuring that activities and conditions on the ground meet or exceed the standard of those outlined at project initiation.

Although conventional commercial timber inventories do not directly measure the biomass in all above-ground tree components, equations developed for general groups of species (Jenkins *et al*., 2003) can be applied to measurements that are taken in order to estimate the total above-ground biomass in a given tree. Similarly, below-ground biomass is estimated by applying a separate equation to the above-ground biomass values (Cairns *et al*., 1997). This equation is a generally accepted means of estimating below-ground biomass (e.g., Brown *et al*., 2004).

2.2.1 Purpose of the Inventory Efforts

The direct sampling efforts on the Bascom Pacific Forest were designed to generate inventory data that achieve the following:

6. Provide current estimates of the standing timber volume and biomass.
7. Provide current estimates of biomass in lying dead wood.
8. Support timber and habitat management activities.
9. In the case of the 2006 inventory, support projections of future timber resources and carbon stocks using the CACTOS growth model (Wensel *et al*. 1986; http://www.cnr.berkeley.edu/~wensel/ cactos/cactoss.htm).
10. In the case of the 2008 inventory update, monitor project activities and resulting changes to carbon stocks.

2.2.2 Live and Standing Dead Tree Inventory Methodology

Two cruise designs were used to generate a conventional commercial timber inventory on the Bascom Pacific Forest that served as the basis for estimating initial carbon stocks. From 2001-2004, inventory data were gathered using a cruise design that was based on variable radius plots and fixed radius subplots (1/250-acre) established on a 6.67 chain fixed grid with intermediate estimate plots. In the beginning half of 2005, inventory data were gathered using a cruise design that was similarly based on variable radius plots and fixed radius subplots (1/100-acre), but on a 5 chain fixed grid. As is typical practice for conventional timber inventories, temporary plots were employed for both cruise designs with the intention of generating inventory estimates at a single point in time. Although version 2.1 of the Forest Protocols requires plots to be "monumented in a way that allows them to be located and revisited for a period of 12 years," the plots installed on the Bascom Pacific Forest were not monumented in such a way that they would be revisited for additional measurements at a later point in time. This was due to the fact that the original intent of the timber inventory did not consider the requirements of the Forest Protocols. Nonetheless, the data collected on each of these plots met all other minimum sampling criteria and are discussed below. (For a comparison of inventory plot identification under both versions of the Protocols, see Section IX. below.)

A third cruise design was employed to estimate the carbon stocks in 2008. The cruise design was based on a uniform grid of variable radius plots and fixed radius subplots (1/100-acre) on a 5.0 chain fixed grid. Unlike the initial inventory, plots installed in 2008 were monumented to provide full compliance with the Forest Protocols.

Plot data gathered during inventory cruises were stored in a Microsoft Access database After stratifying plots into stand types, Wensel and Olson (1993) taper equations were used to calculate individual tree volumes within each plot. Additionally, individual tree biomass was computed using the above- and below-ground biomass equations provided in the Forest Project Protocols. Individual tree volume and biomass estimates were used to derive estimates of stand volumes and biomass. These stand-based estimates served as the basis for the summary inventory and biomass data for the Bascom Pacific Forest.

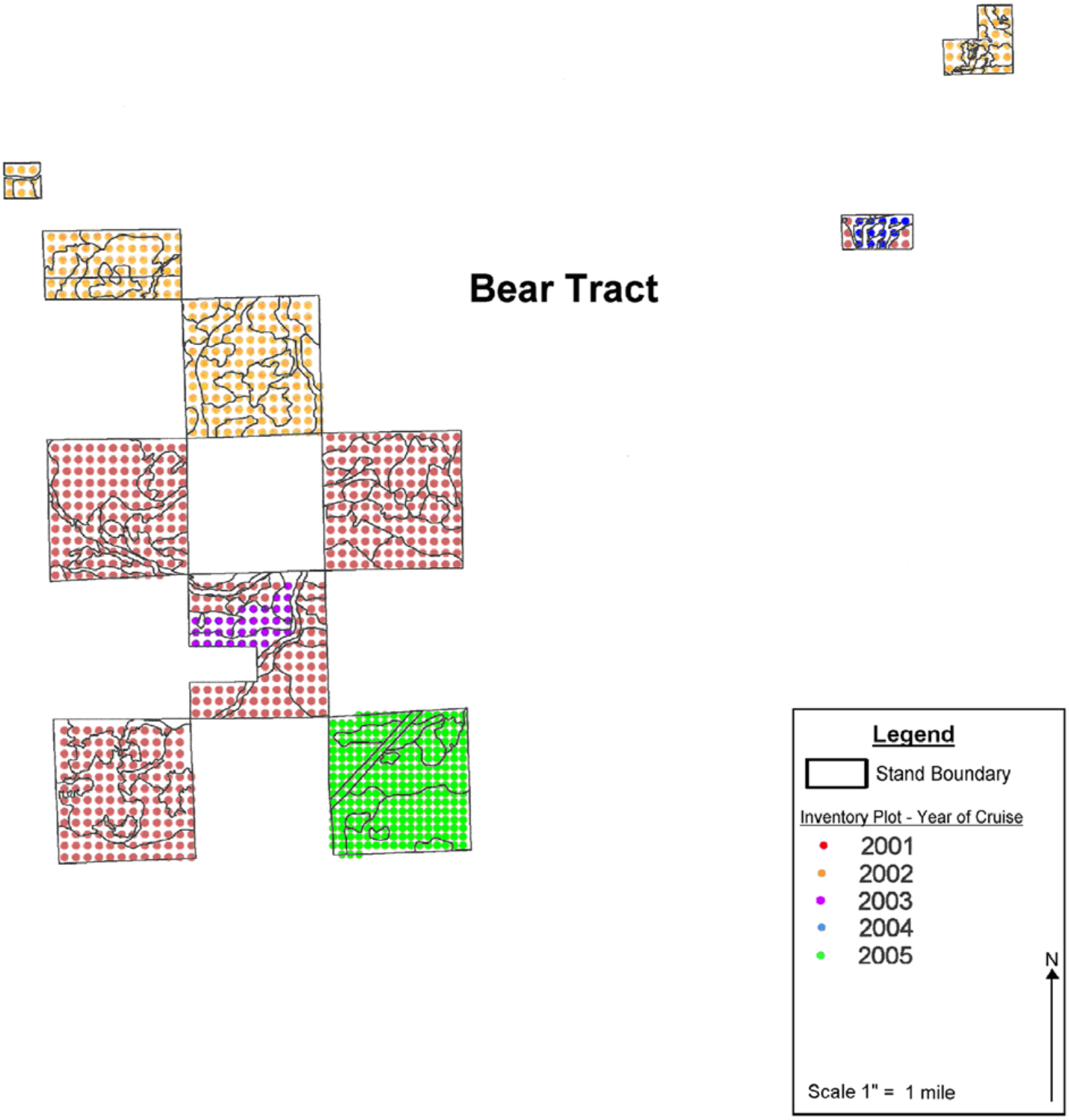


Figure 2. Plot map for live and standing dead tree inventory on the Bear Tract (2001-2005).

Plot Locations

<u>2001-2005</u>

Plots were located on a grid that was provided from a GIS for the property (Figures 2 and 3). From 2001-2004, primary plots were located on a grid pattern spaced 6.67 chains (440 feet) apart, resulting in one plot for every 4.4 acres. Secondary plots were located midway between (220 feet from) primary plots. In 2005, primary plots were located on a grid pattern spaced 5.0 chains (330 feet) apart, resulting in one plot for every 2.5 acres. Secondary plots were located midway between (165 feet from) primary plots. Plots were pre-numbered and displayed on maps supplied to the cruisers. Each plot number is a unique five digit number. Plots were located accurately in the field, using a combination of aerial photos and topographic maps for orienteering. For both cruise designs, the cruiser was free to choose his/her own direction of travel, but was instructed to use the plot numbers provided from the cruise map. Direction of travel from plot to plot was noted on each cruiser's field map.

If the plot center was not within the expected stand type, the cruiser documented the stand type it appeared to be in. For example, if the cruiser arrived at a plot location and determined that the vegetation condition was indicative of a condition in an adjacent stand, the cruiser would make a note and the plot would be assigned to the correct stand. Also, if the unbiased plot location turned out to be outside the property boundary with a high level of certainty, all that will be recorded is that the plot was located on the neighboring landowner. If there was any doubt of property ownership, the plot was recorded as normal.

The cruiser hung a long flag at eye level near the plot center and a short flag near ground level denoting the plot center. The plot number, date, cruiser's initials, and the direction of travel (e.g., 35 degrees Azimuth) were recorded on the flag at eye level. At each road crossing, one long flag was hung with the number of the next cruise plot and the direction of travel (135 degrees Azimuth), cruiser initials and date.

2008

Similar to the initial inventory, plots were located on a grid that was provided from a GIS for the property. Plots were located on a grid pattern spaced 5.0 chains (330 feet) apart, resulting in one plot for every 2.5 acres. Plots were pre-numbered and displayed on maps supplied to the cruisers. Plots were located accurately in the field using a map, compass, pacing, and GPS as necessary to establish plots within one chain of the desired location.

Plots installed in 2008 were monumented using 16-inch lengths of rebar driven into the ground so that only 3-4 inches of each was above ground. The above ground portions of rebar were painted day-glow orange to aid potential efforts to relocate plot centers in the future. Additionally, GPS coordinates of each plot center were recorded and witness tags were installed on nearby trees or other markers to help future relocation efforts. Each tag contained the plot number, true bearing, and slope distance to the center stake. Lastly, a 3-inch wide white band was painted around a witness tree at breast height.

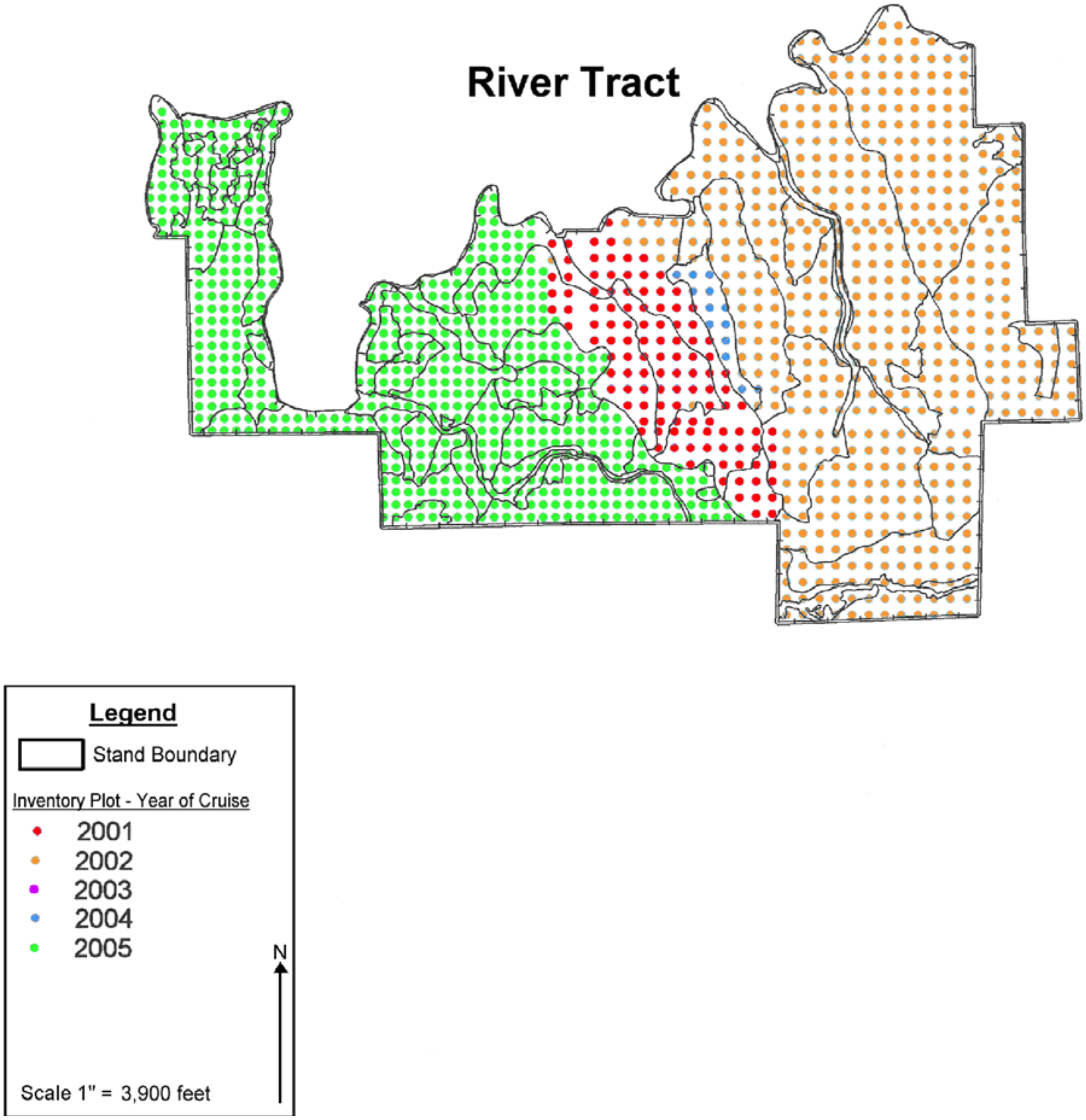


Figure 3. Plot map for live and standing dead tree inventory on the River Tract (2001-2005).

Plot Configurations and Measurement Standards

2001-2004

Each primary plot location consisted of a set of nested plots—a variable radius plot for larger trees and a fixed plot for smaller trees. Primary plots were taken using a variable radius plot with a 20 BAF prism. Trees 4.6 inches diameter at breast height (DBH) and larger were tallied for species and DBH to nearest inch. Snags greater than 10 inches DBH were measured for condition and DBH. A subsample of live measure trees also was taken at each primary plot using a prism with a BAF of 60, recording the species, DBH, total height and crown ratio. Measure trees that were snags were recorded for condition, DBH and total height.

A 1/250th acre regeneration plot (radius of 7.45 feet) was used to measure trees less than 4.6 inches DBH. Cruisers tallied up to ten of the most significant trees that were believed would become free to grow, recording species and DBH class for each tree.

Secondary plots were taken midway between primary plots using a variable radius plot with a 20 BAF. The cruiser tallied trees 4.6 inches DBH and larger by species only, and snags greater than 10 inches DBH by condition.

2005

Each plot location consisted of a set of nested plots—a variable radius plot for larger trees and a fixed plot for smaller trees. Volume plots were taken using a variable radius plot with a 20 BAF. Only trees 7.6 inches DBH and larger were tallied for species and DBH to the nearest inch. Snags greater than or equal to 12 inches DBH and 12 feet in height were measured for condition, DBH and height. A subsample of live measure trees was taken using a BAF of 60. These trees were measured for species, DBH, total height and crown ratio.

A 1/100th acre regeneration plot (radius of 11.78 feet) was used to measure trees less than 7.6 inches DBH. Cruisers tallied up to eight of the most significant trees that appeared to be free to grow. Trees were tallied by species, DBH class, height and live crown ratio. The frequency was recorded when a record represented more than one tree.

2008

Each plot location consisted of a set of nested plots—a variable radius plot for larger trees and a fixed plot for smaller trees. Volume plots were taken using a variable radius plot with a 20 BAF. Live and dead trees 4.6 inches DBH and larger were tallied for species and DBH to the nearest inch. For live trees, live crown was estimated to the nearest 10%. For dead trees, the decay condition was also recorded. Live and dead measure trees were taken using a BAF of 54. These trees were measured for species, DBH, total height and crown ratio.

A 1/100th acre regeneration plot (radius of 11.78 feet) was used to measure trees less than 4.6 inches DBH but above 0.6 inches DBH. The same information as was recorded for trees in volume plots was recorded for live, dead and measure trees in each regeneration plot.

Table 2 below shows a side-by-side comparison of the cruise designs and measurement standards used for the 2001-2004, 2005 and 2008 live and standing dead tree inventories.

Tolerance Standards

Check cruising was conducted on 10% of the plots in each year measurements were taken. The check cruise standards for specified data attributes developed to be consistent with the requirements of the Forest Protocol are listed in Table 3.

Table 2. Cruise designs and measurement standards for the 2001-2004, 2005 and 2008 inventories.

Inventory	**2001-2004**	**2005**	**2008**
Plot Spacing	6.67 chains (440 feet)	5.0 chains (330 feet)	5.0 chains (330 feet)
Plot Density	1 plot per 4.4 acres	1 plot per 2.5 acres	1 plot per 2.5 acres
Primary Plot			
Plot Type	Variable radius	Variable radius	Variable radius
Basal Area Factor	20	20	20
Data Recorded For Each Tallied Tree	- Species (“Hard” or “Soft” recorded for dead trees rather than species) - DBH (live trees >4.6”, dead trees >9.6”) by 1” class	- Species (“Hard” or “Soft” recorded for dead trees rather than species) - DBH (live trees >7.6”, dead trees >11.6”) by 1” class	- Species (including dead trees) - DBH (live and dead trees >4.6”) by 1” class - Decay class for dead trees (Harmon et al. 2007)
Measure Tree Subplot			
Plot Type	Variable radius	Variable radius	Variable radius
Basal Area Factor	60	60	54
Data Recorded For Each Tallied Tree	- Species (“Hard” or “Soft” recorded for dead trees rather than species) - DBH (live trees >4.6”, dead trees >9.6”) by 1” class - Height by 1’ class - Live crown ratio to nearest 10% class	- Species (“Hard” or “Soft” recorded for dead trees rather than species) - DBH (live trees >7.6”, dead trees >11.6”) by 0.1” class - Height by 1’ class - Live crown ratio to nearest 5% class	- Species (including dead trees) - DBH (live and dead trees >4.6”) by 1” class - Decay class for dead trees (Harmon et al. 2007) - Height by 1’ class - Live crown ratio to nearest 10% class
Regeneration Plot			
Plot Type	Fixed radius	Fixed radius	Fixed radius
Plot Size	1/250th acre (7.45 ft radius)	1/100th acre (11.70 ft radius)	1/100th acre (11.70 ft radius)
Data Recorded For Each Tallied Tree	- Species - DBH (<4.6”) by 1” class	- Species - DBH (<7.6”) by 1” class	- Species - DBH (<4.6”) by 1” class
Secondary Plot			
Plot Type	Variable radius	N/A	N/A
Basal Area Factor	60		
Data Recorded For Each Tallied Tree	Species		

Table 3. Tolerance standards applied to plots evaluated during check cruising.

Measurement Theme	Tolerance Standard
Species	Incorrect species cannot exceed 1 in 10 plots checked.
DBH	85% of the trees must match the actual tree DBH class. Of those trees that do not meet this standard, 90% must be within one DBH class. The remaining DBHs may vary by more than 2 classes.
Total Height	±10% of the actual tree height for heights up to 100 feet and ±10 feet for heights greater than 100 feet. Collectively, the recorded heights cannot demonstrate a significant bias compared to the actual heights.
Live Crown Ratio	85% of the trees must match the actual live crown ratio. Of those trees that do not meet this standard, 90% must be within a 10% class of the actual. The remaining can be up to 15% different than the actual.
Missed or Added Trees	The balance of missed or added trees cannot exceed ± 1 tree per 10 plots checked.

Stratification of Stands

Prior to sampling, both the Bear Tract and the River Tract were stratified into stands with relatively homogenous characteristics of species, size and density. Stratification was conducted using aerial photography and digitized for analysis in a GIS. Within the GIS, plot locations were overlaid with stand boundaries to determine the stand type assignment for each plot. Assigning a stand type to each plot allowed stand and volume tables to be developed and expanded by acreage in each stand type.

Data Recording, Storage and Organization

All cruise data was collected either on "Write-in-the Rain" cruise cards or on a handheld device or personal digital assistant (PDA). Data from the cards were entered into a Microsoft Access database form, whereas data from the handheld device or PDA was uploaded to a desktop computer on a consistent basis and hard copies printed.

Data gathered from these sources are maintained and managed within a dedicated database for the project site. This system allows the user to input data, fill in missing heights and live crown ratios, calculate volumes, perform harvest depletions, and project growth.

Data are organized in a hierarchical manner and are represented at the tree, plot and stand level. Individual tree measurements, as outlined above, from a given plot location comprise plot level data. Data from the plot level are then statistically expanded within a stand to create what is commonly referred to as a "tree list." This tree list is a statistical representation of the individual trees that comprise a given stand, based on the sample data.

Volume and Biomass Calculations

Both timber volume (in board feet or thousands of board feet) and biomass (in kilograms or tons) were calculated for individual trees represented in the stand tree lists. Timber volume and biomass may be derived from the same inventory data, yet one is not required to calculate the other. In other words, timber volume does not need to be calculated in order to determine the amount of biomass. Nor does biomass need to be calculated in order to determine the timber volume. Nonetheless, calculating both from the same inventory data serves several purposes. The equations and algorithms used to calculate timber volume have been thoroughly tested and, generally, are a part of common practice in the timber industry in the vicinity of the project. Thus, timber volume calculations have a relatively high degree of certainty associated with them. On the other hand, biomass equations such as those used in this study have not received the same amount of use, especially in the way they are applied here. However, since the same inventory data is used to calculate both timber volume and biomass and since there is a logical relationship between timber volume and biomass (i.e. an increase in timber volume means there is a similar increase in biomass), it is reasonable to use timber volume calculations for quality assurance purposes to ascertain whether biomass calculations seem as though they are being applied properly. This is particularly important when it comes to modeling future biomass stocks, as is described later in this report.

The equations provided by version 2.1 of the Forest Project Protocols, indicated in Table 4, were used to calculate the above- and below-ground biomass pools. Above-ground biomass was calculated for individual trees within the tree list for each stand. Individual above-ground biomass was then converted to a per hectare density value in order to calculate below-ground biomass density. Combining the above-ground and below-ground values produced a total tree biomass density value. In order to convert this value to carbon tons per acre, biomass values are multiplied by 0.5 to convert from biomass to carbon and by 0.001 to convert from kilograms to metric tons, as specified by the Forest Project Protocols, and divided by 2.471 to convert from per hectare to per acre.

Table 4. Equations for tree species biomass estimates.

Above-Ground		
Species	**Biomass (kg) Equation**	**Limitations**
Coast Redwood	*Exp*(-2.0336 + 2.2592 x ln DBH)	Max DBH = 250 cm
Giant Sequoia		
Incense Cedar		
Douglas Fir	*Exp*(-2.2034 + 2.4435 x ln DBH)	Max DBH = 210 cm
Pinus spp.	*Exp*(-2.5356 + 2.4349 x ln DBH)	Max DBH = 180 cm
Abies spp.	*Exp*(-2.5384 + 2.4814 x ln DBH)	Max DBH = 230 cm
Quercus spp.	*Exp*(-2.0127 + 2.4342 x ln DBH)	Max DBH = 73 cm
Tanoak	*Exp*(-2.4800 + 2.4835 x ln DBH)	Max DBH = 56 cm
Below-Ground		
BBD = *Exp*(-0.7747 + 0.8836 x ln ABD)		

- Above-Ground Biomass Equations originally published by Jenkins *et al.* (2003)
- Below-Ground Biomass Equation originally published by Cairns *et al.* (1997)
- DBH = diameter at breast height in centimeters
- BBD = below-ground biomass density (tons/hectare)
- ABD = above-ground biomass density (tons/hectare)

Inventory Updating

All inventory data recorded for the initial inventory were updated at the end of each year, through the project start at the end of 2006, to reflect harvest and growth. Harvest volumes from bureau scale summaries were depleted from the inventory within database for the 2001 through 2005 period prior to project initiation in 2006. Depletions were taken only from stands in which harvest occurred and were implemented in such a fashion as to accurately reflect the harvest by species and DBH classes. Clearcuts and shelterwood removals were completely or nearly completely depleted, respectively. Depletions were taken from the beginning of the year inventory. Once depletions were completed in a given year, a growth simulation was conducted for one growing season.

Growth estimates were conducted using the California Conifer Timber Output Simulator (CACTOS), version 6.3 (Wensel *et al.* 1986; http://www.cnr.berkeley.edu/~wensel/cactos/cactoss.htm). Growth models within CACTOS were adjusted and validated based on permanent plot data from this and adjacent ownerships. Fifteen years of growth data and stem analysis plots were used in developing and improving the modeling effort. CACTOS has proven to be a reliable growth estimator for managed stands of low to moderate stand densities. CACTOS may overestimate growth in stands that do not receive intermediate treatments. An ongoing inventory process will help to reduce the effects of an over-reliance on the growth model. The results from this study reflect growth estimates that are well within the parameters of the model.

Since the initial inventory data were collected over a number of years, stands inventoried prior to the start of project activity were grown out so that estimates of volume and biomass for baseline conditions in all stands were based on the same point in time, i.e. the start of project activities in 2006.

Statistical Calculations

The Forest Project Protocols require that project submitters address the level of statistical confidence they have in the estimates of carbon pools that are reported. Only projects for which the sampling error is within 20% of the estimate of the mean at the 90% confidence level *for all pools combined* are eligible to be registered with the Reserve. If the standard error is below 20% but above 5%, a deduction is applied to the estimated carbon stocks so that the amount of stocks eventually registered account for the degree of uncertainty associated with the inventory.

The mean carbon stock estimates from the stratified sampling methods outlined above served as the basis for evaluating the standard error at the 90% confidence level. Only stands that were sampled and, thus, have statistical information were used in the calculations. The standard error of the mean carbon tons per acre for each stand was determined from the sample variance between sample plots within a given stand. The standard error for individual stands were then weighted by stand acreage and combined to determine the cumulative standard error at the 90% confidence level for each tract.

2.2.3 Lying Dead Wood Inventory Methodology

The purpose of the lying dead wood inventory was to determine the amount of lying dead wood (down woody debris) on the Bascom Pacific Forest, using methods that are consistent with the Forest Project Protocols for estimating carbon in lying dead wood. The project site was first sampled for lying dead wood in 2007. After conducting this initial inventory, it was determined that the minimum specification for the measurement of the diameter of lying dead wood pieces did not meet the measurement standards of the Protocols. The Protocols specify that the minimum average diameter to be measured is 6 inches for pieces at least 10 feet long. The measurement specification for the 2007 inventory was a minimum diameter of 10 inches at the large end of the piece. As a result, a variety of piece sizes likely were not captured by sampling though they should have been. For example, a 10 foot long piece that has a large end diameter of 9 inches and a small end diameter of 5 inches (thus, an average diameter of 7 inches) would not be included as part of the inventory. Omitting such pieces would lead to an underestimation of lying dead wood stocks. To address this initial error, the lying dead wood pool was resampled in 2008 along with the resampling of standing live and dead trees, with the diameter specification adjusted to conform to the measurement standards of the Forest Protocols.

Plot Spacing, Configuration and Locations

The method chosen to inventory lying dead wood for the project site in 2007 was a fixed area plot design. To maximize data collection efficiency, long rectangular plots measuring 5 chains (330 feet) long by 0.5 chains (33 feet) wide, placed end to end across an entire section (where possible) were measured. This design allowed the cruiser to walk the center line of the plot using a string box to record distance, while estimating the plot perimeter location at 16.5 feet either side. Layout of the plots involved placing a string of fourteen (14) consecutive plots in cardinal directions, separated by 10 chains between strings of plots, in each ½ section of ownership. This design allowed the cruiser to travel out on one line and back on the adjacent line where possible. Pairs of strings were separated by 30 chains. Full sections had 56 plots, ½ sections had 28 plots, ¼ sections had 14 plots, and 40 acre blocks had at least 3 plots. Sampling intensity averaged 1 plot per 11.4 acres, or 2.2%. See Figures 4 and 5 below for plot locations in 2007.

Sampling of lying dead wood in 2008 was based on three transects radiating from the same plot centers used to sample standing live and dead trees (see *Plot Locations* in *2.2.2. Live and Standing Dead Tree Inventory Methodology* above). Transects were 22 feet in horizontal distance and radiated from the each plot center at true bearings of 360°, 120° and 240°.

Measurement Specifications

2007

The minimum specification for measurement of a piece of lying dead wood was:

1. ≥10 inches diameter inside bark at the large end
2. ≥10 feet long within the plot
3. >50% of the log diameter is above ground.

For each lying dead wood piece, the following items were recorded:

1. Plot number
2. Average diameter inside bark of the piece in inches measured at the midpoint of its length using a biltmore stick
3. Length of the piece within the plot boundary in feet using a logger's tape
4. Decay status (hard, intermediate or soft).

Decay status was determined by kicking with the boot. A piece was considered hard if the kick bounced off without leaving a mark, intermediate if the kick left a dent in the log, and soft if the kick penetrated the log.

2008

A piece of lying dead wood was tallied if the transect crossed its long axis and met the following minimum specifications:

1. ≥3 inches diameter outside bark where the transect crosses the piece
2. ≥1 foot long
3. >50% of the log diameter is above ground.
4. Not in decay classes 4 or 5 (see below).

For each lying dead wood piece, the following items were recorded:

1. Piece Number, counting along each transect, starting at plot center.
2. Species, if discernable.
    - OH for Hardwood or OC for Conifer if species is not apparent.
    - Record 'NT' for any transect without any pieces tallied.
3. Decay class (Harmon *et al*. 2007):
    - Tally only pieces in classes 1 through 3. Classes 4 and 5 are considered part of the forest floor; a carbon pool not tracked in this analysis. .
    - 1: Leaves still attached and all having intact bark, fine twigs, and branches. Logs originating from cutting may not have branches and twigs, but the cuts appear fresh and have not yet turned gray due to sun bleaching.
    - 2: Starting to decompose, leaves largely are absent, and many of the fine twigs have fallen off the larger branches. Bark is typically loose, but only starting to fall off the log. For all species, there is evidence the surface layers of the wood are decomposing, but the inner, central region of the wood is undecayed unless previously infected with heart rots. For logs originating from cutting, the ends are gray from sun bleaching.
    - 3: Only a few large branches remaining, often in the form of stubs, the bark is falling off in large patches, and evidence of sloughing of sapwood is also evident. The outer wood is easily crushed by hand, although the inner portions can appear completely sound. Are able to support their own weight along most of their length. For certain genera with decay resistant heartwoods, such as *Calocedrus*, *Quercus*, and *Thuja*, decayed sapwood may fall off to the extent that relatively sound heartwood may form the outer surface.
    - 4: Logs cannot support their own weight and most of their length conforms to the contours of the underlying ground. Although circular cross-sections can remain, much of the log forms an elliptical cross-section. Branches, if present, are short stubs, which move when pulled. This indicates decay has spread to the innermost portions of the log and has weakened the wood considerably. Bark, if present, is in small loose patches on the log and found in piles alongside or under the log. In the

case of the genera *Betula* and *Prunus*, the bark loosely surrounds the inner, highly decomposed wood.

- 5: The most decomposed, of elliptical shape (the long axis is often many times that of the short axis), and are beginning to be incorporated into the forest floor. The wood is extremely decayed, usually in the form of cubical brown rot that can be easily crushed by hand. Bark is not evident from the surface (except for the genera *Betula* and *Prunus*) and in most cases underlies the extremely decomposed wood.

4. Diameter outside bark, perpendicular to the long axis where the transect crosses the piece.
5. Length, in feet.

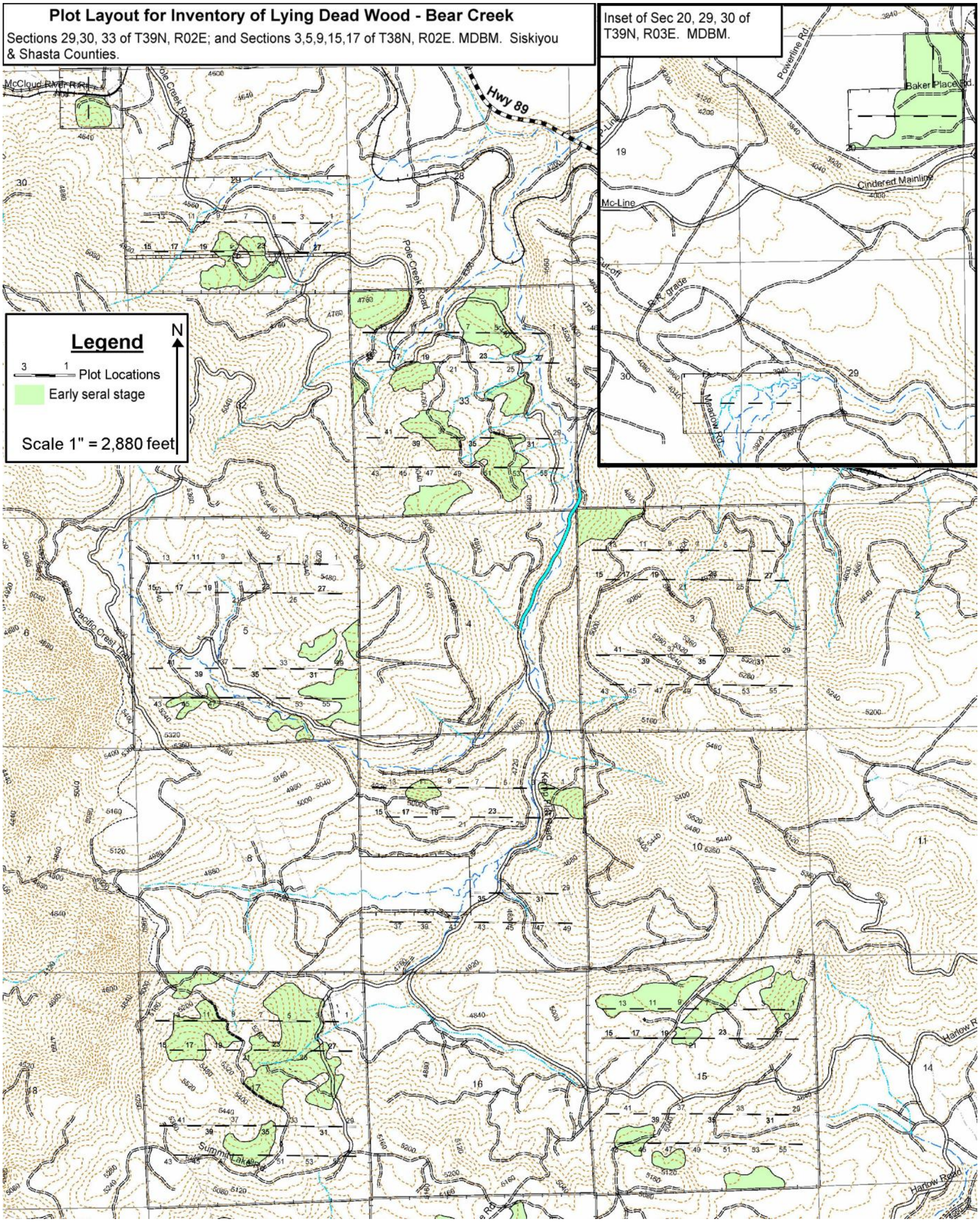


Figure 4. Plot map for lying dead wood inventory on the Bear Tract (2007).

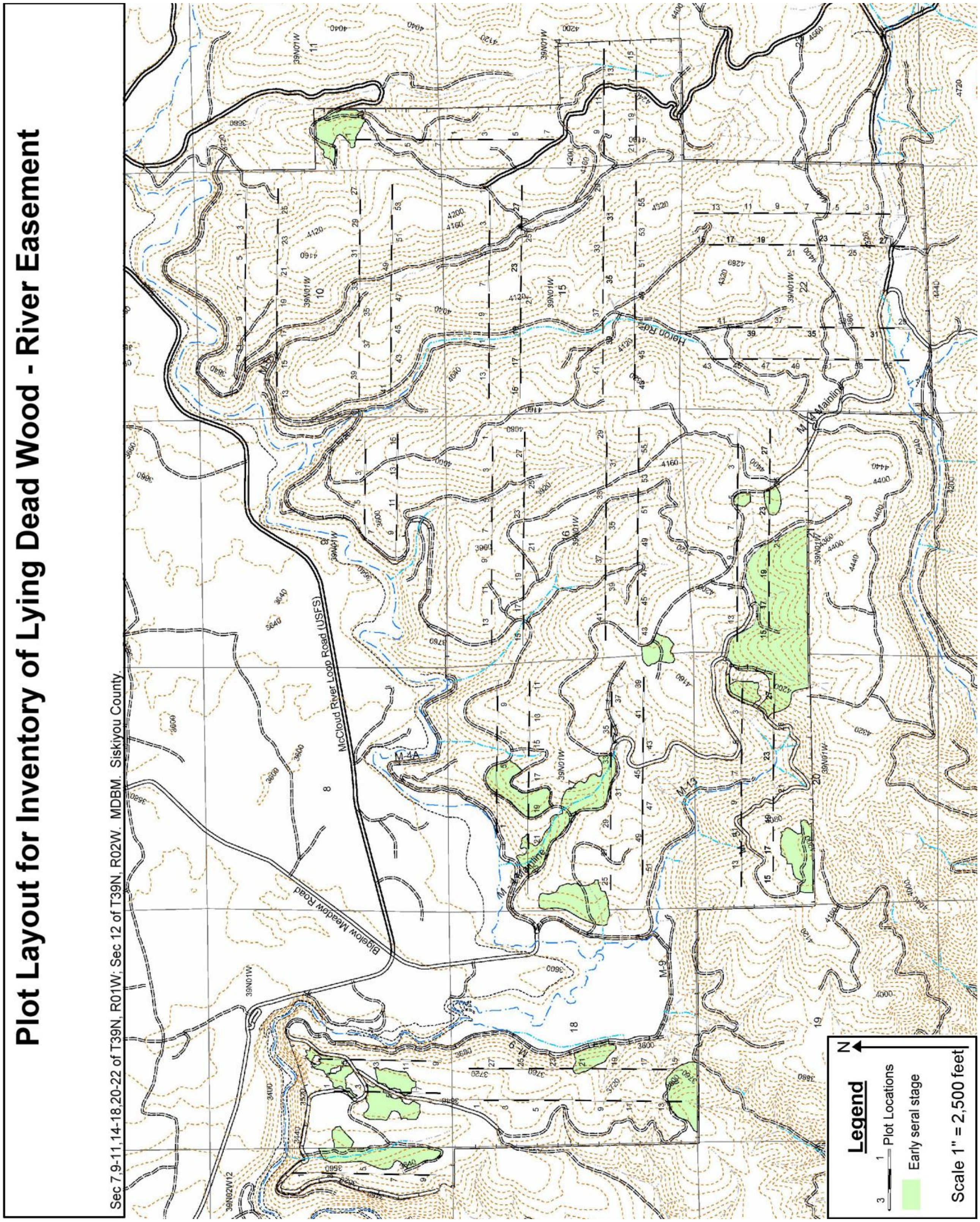


Figure 5. Plot map for lying dead wood inventory on the Bear Tract (2007).

Data Storage and Volume Calculations

Data were entered into a Microsoft Access database. Cubic foot volumes were calculated for each piece using the formula Cubic Feet (ft3) = 0.005454 x (Diameter in inches)^2 x Length (ft). Volumes of lying dead wood were determined by section, and tract. Conversion factors (Tables 5 and 6) were used to convert cubic volume by decay status to weight in metric tons for the 2007 and 2008 lying dead wood inventories.

The amount of carbon was determined by multiplying the lying dead wood biomass (metric tons) by 0.50 as defined in Forest Project Protocol. Plot-based values were then expanded to determine the overall lying dead wood carbon stocks on the Bascom Pacific Forest. The mean carbon stock estimates served as the basis for statistical analysis at the 90% confidence level. Standard error of the mean carbon per acre for the project site was determined from the sample variance between plots in 2007, and between strata in 2008.

Table 5. Dead wood densities (from Brown *et al.*, 2004) used to convert cubic volume to biomass dry weight for 2007 inventory.

Decay Status	Sierran Mixed Conifer Species Dead Wood Density (g/cm^3)**	Density in metric tons per cubic feet (t/ft^3)
Hard	0.50	0.0142
Intermediate	0.32	0.0091
Soft	0.17	0.0048

Table 6. Dead wood absolute densities used to convert cubic volume to biomass dry weight for 2008 inventory.

Decay Class	1	2	3	4	5
Species	*Absolute Density*				
Black Oak	0.611	0.450	0.382	0.241	0.248
Black Cottonwood	0.370	0.422	0.300	0.160	0.110
Douglas-fir	0.386	0.308	0.152	0.123	0.148
Incense Cedar	0.425	0.269	0.231	0.156	0.143
Jeffrey Pine	0.365	0.358	0.217	0.205	0.171
Knobcone Pine	0.368	0.324	0.273	0.169	0.171
Lodgepole Pine	0.378	0.367	0.276	0.169	0.164
Other Conifer	0.340	0.277	0.121	0.138	0.122
Other Hardwood	0.533	0.422	0.325	0.212	0.158
Pacific dogwood	0.533	0.422	0.325	0.212	0.158
Ponderosa Pine	0.338	0.333	0.330	0.129	0.188
Quaking Aspen	0.353	0.422	0.299	0.160	0.110
Red Alder	0.386	0.326	0.197	0.108	0.117
Red Fir	0.478	0.378	0.150	0.143	0.084
Sugar Pine	0.369	0.267	0.155	0.122	0.171
White Fir	0.340	0.277	0.121	0.138	0.122
Willow	0.533	0.422	0.325	0.212	0.158

3.0 Carbon Inventory Results

Summaries for the conventional timber inventory and the carbon inventory have been compiled for the project area for the project initiation year of 2006, as well as for project monitoring that took place in 2008. Summaries at the project level provide the total and per acre volume and carbon stocks by species, as well as total volume and carbon stocks by diameter at breast height for each species.

3.1 Standing Timber Volume and Carbon Stocks

Total net volume, in thousands of board feet (MBF), and carbon stocks, in metric tons, by species for each tract and the project area are shown in Table 7.

Tables 8 and 9 display the timber volume and standing carbon stocks by diameter at breast height (DBH) and species for the project site in 2006 and 2008, respectively.

Table 7. Total net timber volume and standing above-ground live and dead carbon stocks for the project site at project initiation in 2006 and mid-project in 2008.

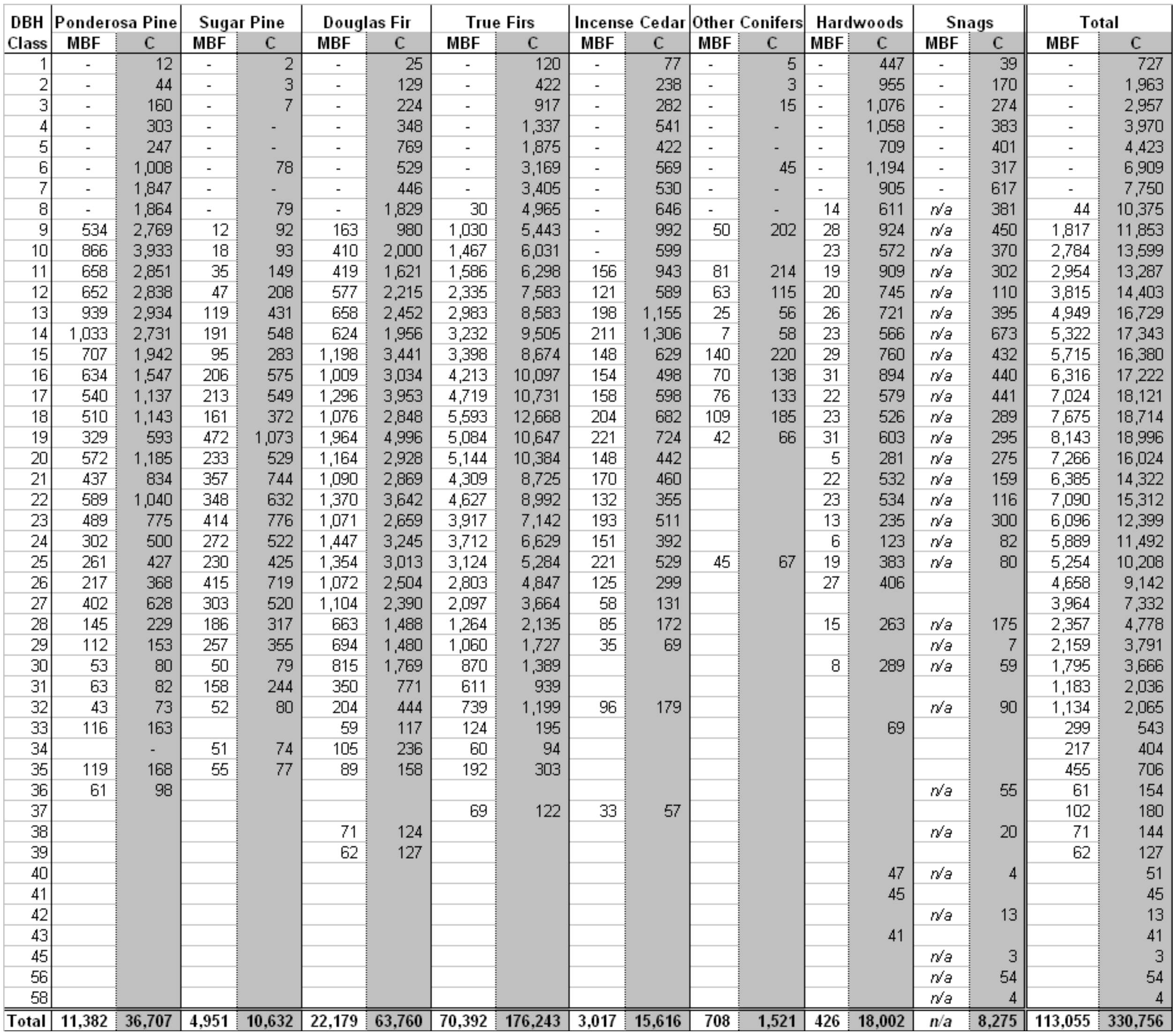
	Species	Total Volume (MBF*)	Volume Density (MBF/acre)	Above-Ground Carbon (metric tons)	Above-Ground Carbon Density (metric tons/acre)
2006	Ponderosa Pine	6,638	0.7	27,267	3.0
	Sugar Pine	4,357	0.5	9,931	1.1
	Douglas-Fir	16,733	1.8	51,697	5.6
	True Firs	60,559	6.6	158,555	17.2
	Incense Cedar	1,879	0.2	13,954	1.5
	Other Conifers	216	0.0	909	0.1
	Hardwoods	1,524	0.2	30,603	3.3
	Snags	*n/a*	*n/a*	*3,142*	0.3
	Total	**91,906**	**10.0**	**296,058**	**32.2**
2008	Ponderosa Pine	11,382	1.3	36,707	4.0
	Sugar Pine	4,951	0.5	10,632	1.2
	Douglas Fir	22,179	2.4	63,760	7.0
	True Firs	70,392	7.8	176,243	19.4
	Incense Cedar	3,017	0.3	15,616	1.7
	Other Conifers	708	0.1	1,521	0.2
	Hardwoods	426	0.0	18,002	2.0
	Snags	*n/a*	*n/a*	*8,275*	0.9
	Total	**113,055**	**12.5**	**330,756**	**36.4**

** Total net MBF (Scribner Short Log Scale - 6” Top)*

Table 8. Total net timber volume (MBF) and standing carbon stocks (metric tons) by DBH class and species for the Bascom Pacific Forest in 2006. Carbon stocks account for above-ground biomass only.

DBH Class	Ponderosa Pine		Sugar Pine		Douglas-Fir		True Firs		Incense Cedar		Other Conifers		Hardwoods		Snags		Total	
	MBF	C	MBF	C	MBF	C	MBF	C	MBF	C	MBF	C	MBF	C	MBF	C	MBF	C
1	-	54	-	6	-	62	-	241	-	209	-	2	-	49			-	624
2	-	84	-	11	-	171	-	707	-	171	-	6	-	233			-	1,384
3	-	78	-	8	-	123	-	471	-	175	-	9	-	1,283			-	2,146
4	-	485	-	19	-	533	-	1,003	-	516	-	8	-	4,309			-	6,873
5	-	459	-	19	-	421	-	1,464	-	538	-	-	-	3,723	n/a	21	-	6,644
6	-	947	-	111	-	539	-	2,601	-	649	-	62	-	5,399	n/a	18	-	10,327
7	-	1,276	-	119	-	817	-	2,870	-	738	-	15	-	2,483	n/a	60	-	8,379
8	3	2,970	-	62	26	1,110	130	4,843	-	730			11	1,693	n/a	55	171	11,463
9	202	2,113	8	100	110	1,055	604	4,873	-	915	6	130	25	1,033	n/a	18	954	10,237
10	385	2,657	20	156	263	1,817	1,184	7,047	16	902	2	22	60	1,340	n/a	105	1,930	14,046
11	382	2,243	41	238	311	1,512	1,324	6,215	81	896	13	90	59	849	n/a	120	2,212	12,164
12	447	2,057	70	316	418	1,947	2,330	8,479	109	980	29	109	136	1,461	n/a	259	3,537	15,609
13	397	1,397	108	401	493	1,968	2,439	7,842	98	815	34	133	50	440	n/a	167	3,620	13,163
14	449	1,460	86	260	805	2,885	3,182	9,270	138	885	9	30	101	757	n/a	250	4,770	15,798
15	283	849	105	315	749	2,445	2,632	6,973	68	383	16	50	115	766	n/a	192	3,967	11,973
16	451	1,210	196	599	1,013	3,206	4,915	12,231	164	778	5	13	182	1,106	n/a	303	6,926	19,447
17	463	1,010	101	295	944	2,777	3,590	8,361	65	262	14	47	118	654	n/a	183	5,294	13,590
18	536	1,172	260	602	1,149	3,271	5,278	11,628	145	576	20	41	101	528	n/a	223	7,488	18,041
19	270	551	219	490	1,088	2,922	3,849	8,173	119	430	4	11	98	481	n/a	101	5,647	13,160
20	443	909	357	786	1,211	3,185	4,984	10,125	154	497	12	25	62	294	n/a	171	7,223	15,993
21	255	459	249	547	1,138	2,864	3,214	6,267	120	369	26	56	77	349	n/a	89	5,078	11,000
22	520	1,003	379	729	1,037	2,563	4,463	8,445	90	273	11	20	74	321	n/a	110	6,574	13,465
23	160	300	209	433	905	2,223	3,047	5,612	76	218	17	30	58	246	n/a	46	4,472	9,107
24	327	522	245	453	897	2,158	3,408	6,259	84	248			40	163	n/a	42	5,000	9,846
25	145	253	187	350	754	1,760	2,846	4,989	85	228			34	136	n/a	16	4,052	7,732
26	91	146	153	271	824	1,792	2,193	3,725	70	165			19	76	n/a	43	3,350	6,219
27	106	161	286	504	577	1,293	1,101	1,829	57	134			5	20	n/a	15	2,133	3,956
28	159	219	254	412	509	1,110	1,258	2,068	39	83			34	127	n/a	51	2,252	4,069
29	37	46	141	233	352	757	797	1,263	5	12			6	24			1,339	2,335
30	68	90	238	374	405	892	705	1,099	12	26			14	53	n/a	85	1,443	2,618
31	3	4	193	321	157	306	418	620	11	23			19	75			801	1,349
32	36	52	106	171	159	335	197	291	5	10					n/a	53	502	912
33	-	-	64	96	82	171	56	84					6	28	n/a	9	209	389
34	20	24	45	65	96	191	182	260	8	12			11	55	n/a	28	361	635
35	3	4	11	18	138	267	56	98	18	33					n/a	23	227	443
36	1	1			33	70	38	49	20	39					n/a	26	91	185
37					11	26	30	41					4	24			45	91
38					19	40							4	23	n/a	35	22	98
39			26	41	60	113			3	5							89	158
40							81	102							n/a	63	81	165
41							27	38									27	38
42															n/a	9	n/a	9
47															n/a	9	n/a	9
48															n/a	55	n/a	55
49															n/a	11	n/a	11
57									21	31							21	31
60															n/a	14	n/a	14
64															n/a	12	n/a	12
70															n/a	34	n/a	34
80															n/a	13	n/a	13
Total	**6,638**	**27,267**	**4,357**	**9,931**	**16,733**	**51,697**	**60,559**	**158,555**	**1,879**	**13,953**	**216**	**909**	**1,524**	**30,603**	**n/a**	**3,142**	**91,906**	**296,058**

Table 9. Total net timber volume (MBF) and standing carbon stocks (metric tons) by DBH class and species for the Bascom Pacific Forest in 2008. Carbon stocks account for above-ground biomass only.



DBH	Ponderosa Pine		Sugar Pine		Douglas Fir		True Firs		Incense Cedar		Other Conifers		Hardwoods		Snags		Total	
Class	MBF	C	MBF	C	MBF	C	MBF	C	MBF	C	MBF	C	MBF	C	MBF	C	MBF	C
1	-	12	-	2	-	25	-	120	-	77	-	5	-	447	-	39	-	727
2	-	44	-	3	-	129	-	422	-	238	-	3	-	955	-	170	-	1,963
3	-	160	-	7	-	224	-	917	-	282	-	15	-	1,076	-	274	-	2,957
4	-	303	-	-	-	348	-	1,337	-	541	-	-	-	1,058	-	383	-	3,970
5	-	247	-	-	-	769	-	1,875	-	422	-	-	-	709	-	401	-	4,423
6	-	1,008	-	78	-	529	-	3,169	-	569	-	45	-	1,194	-	317	-	6,909
7	-	1,847	-	-	-	446	-	3,405	-	530	-	-	-	905	-	617	-	7,750
8	-	1,864	-	79	-	1,829	30	4,965	-	646	-	-	14	611	n/a	381	44	10,375
9	534	2,769	12	92	163	980	1,030	5,443	-	992	50	202	28	924	n/a	450	1,817	11,853
10	866	3,933	18	93	410	2,000	1,467	6,031	-	599			23	572	n/a	370	2,784	13,599
11	658	2,851	35	149	419	1,621	1,586	6,298	156	943	81	214	19	909	n/a	302	2,954	13,287
12	652	2,838	47	208	577	2,215	2,335	7,583	121	589	63	115	20	745	n/a	110	3,815	14,403
13	939	2,934	119	431	658	2,452	2,983	8,583	198	1,155	25	56	26	721	n/a	395	4,949	16,729
14	1,033	2,731	191	548	624	1,956	3,232	9,505	211	1,306	7	58	23	566	n/a	673	5,322	17,343
15	707	1,942	95	283	1,198	3,441	3,398	8,674	148	629	140	220	29	760	n/a	432	5,715	16,380
16	634	1,547	206	575	1,009	3,034	4,213	10,097	154	498	70	138	31	894	n/a	440	6,316	17,222
17	540	1,137	213	549	1,296	3,953	4,719	10,731	158	598	76	133	22	579	n/a	441	7,024	18,121
18	510	1,143	161	372	1,076	2,848	5,593	12,668	204	682	109	185	23	526	n/a	289	7,675	18,714
19	329	593	472	1,073	1,964	4,996	5,084	10,647	221	724	42	66	31	603	n/a	295	8,143	18,996
20	572	1,185	233	529	1,164	2,928	5,144	10,384	148	442			5	281	n/a	275	7,266	16,024
21	437	834	357	744	1,090	2,869	4,309	8,725	170	460			22	532	n/a	159	6,385	14,322
22	589	1,040	348	632	1,370	3,642	4,627	8,992	132	355			23	534	n/a	116	7,090	15,312
23	489	775	414	776	1,071	2,659	3,917	7,142	193	511			13	235	n/a	300	6,096	12,399
24	302	500	272	522	1,447	3,245	3,712	6,629	151	392			6	123	n/a	82	5,889	11,492
25	261	427	230	425	1,354	3,013	3,124	5,284	221	529	45	67	19	383	n/a	80	5,254	10,208
26	217	368	415	719	1,072	2,504	2,803	4,847	125	299			27	406			4,658	9,142
27	402	628	303	520	1,104	2,390	2,097	3,664	58	131							3,964	7,332
28	145	229	186	317	663	1,488	1,264	2,135	85	172			15	263	n/a	175	2,357	4,778
29	112	153	257	355	694	1,480	1,060	1,727	35	69					n/a	7	2,159	3,791
30	53	80	50	79	815	1,769	870	1,389					8	289	n/a	59	1,795	3,666
31	63	82	158	244	350	771	611	939									1,183	2,036
32	43	73	52	80	204	444	739	1,199	96	179					n/a	90	1,134	2,065
33	116	163			59	117	124	195						69			299	543
34		-	51	74	105	236	60	94									217	404
35	119	168	55	77	89	158	192	303									455	706
36	61	98													n/a	55	61	154
37							69	122	33	57							102	180
38					71	124									n/a	20	71	144
39					62	127											62	127
40														47	n/a	4		51
41														45				45
42															n/a	13		13
43														41				41
45															n/a	3		3
56															n/a	54		54
58															n/a	4		4
Total	**11,382**	**36,707**	**4,951**	**10,632**	**22,179**	**63,760**	**70,392**	**176,243**	**3,017**	**15,616**	**708**	**1,521**	**426**	**18,002**	***n/a***	**8,275**	**113,055**	**330,756**

3.2 Lying Dead Wood Carbon Stocks

Total lying dead wood carbon stocks for each Public Land Survey System section (or portions thereof within the property) and the total project area in 2007 are shown in Table 10.

Total lying dead wood carbon stocks for each 2008 inventory stratum and the total project area are shown in Table 11.

Table 10. Estimates of lying dead wood on the Bascom Pacific Forest, by Public Land Survey System section and in total for 2007.

Location	Carbon Density (metric tons/acre)	Total Carbon (metric tons)
38N02E03	2.01	634.6
38N02E05	0.72	230.2
38N02E09	3.16	930.7
38N02E15	1.53	496.8
38N02E17	2.31	746.2
39N02E29	2.29	365.6
39N02E30	2.31	45.1
39N02E33	2.70	846.1
39N03E20	0.41	24.9
39N03E29	0.00	0.0
39N03E30	0.85	17.3
39N01W07	1.96	165.9
39N01W09	3.03	276.5
39N01W10	5.41	1,645.5
39N01W11	0.79	31.4
39N01W14	6.01	707.4
39N01W15	3.87	1,212.3
39N01W16	3.34	1,062.9
39N01W17	2.25	697.5
39N01W18	3.60	605.3
39N01W20	2.39	377.0
39N01W21	3.54	555.2
39N01W22	2.28	742.8
39N02W12	1.91	68.6
Average	**2.72**	**12,486**

Table 11. Estimates of lying dead wood on the Bascom Pacific Forest, by Public Land Survey System section and in total for 2008.

Stratum	Carbon Density (metric tons/acre)	Total Carbon (metric tons)
1	2.9	1,058
2	0.4	38
3	0.6	126
4	1.0	412
5	2.3	540
6	1.1	361
7	1.3	298
8	1.6	733
9	1.2	698
10	2.4	1,357
11	2.2	923
12	2.2	1,355
13	4.9	834
14	1.7	1,750
15	2.3	3,113
16	1.1	86
17	2.0	789
18	1.7	1,046
19	3.5	227
20	4.6	791
21	0.5	75
22	3.2	927
23	1.5	416
Average	**2.0**	**17,952**

3.3 Combined Pools

In order to determine the total carbon stocks for the project site all pools were combined. These pools include live trees (above- and below-ground), standing dead trees (above-ground only), and lying dead wood. Table 12 shows the carbon stocks for all pools in both 2006 and 2008.

Standard Error

The estimated mean carbon density for all carbon pools for the initial inventory at the project starting date in 2006 is 41.7 metric tons of carbon per acre. The standard error of the estimate of the mean at the 90% confidence level in 2006 is 1.23% (90% confidence interval: 41.2 – 42.2 metric tons per acre). The estimated mean carbon density for all carbon pools for the 2008 inventory is 47.2 metric tons of carbon per acre. The standard error of the estimate of the mean at the 90% confidence level in 2008 is 3.8% (90% confidence interval: 45.4 – 49.0 metric tons per acre).

Table 12. Total carbon stocks and carbon density within each pool and in total for the Bascom Pacific Forest.

Carbon Pool	2006 Total Carbon (metric tons)	2006 Carbon Density (metric tons/acre)	2008 Total Carbon (metric tons)	2008 Carbon Density (metric tons/acre)
Live Tree	368,544	40.1	402,457	44.3
Standing Dead Tree	3,142	0.3	8,275	0.9
Lying Dead Wood	12,486	1.4	17,952	2.0
Total	384,172	41.7	428,684	47.2

Although the standard error for the 2008 inventory is higher than for the 2006 inventory, we believe the 2008 inventory is a better inventory for several reasons. First, it is based on a single cruise design. Second, sampling for the 2008 inventory was conducted by a single crew. Third, it was conducted in a single year, at the end of the growing season. Each of these factors helps to increase the consistency of the data collection and the standards by which they were gathered, as well as the certainty about the inventory. Also, since the data that served as the basis for the 2006 inventory was gathered over several years prior to 2006, the inventory had to be grown and harvested through the CACTOS growth model. As a result, an additional layer of uncertainty is added to the 2006 inventory due to the uncertainty associated with the use of growth models since they are dependent on assumptions and parameters that do not perfectly reflect conditions on the ground, such as climatic variability and hydrologic conditions.

4.0 Planned Activities to Increase Carbon Stores

4.1 Modeling Baseline and Project Activities

In order to demonstrate that planned activities produce carbon stocks that are additional to the baseline case, changes to current carbon stocks are projected into the future under both the baseline activity scenario and the project activity scenario. These projections are generated with a growth and yield model that is capable of estimating future stand conditions, using current inventory data and specific management activities as input. As per the Forest Protocols, both scenarios are modeled 100 years into the future from the project starting date.

Baseline projections are determined by modeling changes to current carbon stocks under a management regime that approximates a harvest that maximizes the present net value of the timber resource while abiding to all applicable rules and laws. These baseline projections are compared to simulated carbon stock projections resulting from a myriad of possible management strategies that have the potential of developing relative carbon dioxide reductions. The management activities chosen for the Bascom Pacific Forest are based on terms within the Bascom Pacific Conservation Easement. The difference between the baseline scenario for the Bascom Pacific Forest and the project activity scenario represents the potential emissions reductions that could be achieved by the project.

Efforts were taken to establish baseline and project activity management scenarios that would generate conservative estimates of emissions reductions. In other words, the intent was to err on the side of generating fewer emissions reductions. This meant that when discretion was allowed in order to meet the general goals and objectives of modeling management that could occur under the baseline scenario, choices were generally made that would produce an estimate of baseline stocks that was more rather than less. Conversely, within the framework of the general management goals and objectives established for the project activity scenario, modeling was performed in a manner that would produce an estimate of project activity stocks that was less rather than more. Thus, with both scenarios being modeled conservatively within their overarching management goals and objectives, the difference between the two, and hence the reportable emissions reductions, was minimized.

4.2 Overview of Growth and Yield Modeling

Growth and yield modeling is based on ‘growing’ and ‘harvesting’ inventory data associated with the forest. The organization of inventory data usually includes a ‘tree list’ that represents the forest conditions within a forest stand, which is usually managed in a relational database and can be linked to a spatial database in a geographical information system. This section will discuss details of inventory growth and yield modeling. For the Bascom Pacific Project, growth and yield modeling was conducted using CACTOS, a growth model that has been approved by the Reserve for use in this region. Early growth in plantations was modeled using CONIFERS, a young stand simulator (Ritchie, 2008; http://www.fs.fed.us/psw/programs/ecology_of_western_forests/projects/conifers/). A tree list is assigned to each stand based on the stratified sampling process. The tree lists are ‘grown’ and ‘harvested’ based on their silviculture assignments within CACTOS. Modeling results are output on a 5-year basis, with a total modeling period of 100 years as required by the Forest Project Protocols.

4.3 Methodologies and Assumptions used to Model the Bascom Pacific Baseline Activity Scenario

As stated in the Background section, the baseline approach for a forest management project pursuant to version 2.1 of the Forest Protocols is a performance standard approach, reflecting the silvicultural practices required by Option C in sections 913.11, 933.11 and 953.11 of article 3 of the California Forest Practice Rules (14 CCR). The effects of watercourse rules and endangered species laws were also considered in the baseline analysis. Scenario Goal

The baseline activity scenario strived to maximize the net present value of the forest with only legal constraints to harvesting considered.

4.3.1 General Description

The upslope stands (stands outside of watercourse buffers and not part of designated sensitive habitat areas) on the project area sum to approximately 8,250 acres, or 92% of the project area. Watercourse protection areas include approximately 500 acres (a conservative estimate based on GIS-derived stream segment lengths and the maximum buffer widths specified in 14 CCR), or 5% of the project area, and designated sensitive habitat areas include approximately 280 acres, or 3% of the project area. After the area was researched for the presence of Northern Spotted Owls, it was determined that none are present on the property. Therefore no special mitigation is required.

4.3.2 Upslope Stands

The harvesting assumptions incorporated an even-aged harvesting regime on all upslope stands based on 60-year clearcut rotations. This rotation period is based on the regeneration length specified by Option (C) of 14 CCR for evenaged management on Site Class III lands. Option (C) also generally limits the size of clearcuts to 20 acres (allowing for up to 40 acres under certain conditions) and prohibits the clearcutting of adjacent stands. This adjacency rule was managed in the modeling process by partitioning the forest into 4 units of similar acreage, each representing a 5-year harvesting plan. Therefore, all stands that were stocked with trees 60 years or older were to be ‘harvested’ in the baseline model over a 20-year period. Stands were prioritized for harvesting based on their level of stocking – older and better stocked stands were harvested earlier than younger and less stocked stands.

Regeneration in clearcut stands was accomplished by assuming that 300 trees were planted on a per acre basis, where 200 trees were ponderosa pine and another 100 trees were Douglas-fir. An assumed 8% brush cover was also included in the post-harvest stand to mimic real life competitive conditions affecting growth among the seedlings following harvest.

Stands that were modeled with clearcut management were followed up with commercial thinning 45 years later. The thinning strategy removed 30% of the basal area from the stand by harvesting from among the smallest 30% of the diameter classes in the stands. These stands were clearcut a second time 15 years later, 60 years following the initial clearcut harvesting.

Table 13 below displays the acreage harvested under each treatment type in each five-year period for the baseline activity scenario.

4.3.3 Watercourse Stands

Watercourse stands will be harvested in the baseline scenario using single tree selection silviculture methods. The harvest will be limited in each stand to 35% of the standing volume every 10 years. This method approximates the selective harvesting permitted within stream zones while allowing a gradual increase in stand density over time. It is the intent of this harvesting approach to increase the inventory volume over time in this area.

4.3.4 Sensitive Stands

The sensitive stands were not considered for harvest in the baseline activity scenario.

4.4 Methodologies and Assumptions used to Model the Bascom Pacific Project Activity Scenario

As discussed previously in the *Section 1.2 Climate Action Reserve Forest Protocol and Its Key Principles*, a forest management project must demonstrate that it is additional by showing that the planned project activities exceed the applicable mandatory forest management laws used to characterize the project baseline.

The Bascom Pacific Conservation Easement specifies the allowable silviculture activities that can occur. The easement allows for uneven age harvest, as well as variable retention harvest with a maximum opening size of 10 acres. Harvest is limited to 80% of net timber growth per decade until an average conifer board foot stocking level of 25 thousand board feet per acre has been achieved. Harvest of up to 100% of growth can occur at that time.

4.4.1 Scenario Goal

The project activity scenario implemented the goals within the conservation easement.

4.4.2 General Description

The project scenario did not specify different management activities between the upslope stands and the watercourse buffers since only one silviculture activity was applied to all forested stands. The sensitive stands that comprise approximately 3% of the project area were not considered for harvest. Approximately 160 acres of brush-covered stands were present in the upslope areas. As with the baseline activity scenario, since no Northern Spotted Owls are present on the property, no special mitigation was required.

4.4.3 Upslope Stands and Watercourse Stands

These stands were managed with single tree selection. Harvests in these stands occurred every 10 years, which was intended to allow for revegetation of disturbed soils, establishment of regeneration trees, and sufficient volume growth to make the next harvest entry economically feasible. 80% of the growth in these stands was harvested at each entry. If the average conifer stocking level across the property reached 25 thousand board feet, harvest of up to 100% of the growth was allowed at that time.

Table 13 below displays the acreage harvested under each treatment type in each five-year period for the project activity scenario.

4.4.4 Brush-covered Stands

These stands were immediately managed to reduce brush competition to 8% cover on the landscape. Trees were then 'planted' to 200 trees per acre of ponderosa pine and 100 trees per acre of Douglas-fir. These stands were grown for 45 years at which point selection harvests occurred on a 10-year frequency.

Table 13. Acreage harvested under each treatment type by period for both the baseline activity and project activity scenarios.

	Harvest Acreage			
	Baseline Scenario		Project Scenario	
Period Beginning	*Clear-Cut*	*Thinning*	*Clear-Cut*	*Thinning*
2006	1,980	470	146	3,599
2011	1,984			4,638
2016	1,949	470		3,580
2021	1,914			4,638
2026		470		3,580
2031				4,638
2036		513		3,634
2041				4,638
2046	42	624		3,788
2051	93	2,194		4,747
2056		2,454		4,085
2061	193	1,949		4,753
2066	2,222	2,384		4,085
2071	1,984			4,760
2076	1,949	470		4,085
2081	1,914			4,760
2086		470		4,085
2091		42		4,768
2096		563		4,090
2101				4,768

4.5 Methodologies and Assumptions used to Model Wood Products

Carbon stored in wood products is an optional reporting pool under version 2.1 of the Forest Protocols. In recognition of the fact that some amount of live tree carbon continues to be stored in wood products after timber harvest and manufacturing, contributions and changes to carbon stores in wood products were calculated based on projected harvests in both the baseline activity and project activity modeling scenarios.

The authors note that accounting of the long-term stores in harvested wood products net of primary and secondary greenhouse effects (e.g., logging and manufacturing associated losses, fuels combustion from same and transportation, etc.) is difficult if not impossible to ascertain with accuracy at the level of an individual project absent more comprehensive accounting for the forest sector overall and the flow of wood within the forest sector and across to other sectors.

At the project level, unlike on-site forest carbon stocks and flux, post-harvest wood products carbon flows out of the project owner's control; end uses and losses vary widely along the chain of custody; and the ultimate destiny of the harvested wood products carbon is not amenable to independent verification. The best available data on which to base these necessarily general calculations has relatively high uncertainty (Skog communication to the Reserve's Work Group 2009). Nonetheless, this is what has been used to create the wood products in use and in landfills tables utilized in the Department of Energy's 1605(b) program and, by derivation, to underpin the Forest Protocols. The challenge is how to begin to conservatively quantify and account for harvested wood products carbon at the project level given the above constraints. Since the amount of harvested wood products produced under the baseline scenario is generally higher over the course of the project lifetime, a conservative accounting would err on the side of reporting more wood products carbon than less. Thus the baseline stocks would increase relative to the project activity stocks.

Ultimately this accounting challenge needs to be resolved through a comprehensive system that allows forest owners to account for logs delivered to mills net of harvest and transportation based emissions. Losses and continued stores associated with primary and secondary processing, transportation, construction, biomass energy, other uses, landfills, recycling, etc., would be accounted for in their respective sectors. Such an integrated approach to forest accounting would provide the basis for crediting the use of wood over more carbon intensive fuels and building materials in their respective sectors.

In the case of the subject Bascom Pacific project modeling exercise, as with other modeling results, projected harvest volumes are output on a 5-year basis. Since the methodology outlined in the Forest Protocols for calculating changes to the wood products pool incorporates annual decay rates, projected harvest volumes were annualized, with the assumption that the volume of timber harvested during each year within a given 5-year modeling period remained constant. For example, if 5,000 thousand board feet (MBF) were projected to be harvested during a given 5-year model output period, it was assumed that 1,000 MBF was harvested in each of the years during that period.

Annual harvested timber volumes were separated by species and species specific conversion factors were applied to convert from board foot volumes into wood weight and, subsequently, into carbon weight. These carbon weights were then totaled to determine the total weight of carbon harvested for transfer to the wood products pool. But not all wood harvested and delivered to a mill actually makes it into wood products due to inefficiencies in the process to convert a whole log into a finished wood product. As per the Forest Protocols, an efficiency factor of 60 percent is applied to the harvested carbon weight. Thus, 40 percent of the carbon weight is deducted and is considered to be immediately decayed and emitted back to the atmosphere.

The remaining carbon weight is allocated into different wood product classes in order to apply decay rates specific to each product class throughout the project lifetime. Thus, in any given year, the carbon weight harvested and processed into a specific wood product class in a given year is added to the running total weight for that wood products class. Of the wood that actually makes it into finished wood products for this project, it was assumed that 47.5 percent of harvested wood was processed into lumber that was incorporated into single-family homes (post-1980) and into multifamily houses, each a separate wood product class. The remaining 5 percent of harvested wood was assumed to be processed into lumber used for residential maintenance and repair. The allocation of harvested timber into various product classes was determined through discussions with local foresters knowledgeable of the wood products processed by the mills that have received logs from the project site during recent harvests. It was assumed that such mills would continue operation throughout the project lifetime, that they would continue processing the same wood product classes, and that the proportional distribution of logs received by them into the various wood product classes would remain the same.

For each year of the project, the total carbon weight for each wood products class is determined by adding the carbon weight of the wood products processed in the current year to the carbon weight of the wood products in the same class remaining from the previous year. A product class-specific decay rate is then applied to this total carbon weight to determine the amount of carbon that remains sequestered in wood products for the current year. Annual wood products carbon is determined by summing the remaining carbon weights from each individual wood product class. Furthermore, the remaining carbon weights from each individual wood product class are carried forward to calculate the total carbon in each class the following year. Decay rates are provided in the Forest Protocols and are based on the work of Row & Phelps (1996) and Skog & Nicholson (2000), which identify the half-life of carbon by wood product class. The half-life of the wood products classes applicable to this project are as follows: single-family homes (post-1980) = 100 years, multifamily houses = 70 years, and residential maintenance and repair = 30 years. As provided in the Forest Protocols, the general formula used to calculate annual wood products carbon for a given wood product class is as follows:

$$WP = (X + Y) + [(X + Y) * \ln(0.5) / Z]$$

Where:

X = weight of carbon (metric tons) harvested and transferred to the wood product class during the current year

Y = weight of carbon (metric tons) remaining from the previous year

Z = the half life, in years, of the wood product class

This calculation is performed annually for each wood product class based on the projected timber harvest volumes in a given year for each scenario. These results for individual wood product classes are summed to determine the total amount of carbon in wood products each year. In effect, the amount of wood products carbon calculated in a given year (WP_x) becomes the value for Y used to calculate the amount of carbon in the wood products pool the following year (WP_{x+1}).

5.0 Results of Modeling Activities

5.1 On-Site Carbon Pools Modeling Results

Tables 14 and 15 show the results of the modeled projections for the baseline activity scenario and the project activity scenario, respectively. Results in these tables and in the initial comments here indicate on-site carbon pools only. The wood products pool results are indicated in a separate sub-section later.

The baseline scenario carbon stocks follow a pattern typical of evenage-managed forests, whereby timber stocks are rapidly depleted and then regrown at a slower pace over a longer period of time. In this case, a specific rotation length was specified, producing an evident cyclical pattern over 60 years (Figure 6) in which the first 20 years are marked by successive clearcut treatments, followed by a 40-year growth period before the first stands that were harvested may be clearcut again. During the 40 years of growth, commercial thinning entries occur, as specified in the baseline activity scenario description above. Although such treatments cause small reductions in carbon stocks, they serve to stimulate more rapid growth in the residual stand, and thus more rapid carbon sequestration. Clearcutting is projected to reduce carbon stocks on the Bascom Pacific Forest from 384,172 metric tons (41.7 tons/acre) at project initiation in 2006 to 97,783 metric tons (10.6 tons/acre) in 2026. At the start of the second clearcutting cycle in 2066, carbon stocks would reach 507,954 metric tons (55.2 tons/acre) before being reduced to 134,728 metric tons (14.6 tons/acre) in 2086. At the end of the 100-year modeling period, the site would have 307,096 metric tons of carbon (33.4 tons/acre). The total volume harvested under the baseline scenario is projected to be approximately 448,000 thousand board feet.

Under the project activity scenario, the overall carbon stocks on the site are projected to gradually increase over time (Figure 6). This is due to the easement restriction that specifies that, until the average stocking for the site reaches 25 thousand board feet per acre, only 80% of growth may be harvested. Since the stocking on the site is not projected to achieve this threshold during the 100-year modeling period, harvest levels are kept at an average of about 77% of growth. Carbon stocks on the project site are projected to increase from 384,172 metric tons (41.7 tons/acre) in 2006 to 603,458 metric tons (65.6 tons/acre) in 2106. Total harvest volume during the modeling period is projected to be about 418,000 thousand board feet, or approximately 93% of the volume harvested under the baseline scenario.

Emissions reductions that would be expected to be generated by the Bascom Pacific Forest Project are determined by comparing the projected carbon stocks under the project activity scenario over time to those projected under the baseline activity scenario over time. According to the Forest Protocols, subtracting the baseline activity carbon stocks from the project activity carbon stocks in a given year determines the “project carbon” for that year. Project carbon may also be considered the cumulative carbon (or carbon dioxide) reductions generated by a project at that given point in time. As such, a positive project carbon value indicates that more carbon dioxide has been removed from the atmosphere under the project activity scenario than would have been removed under the baseline activity scenario. However, in order to determine annual emissions reductions, the Protocols stipulate that project carbon from the previous year be subtracted from the project carbon from the current year. Thus, a positive difference indicates a reduction in carbon stocks or carbon dioxide emissions from one year to the next, whereas a negative difference indicates an increase is carbon stocks or carbon dioxide emissions.

Figure 6 and Table 16 provide a comparison of the projected baseline activity and project activity carbon stocks throughout the 100-year modeling period, as well as cumulative carbon dioxide reductions and periodic carbon dioxide reductions. In this case, periodic emissions reductions are reported rather than annual emissions reductions since modeling was performed on a 5-year basis. The cumulative CO_2 reductions achieved at the end of the 100-year modeling period are 1,086,466 metric tons (118.1 tons/acre). However, the maximum cumulative carbon dioxide reductions achieved during the project lifetime, 1,632,062 metric tons of CO_2 (177.4 tons/acre), would be achieved in 2086 at the end of the second clearcut cycle. The minimum cumulative carbon dioxide reductions during the modeling period, 161,659 metric tons of CO_2 (17.6 tons/acre), would occur immediately prior to the start of the second clearcut cycle in 2066, coinciding with the peak carbon stocks achieved by the baseline scenario. The maximum periodic carbon dioxide reductions would occur in 2021, resulting in 428,611 metric tons of additional CO_2 (46.6 tons/acre) sequestered since 2016. On the other hand, the greatest periodic carbon dioxide emissions (i.e. minimum reductions) relative to the baseline would occur when 227,274 metric tons of CO_2 (24.7 tons/acre) would be emitted between 2061 and 2066.

5.2 Wood Products Modeling Results

The incorporation of the wood products pool accounting into the modeling results increases the projected carbon stocks under both the baseline activity and project activity scenarios. Yet the impact on the carbon stocks in each scenario varies due to differences in the amount of timber harvested during the project lifetime. Since the total carbon stocks in each scenario are affected differently, the resulting emissions reductions are also affected, especially in comparison to when the wood products pool is not included in project accounting.

Over the life of the project, 447,877 MBF are harvested under the baseline activity scenario, whereas 417,563 MBF are harvested under the project activity scenario (Tables 14 and 15). The amount of timber harvested in any given period of time varies considerably under the baseline activity scenario, with significant pulses during the periods in which clearcutting occurs, more modest harvest volumes when intermediate thinning takes place, and no volume harvested in some periods as standing timber volume is allowed to accumulate on clearcut sites. Although the baseline activity scenario exhibits an average harvest rate of about 4,475 MBF per year, as much as 7,413 MBF per year are harvested per year during the initial clearcut phase and up to 14,820 MBF per year in the second clearcut phase, but only between about 1,000 and 3,000 MBF per year during intermediate thinnings and 0 MBF during fallow years. The wood products carbon pool reflects these changes by accumulating rapidly during clearcutting phases, and more slowly during intermediate thinning phases (Figure 7). But during the periods in which no harvesting occurs, decay of existing wood products leads to a slight decrease in the overall stocks in this pool. At the end of the project lifetime, the baseline activity scenario has a total of 88,775 metric tons of carbon in the wood products pool.

Table 14. Projections of inventory volumes, harvest volumes and carbon stocks under the Baseline Activity Scenario.

Year	Acres Harvested	Total Net Board Foot Volume (MBF)	Total Net Conifer Board Foot Volume (MBF)	Net Conifer Board Foot Growth Per Year (MBF/yr)	Annual Net Conifer Board Feet Harvested (MBF/yr)	Annual Net Conifer Volume Harvested as % of Total Net Conifer Volume	Carbon Above-ground (mt)	Carbon Below-ground (mt)	Lying Dead Wood (LDW) Carbon (mt)	Total Onsite Carbon (Above, Below & LDW) (mt)	Total Onsite Carbon Density (mt/acre)	Harvested Wood Products Carbon (mt)	Total Carbon, (Onsite & Harvested Wood Products) (mt)	Total Carbon Density (Onsite & Harvested Wood Products) (mt/acre)
2006	2,450	91,906	90,382	4,044	5,255	5.81%	296,058	75,629	12,486	384,172	41.7	0	384,172	41.7
2011	1,984	85,845	84,326	2,878	5,740	6.81%	268,126	69,288	12,486	349,899	38.0	7,601	357,500	38.9
2016	2,419	71,453	70,015	2,234	7,413	10.59%	213,124	56,566	12,486	282,176	30.7	15,563	297,739	32.4
2021	1,914	45,411	44,118	645	6,036	13.68%	135,075	37,806	12,486	185,367	20.1	25,593	210,959	22.9
2026	470	17,597	17,164	1,742	726	4.23%	65,385	19,913	12,486	97,784	10.6	33,187	130,970	14.2
2031	-	22,771	22,241	1,711	-	0.00%	89,664	26,322	12,486	128,471	14.0	32,768	161,239	17.5
2036	513	31,423	30,794	3,642	1,091	3.54%	121,007	34,304	12,486	167,797	18.2	31,325	199,122	21.6
2041	-	44,274	43,552	3,784	-	0.00%	161,707	44,321	12,486	218,514	23.7	31,531	250,045	27.2
2046	708	63,295	62,474	6,379	1,476	2.36%	201,980	53,945	12,486	268,411	29.2	30,157	298,567	32.4
2051	2,315	87,898	86,988	7,086	2,318	2.66%	248,892	64,877	12,486	326,254	35.5	30,983	357,238	38.8
2056	2,454	111,468	110,830	9,401	2,933	2.65%	288,957	74,024	12,486	375,466	40.8	32,995	408,461	44.4
2061	2,145	143,869	143,168	10,071	1,842	1.29%	339,825	85,427	12,486	437,738	47.6	35,812	473,550	51.5
2066	4,606	185,078	184,317	10,133	14,820	8.04%	397,377	98,092	12,486	507,954	55.2	36,929	544,883	59.2
2071	1,984	161,369	160,882	5,413	11,064	6.88%	329,940	83,228	12,486	425,653	46.3	56,771	482,425	52.4
2076	2,419	133,145	132,629	5,271	12,858	9.69%	260,650	67,578	12,486	340,713	37.0	70,301	411,014	44.7
2081	1,914	95,239	94,692	922	10,673	11.27%	178,508	48,366	12,486	239,360	26.0	85,831	325,190	35.3
2086	470	46,518	45,940	3,735	2,404	5.23%	94,635	27,607	12,486	134,728	14.6	97,519	232,247	25.2
2091	42	53,200	52,595	2,049	28	0.05%	119,096	33,825	12,486	165,407	18.0	96,741	262,148	28.5
2096	563	63,330	62,702	5,837	2,900	4.63%	150,833	41,677	12,486	204,995	22.3	92,579	297,574	32.3
2101	-	78,037	77,385	4,186	-	0.00%	192,136	51,615	12,486	256,236	27.8	92,772	349,008	37.9
2106		98,991	98,316				233,330	61,280	12,486	307,096	33.4	88,775	395,871	43.0

Table 15. Projections of inventory volumes, harvest volumes and carbon stocks under the Project Activity Scenario.

Year	Acres Harvested	Total Net Board Foot Volume (MBF)	Total Net Conifer Board Foot Volume (MBF)	Net Conifer Board Foot Growth Per Year (MBF/yr)	Annual Net Conifer Board Feet Harvested (MBF)	Annual Net Conifer Volume Harvested as % of Total Net Conifer Volume	Carbon Above-ground (mt)	Carbon Below-ground (mt)	Lying Dead Wood (LDW) Carbon (mt)	Total Onsite Carbon (Above, Below & LDW) (mt)	Total Onsite Carbon Density (mt/acre)	Harvested Wood Products Carbon (mt)	Total Carbon, (Onsite & Harvested Wood Products) (mt)	Total Carbon Density (Onsite & Harvested Wood Products) (mt/acre)
2006	3,834	91,906	90,382	4,349	2,944	3.26%	296,058	75,629	12,486	384,172	41.7	0	384,172	41.7
2011	4,641	99,392	97,406	4,435	3,471	3.56%	320,776	81,182	12,486	414,443	45.0	4,258	418,701	45.5
2016	3,605	104,416	102,224	4,557	3,098	3.03%	330,570	83,368	12,486	426,424	46.3	9,089	435,512	47.3
2021	4,641	112,552	109,518	4,490	4,200	3.83%	347,020	87,023	12,486	446,529	48.5	13,165	459,695	50.0
2026	3,605	114,808	110,969	4,629	3,189	2.87%	351,374	87,987	12,486	451,846	49.1	18,655	470,502	51.1
2031	4,641	123,117	118,168	4,598	4,214	3.57%	369,618	92,012	12,486	474,116	51.5	22,441	496,557	54.0
2036	3,605	125,391	120,086	4,849	3,266	2.72%	372,516	92,649	12,486	477,651	51.9	27,546	505,197	54.9
2041	4,641	134,515	128,003	4,875	4,161	3.25%	391,969	96,911	12,486	501,366	54.5	31,056	532,422	57.9
2046	3,648	137,582	131,571	5,122	3,591	2.73%	392,433	97,013	12,486	501,932	54.5	35,710	537,642	58.4
2051	4,641	146,426	139,229	5,134	4,232	3.04%	409,827	100,802	12,486	523,115	56.8	39,337	562,452	61.1
2056	4,106	150,138	143,740	5,438	3,897	2.71%	411,321	101,127	12,486	524,934	57.0	43,737	568,671	61.8
2061	4,783	158,944	151,444	5,681	4,361	2.88%	426,851	104,494	12,486	543,830	59.1	47,464	591,294	64.3
2066	4,106	165,359	158,044	5,869	4,457	2.82%	433,611	105,954	12,486	552,051	60.0	51,703	603,755	65.6
2071	4,783	173,450	165,102	6,031	4,527	2.74%	442,425	107,855	12,486	562,765	61.2	55,901	618,666	67.2
2076	4,106	180,590	172,619	6,117	4,974	2.88%	448,311	109,122	12,486	569,919	61.9	60,020	629,940	68.5
2081	4,783	187,333	178,337	6,351	4,575	2.57%	450,844	109,667	12,486	572,997	62.3	64,610	637,607	69.3
2086	4,106	195,697	187,218	6,282	5,345	2.86%	456,541	110,890	12,486	579,917	63.0	68,428	648,344	70.5
2091	4,783	201,309	191,899	6,515	4,757	2.48%	456,000	110,774	12,486	579,259	62.9	73,199	652,458	70.9
2096	4,106	210,251	200,690	6,481	5,536	2.76%	465,841	112,884	12,486	591,211	64.2	76,915	668,125	72.6
2101	4,783	215,902	205,417	6,665	4,718	2.30%	465,974	112,912	12,486	591,372	64.3	81,602	672,974	73.1
2106		225,459	215,151				475,931	115,042	12,486	603,459	65.6	84,908	688,367	74.8

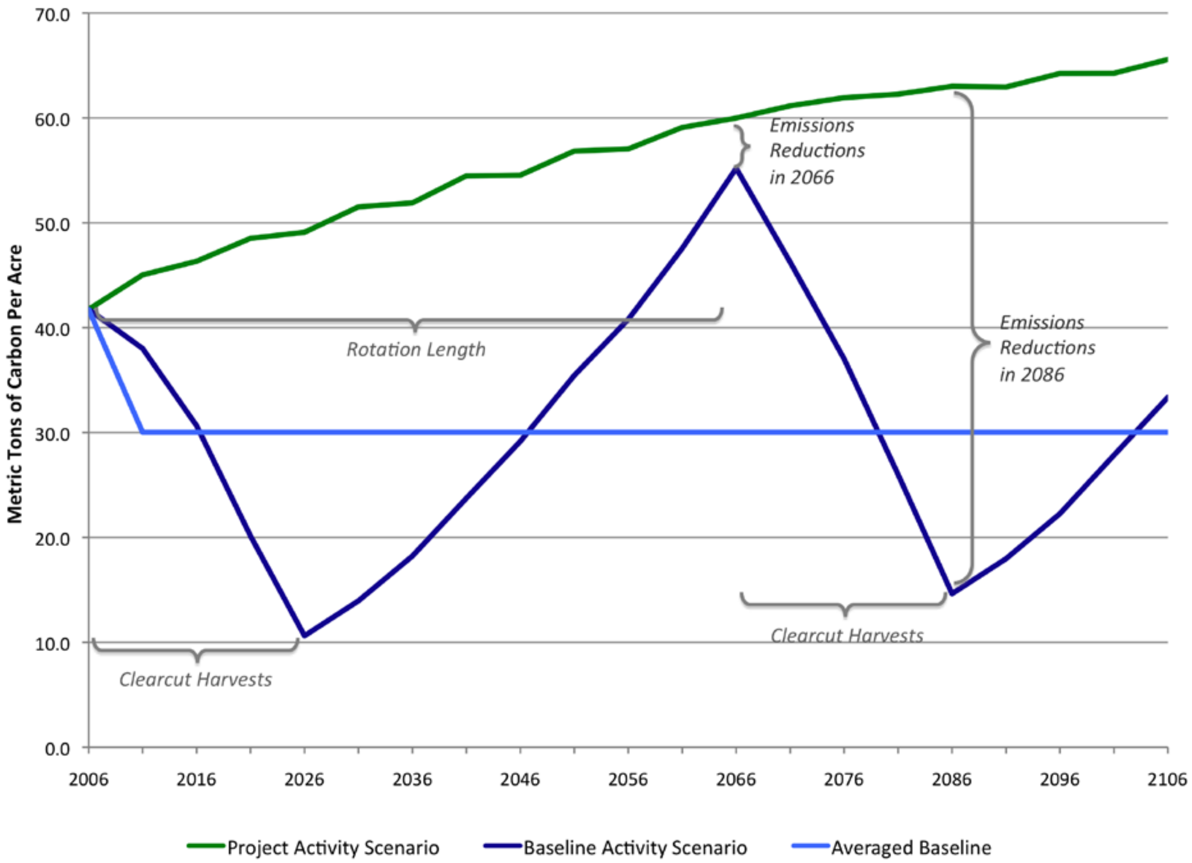


Figure 6. Comparison of projected baseline activity scenario and project activity scenario carbon stocks on a per acre basis over the 100-year project lifetime. The averaged baseline activity value is also shown. All scenarios have the same initial carbon stocks at the project start date in 2006. The averaged baseline curve begins at this same starting value, but achieves the average value by the end of the first 5-year reporting period by being reduced annually in equal increments.

Table 16. Comparison of carbon dioxide stocks produced by the Baseline Activity Scenario and the Project Activity Scenario, and summary of emissions reductions achieved by the Bascom Pacific Project. The table includes emissions reductions calculations based on a comparison between the Project Activity Scenario and the average carbon stocks determined for the Baseline Activity Scenario. Shaded columns indicate the inclusion of the wood products in calculated carbon dioxide totals.

	Baseline Activity Scenario		Project Activity Scenario		Forest Project Protocol CO_2 Reductions Calculations				CO_2 Reductions Calculations Based On Averaged Baseline					
							Including Wood Products					Including Wood Products		
Year	Baseline Metric CO_2 Tons	Baseline Metric CO_2 Tons w/ Wood Products	Project Activity Metric CO_2 Tons	Project Activity Metric CO_2 Tons w/ Wood Products	Cumulative CO_2 Reductions	Periodic CO_2 Reductions	Cumulative CO_2 Reductions	Periodic CO_2 Reductions	Averaged Baseline CO_2 Metric Tons	Cumulative CO_2 Reductions	Periodic CO_2 Reductions	Averaged Baseline CO_2 Metric Tons	Cumulative CO_2 Reductions	Periodic CO_2 Reductions
2006	0	1,408,375	0	1,408,375	0		0		-	0		-	0	
2011	7,601	1,310,594	4,258	1,534,958	-3,342	(3,342)	224,364	224,364	48,844	(44,586)	(44,586)	1,192,310	342,648	342,648
2016	15,563	1,091,513	9,089	1,596,588	-6,475	(3,132)	505,076	280,711	48,844	(39,756)	4,830	1,192,310	404,279	61,630
2021	25,593	773,377	13,165	1,685,241	-12,427	(5,953)	911,864	406,788	48,844	(35,679)	4,077	1,192,310	492,931	88,653
2026	33,187	480,137	18,655	1,724,859	-14,531	(2,104)	1,244,722	332,858	48,844	(30,189)	5,490	1,192,310	532,549	39,618
2031	32,768	591,102	22,441	1,820,379	-10,327	4,205	1,229,276	(15,446)	48,844	(26,403)	3,786	1,192,310	628,069	95,520
2036	31,325	729,982	27,546	1,852,053	-3,779	6,548	1,122,071	(107,205)	48,844	(21,298)	5,105	1,192,310	659,743	31,674
2041	31,531	916,667	31,056	1,951,860	-475	3,304	1,035,193	(86,878)	48,844	(17,789)	3,510	1,192,310	759,550	99,807
2046	30,157	1,094,548	35,710	1,970,995	5,554	6,029	876,447	(158,746)	48,844	(13,134)	4,654	1,192,310	778,685	19,135
2051	30,983	1,309,634	39,337	2,061,950	8,354	2,801	752,316	(124,131)	48,844	(9,507)	3,627	1,192,310	869,640	90,955
2056	32,995	1,497,420	43,737	2,084,749	10,742	2,388	587,329	(164,987)	48,844	(5,107)	4,400	1,192,310	892,439	22,799
2061	35,812	1,736,034	47,464	2,167,683	11,652	910	431,649	(155,680)	48,844	(1,380)	3,727	1,192,310	975,373	82,934
2066	36,929	1,997,540	51,703	2,213,364	14,775	3,123	215,824	(215,826)	48,844	2,859	4,240	1,192,310	1,021,054	45,681
2071	56,771	1,768,569	55,901	2,268,030	-871	(15,646)	499,461	283,637	48,844	7,056	4,197	1,192,310	1,075,720	54,666
2076	70,301	1,506,777	60,020	2,309,359	-10,280	(9,410)	802,582	303,121	48,844	11,176	4,120	1,192,310	1,117,049	41,329
2081	85,831	1,192,148	64,610	2,337,468	-21,220	(10,940)	1,145,320	342,739	48,844	15,766	4,590	1,192,310	1,145,158	28,109
2086	97,519	851,418	68,428	2,376,831	-29,091	(7,871)	1,525,413	380,092	48,844	19,583	3,817	1,192,310	1,184,521	39,363
2091	96,741	961,036	73,199	2,391,912	-23,543	5,549	1,430,876	(94,537)	48,844	24,354	4,771	1,192,310	1,199,602	15,081
2096	92,579	1,090,907	76,915	2,449,348	-15,664	7,879	1,358,441	(72,435)	48,844	28,070	3,716	1,192,310	1,257,038	57,436
2101	92,772	1,279,464	81,602	2,467,123	-11,170	4,494	1,187,660	(170,781)	48,844	32,758	4,687	1,192,310	1,274,814	17,776
2106	88,775	1,451,262	84,908	2,523,552	-3,867	7,303	1,072,290	(115,370)	48,844	36,063	3,306	1,192,310	1,331,242	56,429

The project activity scenario exhibits more consistent harvest rates over time, with harvests occurring every year during the project lifetime and ranging from about 3,000 MBF per year to 5,500 MBF per year, with an average of about 4,175 MBF per year over the project lifetime. The wood products carbon pool reflects this consistent rate of harvest by increasing consistently throughout the project lifetime (Figure 7). At the end of the project lifetime, the project activity scenario has a total of 84,908 metric tons of carbon in the wood products pool.

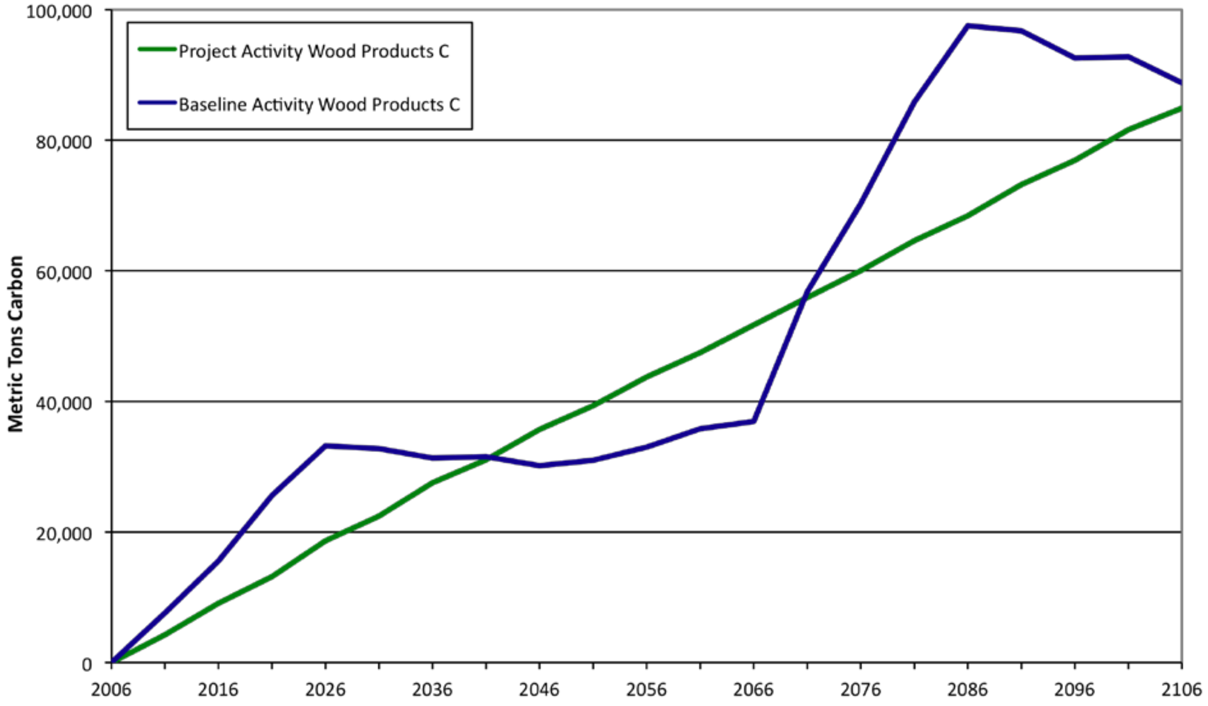


Figure 7. Baseline activity and project activity wood products pool stocks over the 100-year project lifetime.

Combining the wood products pool with the standing live tree, standing dead tree and lying dead wood pools increases the amount of carbon stored under both the baseline activity and project activity scenarios (Figure 8). Yet since each scenario differs in the amount of carbon transferred into the wood products pool both annually and throughout the project lifetime, the emissions reductions generated by the project are affected when the wood products pool is incorporated into the project accounting. Table 16 reveals that the emissions reductions under the standard calculations (project activity CO_2 – baseline activity CO_2) are generally lowered over the project lifetime compared to when wood products are not considered. At the end of the project lifetime, the cumulative emissions reductions are 14,176 tons of CO_2 less when wood products are considered than when they are not. However, from 2046 to 2066, emissions reductions for the project are actually higher when wood products are incorporated.

When the baseline values are averaged over the project lifetime, inclusion of wood products increases the baseline average by 179,064 tons of CO_2. Incorporating wood products also increases the cumulative emissions reductions at the end of the project lifetime by 132,208 tons of CO_2. However, cumulative emissions reductions including wood products remains lower than emissions reductions without wood products until 2066, at which point emissions reductions including wood products is greater through the remainder of the project lifetime.

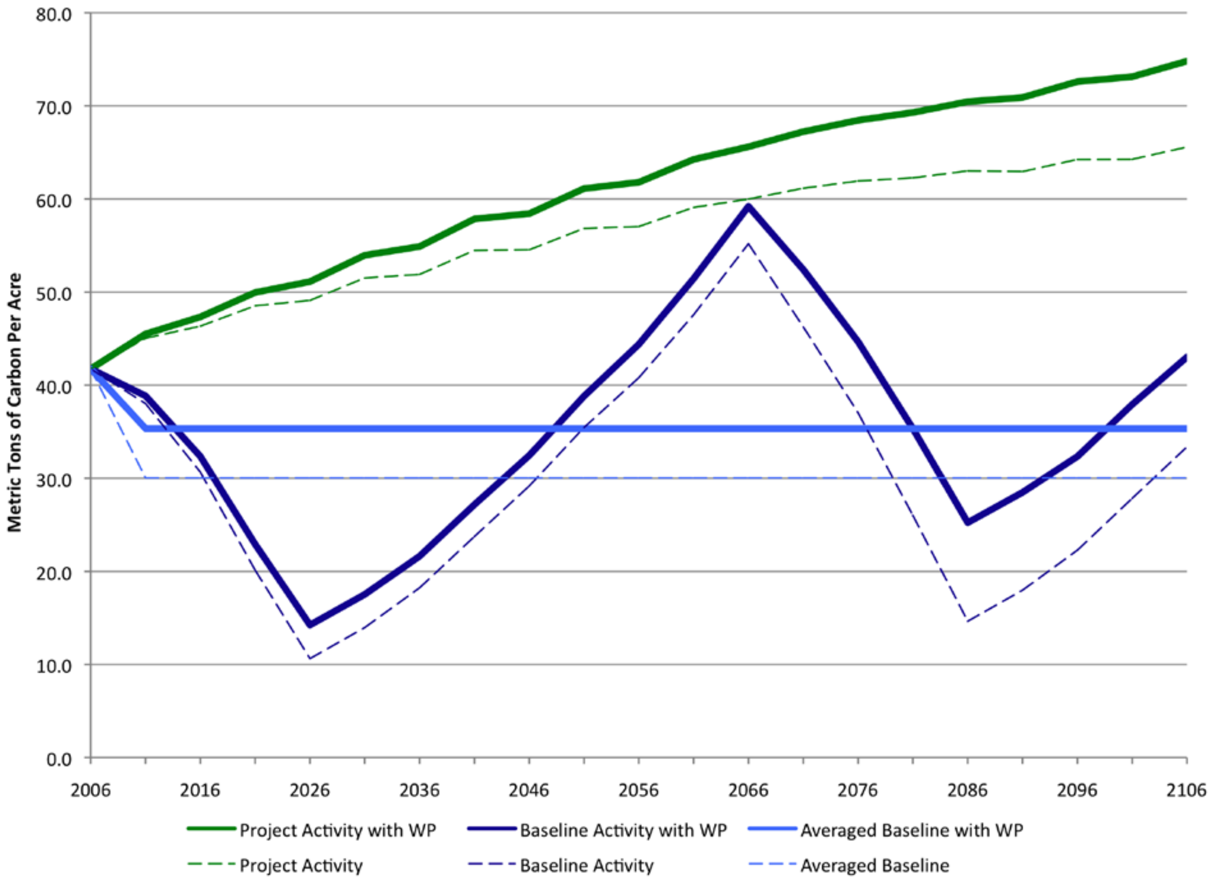


Figure 8. Baseline and project activity carbon stocks, both with and without wood products pool stocks, over the 100-year project lifetime on a per acre basis. The averaged baseline activity value is also shown. All scenarios have the same initial carbon stocks at the project start date in 2006. The averaged baseline curve begins at this same starting value, but achieves the average value by the end of the first 5-year reporting period by being reduced annually in equal increments.

5.3 2008 Project Stocks Monitoring

The 2008 carbon inventory update suggests that project stocks increased during the two-year time span since the project was initiated in 2006 (Table 17). Total carbon increased 44,512 metric tons between 2006 and 2008, from 384,172 metric tons to 428,684 metric tons. Of this increase, live tree carbon accounted for 33,912 metric tons, standing dead trees accounted for 5,133 metric tons, and lying dead wood accounted for 5,466 of the increase, though the increases in both dead pools may be due in part to changes made to the sampling methodologies used in 2008. Regardless, since the emissions reductions for a project are based on the difference between the project activity stocks and the baseline activity stocks, this increase in actual project stocks over the anticipated amount results in a corresponding increase in emissions reductions through the year 2008.

Table 17. Total carbon and carbon density in 2006 and 2008 for required reporting pools, and including the wood products pool.

	Total C (mt)			**C Density (mt/acre)**			**% Change from 2006 to 2008**	
	2006	**2008**		**2006**	**2008**			
Carbon Pool		*Projected*	*Actual*		*Projected*	*Actual*	*Projected*	*Actual*
Live Tree	368,544	380,653	402,457	40.1	41.4	44.3	3.3%	9.2%
Standing Dead Tree	3,142	3,142	8,275	0.3	0.3	0.9	0.0%	163.4%
Lying Dead Wood	12,486	12,486	17,952	1.4	1.4	2.0	0.0%	43.8%
Total	384,172	396,280	428,684	41.7	43.1	47.2	3.2%	11.6%
Wood Products	0	1,727	184	0.0	0.2	0.0	n/a	n/a
Total	384,172	398,007	428,868	41.7	43.3	47.2	3.6%	11.6%

Modeling of the baseline activity scenario projected a 2008 baseline stocking of 370,463 metric tons of carbon. Modeling of the project activity scenario predicted that stocks at the project site would increase to 396,280 metric tons. As such, the projected amount of emissions reductions for 2008 was 25,817 metric tons of carbon, or 94,647 tons of carbon dioxide. However, the inventory update in 2008 established project stocks of 428,684 metric tons, which result in actual emissions reductions equaling 58,221 metric tons of carbon, or 213,438 tons of CO_2.

Incorporating the wood products pool into the calculations for 2008 stocks impacts the resulting emissions reductions. Including wood products carbon in the baseline stocks for 2008 produces a baseline value of 373,545 metric tons of carbon, an increase of just over 3,000 metric tons. Adding wood products to the actual 2008 project stocks, based on the volume of timber harvested on the project site through the end of 2008, increases the actual project stocks to 428,868 metric tons of carbon, an increase of less than 200 metric tons. Since the baseline stocks are increased more than the project stocks with the addition of wood products carbon, the resulting emissions reductions are reduced to 55,323 metric tons of carbon, or 202,814 tons of CO_2.

6.0 Discussion of Modeling Results

6.1 On-Site Carbon Pools

Significant carbon dioxide emissions reductions would be expected to be achieved over a 100-year time period on the Bascom Pacific Forest given the assumptions and management scenarios used to model the baseline activity and project activity carbon stocks. Approximately 32.2 metric tons of additional C/acre, or 118.1 metric tons of CO_2/acre, would be stored on the site at the end of the project lifetime, equating to an annualized accrual rate of 0.32 metric tons of C/acre, or 1.18 metric tons of CO_2/acre, per year.

Yet the emissions reductions achieved from year to year fluctuate considerably throughout the modeling period, with significant reductions achieved during some periods and significant emissions produced during other periods. The results of these projections have significant implications for the annual carbon stocks reporting that would occur throughout the project lifetime, as required by the Forest Protocols. Based on the results here, the project developer would be able to report emissions reductions in years when the difference between the baseline activity and project activity stocks increases. But in years when the difference between the baseline activity and project activity stocks decreases, the project developer would be required to report an increase in emissions, also known as a reversal.

Given the relatively consistent increase in carbons stocks under the project activity scenario, these reversals in reductions trends are clearly caused by the baseline activity scenario (Figure 6). Periods during which clearcut harvests are occurring swiftly remove timber from the site, resulting in a rapid decline in baseline activity carbon stocks. Emissions reductions calculated during these periods increase at an even greater rate since the project activity carbon is increasing while the baseline activity carbon is decreasing.

This trend is reversed, though, once the clearcut harvest period ends in the baseline activity scenario and the forest remains relatively fallow while the stands are allowed to regenerate until the end of the 60-year rotation period. During these growth periods, the rate at which carbon stocks increase in the baseline scenario is significantly higher than the rate of increase exhibited by the project scenario. As a result, calculations of emissions reductions during these periods produce a negative value. In other words, the project activity is sequestering less carbon per year than the baseline activity. Thus, the project activity may be said to be producing CO_2 emissions relative to the baseline activity during such periods.

While the Protocol stipulates the 100 year "permanence period", this situation highlights the potential importance of the time scale used for the analysis. The time scale used for this analysis, as guided by the Forest Protocols, is 100 years. The net emissions reductions generated after 100 years in this instance (i.e. in 2106) are 1,086,466 metric tons of CO_2. However, if the analysis was to end just 20 years earlier in 2086, the net emissions reductions that could be said to have been generated are 1,632,062 metric tons of CO_2, or 545,596 metric tons more than after 100 years. Yet an analysis period ending only 20 years prior to that (i.e. 2066) would produce net emissions reductions of merely 161,659 metric tons of CO_2, or 924,807 metric tons less than after 100 years. Thus, the perceived overall benefits of the project vary considerably over time and may be dependent on the timeframe that is considered.

One could then take the point of view from this flux in emissions reductions that those to be considered additional (or permanent) under the current version of the Protocols should be limited to the minimum difference between the project activity and the baseline activity over the project lifetime. Determining the permanent emissions reductions based on this minimum value is a logical conclusion if one holds that any carbon emitted between the peaks in the baseline curve is irrelevant since it will be re-captured prior to the start of each clearcutting cycle. In the case presented here, the minimum difference is 161,659 metric tons of CO_2 over the 100-year modeling timeframe.

Yet, on the other hand, it is also reasonable to argue that the average value of the baseline curve throughout the 100-year modeling period should determine the emissions reductions for a project. This is because the long term net effect of the project relative to such a baseline is the removal of X tons of CO_2 from the atmosphere on average throughout time, with fluctuations of Y tons above or below X at any given point in time. The application of this concept to our results is shown in Figure 1 and Table 16. The average baseline CO_2 stocks for the 100-year modeling period are 1,013,246 metric tons, or 110.1 tons per acre. Throughout the project lifetime, periodic emissions reductions would simply mirror the changes in the project activity stocks, increasing when they increase and decreasing when they decrease.

During the modeling period in this study, the project activity steadily increases from 153.1 tons of CO_2 per acre to 240.4 tons per acre. If an average baseline approach is taken, when looking at periodic reporting, the first reporting period would see an initial pulse of an unusually high amount of emissions reductions projected due largely to the baseline stocks decreasing rapidly from the initial starting stocks, which are the same as the project activity starting stocks. In this case, the projected emissions reductions based on an averaged baseline in the first reporting period would be 506,101 metric tons of CO_2, or 55.0 tons of CO_2 per acre. Throughout the 100-year modeling period, emissions reductions would be generated more consistently, with only one 5-year period during which a minor emission would be projected to occur due to harvest activities removing slightly more carbon than is sequestered. The cumulative emissions reductions based on an averaged baseline would be 1,199,034 metric tons of CO_2, or 130.3 tons of CO_2 per acre, an amount slightly higher than what would be reported under the current Protocols (1,086,466 metric tons of CO_2).

Another benefit of calculating an average value for the baseline curve is it allows us to further parse the causes of the emissions reductions results. Since the initial CO_2 stocks (1,408,375 metric tons) are higher than the average baseline CO_2 stocks (1,013,246 metric tons), this 395,129 metric ton difference may be considered the avoided depletion of stocks that result from the project activity occurring on the Bascom Pacific Forest rather than the baseline activity. Thus, of the 1,199,034 metric tons of additional CO_2 sequestered by the end of the project lifetime, approximately 33 percent can be attributed to the avoiding the depletion of stocks that would have taken place if the baseline activities were allowed to occur. On the other hand, 67 percent of the total emissions reductions can be attributed to additional carbon sequestered as a direct consequence of the project activities.

Given that the baseline is an evaluation of a hypothetical without-project scenario, there are no real-world consequences in terms of additional CO_2 being removed from the atmosphere in one year and emitted the next year when such removals and emissions are "caused" primarily by changes occurring in the baseline activity. Thus, assuming the pattern of large fluctuations in the baseline scenario developed in this study would continue if the modeling period was extended indefinitely, it seems reasonable to calculate a steady-state baseline value based on the average stocking under the baseline scenario over the 100-year modeling timeframe. Using an appropriate steady-state value for the baseline curve would simplify emissions reductions accounting, eliminating confusion and producing a result that more accurately estimates the 100 year atmospheric benefits of the project. However, given that the potential emissions reductions that may be reported increased in this case when an averaged baseline was applied, more thorough evaluation may be necessary to ensure the appropriateness of accounting for emissions reductions in this manner. Further, the benefits of using an averaged baseline depend on the project actually extending for its anticipated 100-year lifetime. If a project is terminated prior to its 100-year lifetime the accounting of emissions reductions will be inaccurate unless the project average baseline were recalculated to the point of early termination and all previously issued emissions reductions were adjusted accordingly.

For a landowner selling emissions reductions, managing the fluctuating emissions reductions levels that are an artifact of the baseline forest management pattern would be very challenging. A buyer typically requires that the emissions reduction be permanent, so the period in which reversals occur due to forest regrowth prior to another regeneration harvest presents a problem. The seller would need to provide replacement emissions reductions or create another kind of arrangement with the buyer, perhaps "borrowing" against future years' reductions at a discounted value to account for the performance risk.

6.2 Wood Products

The inclusion of the wood products pool in calculating emissions reductions has the net effect of lowering the overall emissions reductions that would be generated by 14,176 tons of CO_2, by the end of the 100-year project lifetime (Table 16 and Figure 9), a decrease of 1.3 percent. Such a small decrease is due to the harvest volume under the project activity scenario being over 93 percent of the volume harvested under the baseline activity scenario. Considering the difficulties CACTOS and other growth models have with accurately projecting growth in managed older forests, it may be that the harvest volume projected for the project activity scenario is inaccurate. Thus, in reality the volume harvested under the project activity may be equal to or greater than the baseline activity harvest volume. As such, accounting for the wood products pool may prevent a decrease in cumulative emissions reductions at the end of the project lifetime and may even cause an increase in emissions reductions. Nonetheless, although projected emissions reductions are lower by the end of the project, the different rates and timing of harvest cause cumulative emissions reductions to be higher during the period 2046 to 2066. This reveals again that the end of project conditions do not reliably indicate conditions that may occur throughout the course of the project lifetime.

If the average value of the baseline curve is used to calculate emissions reductions, the projected emissions reductions are increased by 132,208 tons of CO_2, or 11 percent. Yet again, a comparison between emissions reductions with and without wood products during the 100-year project lifetime shows that cumulative emissions reductions are lower from project initiation through 2061 when accounting for wood products carbon, and then become higher and remain so through the end of the project lifetime. Thus, the inclusion of wood products has a more nuanced impact than simply raising or lowering the emissions reductions. This is especially true given the requirement of project developers to report their stocks and emissions reductions annually, and remeasure their stocks at least every 12 years. In the case of this project, accounting for wood products has the effect of minimizing the fluctuations in reported emissions reductions from year to year. However, as illustrated in Figure 9, this effect is not drastic since wood products generally account for a small percentage of the total difference between the baseline and project activity carbon stocks in any given year.

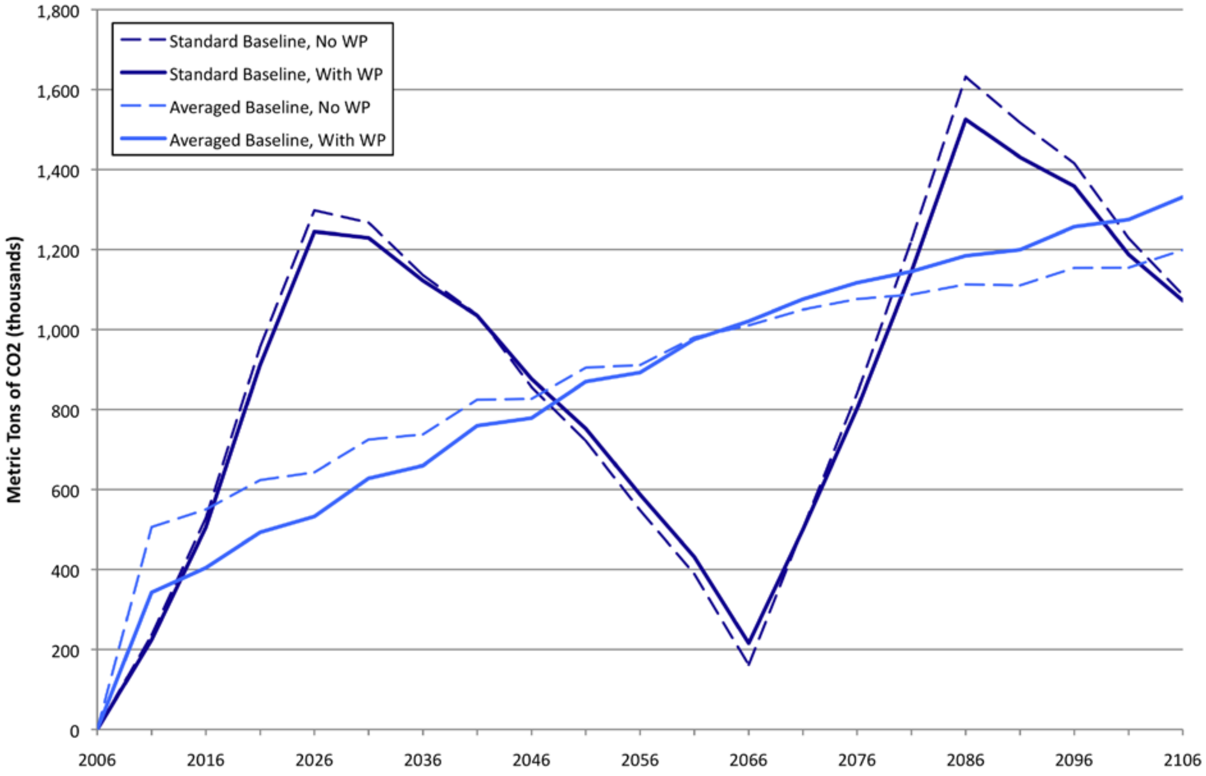


Figure 9. Cumulative emissions reductions over the 100-year project lifetime, using standard and averaged baseline values, and both with and without wood products pool stocks. The inclusion of wood products has the effect of decreasing the difference between the amount of emissions reductions generated from one period to the next.

6.3 2008 Project Stocks Monitoring

The remeasurement of live tree, standing dead tree and lying dead wood pools in 2008 indicated that carbon stocks within each pool and in total increased more than projected for the Bascom Pacific Forest over the two years since project initiation (Table 17). Overall carbon stocks were projected to increase by 12,108 metric tons of carbon over two years (3.2 percent), or 0.7 tons per acre per year. This increase was projected to be caused solely by changes to the live tree pool. Both the standing dead tree and lying dead wood pools were assumed to remain constant over the project lifetime. But the 2008 inventory estimated an increase in the live tree pool of 33,912 metric tons (9.2 percent), or 2.1 tons per acre per year, nearly three times the projected increase, while the standing dead tree and lying dead pools each increased by over

5,000 metric tons (163.4 percent and 43.8 percent, respectively), or 0.3 tons per acre per year. Assuming the 2006 and 2008 inventories provide an adequate basis for comparison, total carbon stocks increased by 11.6 percent, nearly four times more than projected, at a rate of 2.7 tons per acre per year.

These deviations from projected values can be attributed to several sources, six of which are addressed below. The degree to which each source contributed to the deviations observed can not be determined. First, activities that took place on the project site from 2006 to 2008 did not match the activities that were projected to occur. Project activity projections were based on a harvest rate of approximately 3,000 MBF per year in 2007 and 2008. But only about 10% of this amount was harvested from the project site. As a result, less carbon was removed through harvest and more was allowed accumulate than was originally projected, contributing to the increase in 2008 carbon stocks over the projected amount.

Second, as previously noted, the initial lying dead wood inventory did not fully comply with the measurement standards outlined by the Forest Protocols. The minimum specification used for length measurements (pieces ≥10 inches diameter inside bark at the large end) would not have captured all pieces that would have been captured if the inventory was in full compliance (pieces with an average diameter ≥6 inches). For example, a 10 foot long piece of wood that was 9 inches in diameter on the large end and 7 inches in diameter on the small end (i.e. average diameter of 8 inches) would not have been counted, although a significant number of lying dead wood pieces of similar dimensions could exist on a property that undergoes timber harvests on a regular basis, as is the case with the Bascom Pacific Forest. Thus, the 2006 inventory likely underestimated the amount of carbon in the lying dead wood pool, accounting for a portion of the increase in the lying dead wood stocks.

Third, the standing dead tree and lying dead wood pools were both assumed to remain constant over time. This is primarily due to the inability to model changes in either pool in a reliable manner. As a result, any measured changes in either pool would cause a deviation from projected stocks.

Fourth, each inventory was based on a slightly different measurement methodology. Although the measurement specifications used were in compliance with the standards outlined by the Forest Protocols (with the exception of the initial lying dead wood inventory), the cruise designs for the 2006 and 2008 inventories were slightly different. As a result, live trees, snags or pieces of lying dead wood of a certain specification may have been captured by the initial inventory but not by the 2008 inventory, and vice versa. For example, the initial inventory called for the tallying of up to only a certain number of trees below 4.6 inches DBH within regeneration sub-plots, whereas the 2008 inventory did not place a limit on the number of trees to be tallied in regeneration sub-plots.

Fifth, since both inventories are estimates based on the statistical expansion of sample measurements made on the project site, the sampling error associated with sample-based inventories contributes to uncertainty around each estimate. Even if the other sources of difference addressed here were eliminated, it would be highly unlikely that two sample-based inventories would produce exactly the same results. That being said, it is not possible—short of measuring all trees on the project site—to determine whether each inventory over- or underestimated the actual carbon stocks.

Finally, there is uncertainty (i.e. a degree of error) associated with model-based projections since the assumptions and parameters that serve as the basis for such projections do not reflect reality perfectly. This uncertainty comes into play twice for this project. The project activity projection has uncertainty associated with it. But the initial inventory has some additional uncertainty associated with it since all of the stands were inventoried prior to 2006 and then updated (i.e. growth was projected) to the project start date. As a result, the uncertainty associated with the initial inventory may compound the uncertainty associated with the project activity projections.

Regardless the causes, even though the project activity modeling underestimated the amount of emissions reductions that were generated through 2008, the Forest Protocols specify that emissions reductions are calculated for a given year by finding the difference between the baseline stocks and the reported stocks on the project site. Since a complete remeasurement of the project stocks took place in 2008, the emissions reductions for that year would be based on the difference between the project stocks from the new inventory and the baseline stocks. The initial project activity projections would have no bearing on the emissions reductions calculated for 2008. Thus, even though the emissions reductions through 2008 were projected to be 94,647 tons of CO_2, the actual emissions reductions that would be reported, and subject to verification, through 2008 are 213,438 tons of CO_2. Similar underestimations would be expected in subsequent years if there continued to be no harvest activities on the project site.

Of note, under the annual stock change accounting requirements of the Protocols, emissions reductions that would be reported and subject to verification in subsequent years would be only those above and beyond the 213,438 tons reported in 2008. For example, if the project developer estimated a total of 220,000 tons of CO_2 stocks on the project site in 2009, the reportable emissions reductions would be 6,562 tons of CO_2 (220,000 tons minus 213,438 tons).

7.0 Discussion of Application of the Forest Protocols

Overall, the results of the application of version 2.1 of the Forest Protocols appear to provide practical but rigorous accounting of emissions reductions to internationally acceptable standards. Nonetheless, there are a number of areas where we recommend changes to provide more efficient and accurate application, while still adhering to the desired level of rigor.[2] As the work on this paper progressed, the Protocol itself went through revision, with the result that some of our recommendations were subsequently incorporated to the new version 3.0. The following discussion incorporates our experience and recommendations for applying, clarifying and/or amending version 2.1 of the Forest Protocols, as well as some additional discussion of the implications of changes made in version 3.0 if these new provisions were applied to a project such as the Bascom Pacific Forest.

7.1 Carbon Stocks Inventory

The initial conditions inventory, when properly specified, can be cost effectively undertaken concurrent with a conventional timber inventory but does add expense. The greater expense is due to the generally higher statistical confidence required in sampling[3] and the inclusion of additional inventory elements such as standing and down dead biomass. Further, the requirement for permanent marking of plot centers is a costly variance from the standard timber inventory practice of temporary flagging. Version 3.0 of the Forest Protocols eliminates the requirement for permanent monumenting, while still requiring temporary flagging so that verifiers can locate plot centers. In addition to the specific requirements of different project types under the Protocols, inventory costs vary with the size and heterogeneity of the property, not unlike timber inventories. Larger more homogenous properties will cost less to inventory than the mid-size, relatively diverse Bascom Pacific property.

The use of the equations provided by Jenkins *et al*. (2003) to convert inventory data into carbon stock estimates appears to establish a decent estimation. However, the Jenkins equations are based on data from broad species groupings that are more appropriate for national or regional scale estimates of biomass and carbon rather than project scale estimates. For example, the equation used for ponderosa pine by the Forest Protocols is a generalized equation developed from 43 separate regression equations for 14 different species in the *Pinus* genus. Of those 43 regression equations, only 5 are representative of Ponderosa pine. Another example worthy of mentioning is the equation used in the Forest Protocols for coastal redwood/giant sequoia/incense-cedar. In this case, the generalized equation was developed from 21 different regression equations for roughly 9 different species across 6 separate genera. Of these 21 equations, only one is representative of giant sequoia and one is representative of incense cedar.

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[2] The hypothetical application of the Forest Protocols to the Bascom Pacific property undertaken in this Project confirms similar experiences of the Pacific Forest Trust in other projects developed under the Forest Protocols. Our discussion incorporates our experience and recommendations derived from these other projects as well.

[3] Lower sampling confidence intervals (i.e., greater than +/-5% at the 90% confidence interval)

No equations for coastal redwood were used to create the generalized equation representing that species in the Forest Protocols.

Furthermore, the only data the Jenkins equations use to estimate biomass is diameter at breast height. Although the use of the Jenkins equations may be adequate for national-level estimates or for a given project for which the Jenkins equations have been tested to ensure they produce accurate estimates for all species involved, there is often too much variability within an individual forest site and between forest sites to use a nationally generalized equation at the project level.

As a result of these generalizations, estimates of carbon stocks for a given project may be higher or lower than is truly the case. Whether the estimate is higher or lower than reality (as well as the how much higher or lower) depends on the exact species representation and tree sizes involved. Regardless, the United States Forest Service's Forest Inventory and Analysis (FIA) program have developed tree biomass equations that are species specific and are based on, at a minimum, the cubic foot volume of the bole, and often the diameter at breast height and height in order to calculate bark and branch biomass separately from bole biomass. Thus, the FIA equations are considered to estimate more accurately the true carbons stocks in a given forest. Indeed, version 3.0 of the Forest Protocols replaces the Jenkins equations with those used by the FIA.

7.2 Baseline Characterization

Using the guidance of version 2.1 of the Forest Protocol, the Baseline is not challenging to develop and model, given the relatively specific set of regulations under which forest practices are conducted in California. We note that in addition to the fact that version 2.1 of the Forest Protocols requires the use of Option C as the standard for modeling state level harvest volume regulation, as a property and ownership that is less than 50,000 acres in size, Option C is the specific sustained yield rule under which the Bascom Pacific is operated, therefore Option C forms the basis for state forest practice regulatory analysis under both version 2.1 and 3.0.

However, in a project such as Bascom Pacific where "business as usual" timber harvest can often be characterized by a series of clear-cuts and regrowth, we would recommend that the harvest regime modeled in the baseline produce a more balanced and regular flow of growth and harvest to more accurately represent the net baseline stores over the 100-year project; e.g., a series of clear cuts and intermediate treatments initially followed by intermediate treatments and selection harvests, as feasible legally and financially. As discussed earlier, removal of the large fluctuations that are derived from the repeated pattern of high intensity removal and subsequent regrowth simplifies the accounting of resulting emissions reductions without sacrificing long-term accuracy.

Even with this approach to characterizing the Baseline, we believe the use of an averaged baseline in version 3.0 against which annual stock changes are measured represents a significant improvement, given the management and accounting implications inherent in silvicultural cycles, described earlier.

7.2.1 Accounting implications of an averaged Baseline in the event of early project termination

We note that the use of an averaged baseline could in some circumstances present a challenge to the accuracy of the whole accounting system set up in the Forest Protocols if early termination of a project occurs (i.e., intentional termination prior to the 100-year project lifetime). The potential inaccuracy of project accounting could cast a shadow of uncertainty and impermanence on the whole system absent appropriate measures to mitigate for over-crediting that could occur. If a project were terminated prior to the average stocks for the actual project period equaling the averaged Baseline stocks for the 100-year intended project lifetime, the registered emissions reductions could be materially higher or lower than they would be if the baseline had not been averaged. For instance, in a project where the forest is relatively young, the baseline activity would include a period of growth to merchantability that extends 10 to 40 years from the date of project initiation. In this instance, baseline stocks prior to averaging would reflect such business as usual growth until the conditions when timber harvest would legally and financially be feasible. With the use of an averaged baseline, the average stocks for the baseline could be lower than the non-averaged baseline projection for this period, leading to over-crediting of emissions reductions. To address the potential inaccuracy in the measurements of a project that is terminated early, version 3.0 of the Protocol requires a greater than 1:1 replacement value on a schedule that declines from 1.4 to 1.0 to fund reversals in the first 50 years of the project.

7.2.2 Use of a "Common Practice" metric to better assure conservative estimates of emissions reductions in the case of avoided depletion of carbon stocks

One area of concern that we have encountered in developing and reviewing some emissions reduction projects under version 2.1 is whether the depletion of standing live carbon stocks could be exaggerated in a Baseline methodology that only uses an explicit regulatory test. Some observers feel that the result of actual forest practices on the ground have produced higher average carbon stocks than would be generated through the application of the version 2.1 baseline methodology. Version 3.0 addressed this matter by adding the financial feasibility test (previously considered implicit by some practitioners) and by adding the Common Practice standard below which above-average carbon stocks could not be depleted.

The implication of these changes is not fully understood yet due to the lack of experience in the application of the more complex Baseline methodology of the new version. Further, simple comparisons using existing data are rendered difficult by other changes to the Protocol, including new assessments and adjustments for leakage, differences in accounting for harvested wood products, and overall measurement differences due to the switch to the FIA biomass equations. While it is beyond the scope of this paper to completely remodel the Bascom Pacific project under the new requirements, we compared the FIA mean live carbon stocks for the Southern Sierra Nevada – Southern Cascades Assessment Area in which the project resides, as identified in version 3.0 (39 mt C/acre) with the starting live carbon stocks indicated in the 2006 inventory (40 mt C/acre) to determine if there would still be the ability to account for the avoided depletion of this relatively well stocked commercial forest. While the starting stocks are above the Common Practice metric selected by the Reserve, the new baseline would permit only one mt C/acre (or 3.67 mt CO_2/acre) or a total of approximately 30,500 mt CO_2 total for the project to be credited toward issuance of CRTs. While under version 2.1, the baseline averaged 30 mt C/acre, overall crediting for avoided depletion under version 3.0 would be limited to the higher level of 39 mt C/acre. The results estimated here are quite tentative; nonetheless, they suggest that the emissions reductions attributable to the avoided depletion of standing carbon stocks could be reduced by about 90%. We also prepared rough estimate of the impact of the new Common Practice limit on crediting for avoided depletion of a well stocked redwood forest which suggested a reduction of 50% under version 3.0 vs. version 2.1.

Such a significant difference in accounting for avoided depletion of well-stocked stands adopted in version 3.0 of the Forest Protocol raises a number of policy and statistical questions that we believe require further review and analysis. We note that all carbon accounting is driven by policy goals, e.g., to encourage measurable and verifiable reductions in GHG emissions through a range of activities, which for forests, include avoiding the loss or depletion of existing forest carbon stocks. As to the latter project activity, the first question arises, what is the appropriate Baseline reference point against which conservation of the existing stores in a carbon rich older forest is benchmarked? The next question is, given a particular Baseline methodology, would the level of calculated emissions reductions awarded be sufficient incentive for a forest owner to undertake the project and make an enforceable commitment to avoiding the depletion of the forest to the extent permitted by law and rewarded by the marketplace? While some feel that only one or the other of these two questions needs to be satisfactorily answered, we believe both do if we are to gain participation in development of emissions reductions projects and make headway against the market forces that have made forest loss and depletion the second greatest source of excess CO_2 in the atmosphere.

The stakeholder work group that developed much of what is contained in version 3.0 of the Protocol had a similar discussion in regard to encouraging participation among forest owners who have forests with carbon stocks below the Common Practice level: Should these owners be required to grow their stocks to at least the FIA live stocks mean in order to receive credit? The majority of the work group believed that this would severely limit participation so the policy judgment was made to allow credit for sustained increases in stocks from a specified Baseline level regardless of whether those stocks would ever increase to the Common Practice level for the relevant Assessment Area. By this and other examples we can see that the rules for emissions reductions accounting are driven by policy goals that are then supported by using scientifically grounded measurement and other criteria to assure conservative quantification.

Another concern we have with the use of the FIA mean live carbon stocks as the metric that represents Common Practice is whether the reference population of plots is correctly defined and statistically sufficient. The plot data used for version 3.0 comprises all private forestland, whereas the project type is for managed forests. Common Practice among commercially managed forests has tended to drive inventory levels down toward an economically optimal level that in our experience tends to be less than the Common Practice metrics presented in version 3.0. This may be due to inclusion of data from private forests that are voluntarily or legally reserved from harvest, potentially skewing the mean upward with the inclusion of these "uncommon" forests in the defined population. Further, it is arguable that the mean is the appropriate reference point for avoided depletion at all as the majority of the landscape may have lower stocking levels, but small pockets of older forest pull the average upward for the region. These anomalous older forests are just the ones that are most at risk of depletion, so it is reasonable to suggest they not be compared to a number that includes them, but rather to the business-as-usual managed forest landscape shaped by market forces. The question of statistical sufficiency speaks to whether there are adequate plots representing the appropriate population from which to generate a reliable estimate of live carbon stocks. The quality of the FIA data varies from state to state and eco-region to eco-region.

7.2.3 Application outside of California

The Baseline methodology utilized in the Forest Protocols could be applied outside of California fairly readily. This would require characterizing the regulatory threshold prevailing in the jurisdiction in which a project is located; however this characterization is performed in timber appraisals routinely used to value and transact tens of millions of acres of timberland across the country. Further, using appraisal standards for baseline characterization would assure that Baseline conditions represent not only legally binding limits such as regulations or pre-existing title encumbrances, but also address the physical and financial feasibility of the activities. Version 3.0 incorporates both a regulatory and financial feasibility test to enable Baseline development in jurisdictions across the U.S. As the first project is developed in any new forest type and jurisdiction, there will be considerable effort required to conservatively characterize and justify the Baseline assumptions for business-as-usual activity. We also note that the FIA data-set nationally is not seamless and varies in its consistency and intensity of sampling. This may present problems for the use of the FIA mean as the Common Practice benchmark when projects are developed in various parts of the country.

7.3 Project Activity Modeling

While it is appropriate to verify the Project projections once at the initial Project Certification (absent material changes in inventory data), in practice, we note that the use of modeling to project emissions reduction from Project activity only provides very generalized guidance for potential emissions reductions unless the Project model is well-maintained and updated over time. Indeed, project activity projections play an important role in helping to manage the disposition of emissions reductions by placing short-term emissions reductions generated by the project within the context of the long-term emissions reductions profile forecast for the project. Thus, project developers (with projects registered under version 2.1 of the Forest Protocols) can then limit the sales of emissions reductions generated early during the project lifetime in order to ensure that enough emissions reductions are maintained to cover any anticipated future reversals (e.g., those caused by fluctuations in the baseline). To be an on-going management tool, the model results need to be recalibrated by project owners over time to reflect actual timber harvest, other forest management activities and the inevitable differences between modeling and actual inventories that will arise over time.

7.4 Harvested Wood Products

As discussed above, the inclusion of harvested biomass transferred to wood products increases the realism of the accounting generally, but lacks the same degree of rigor that is required of the other carbon pools. There are great uncertainties associated with tracking and measuring wood products along the chain of custody. Furthermore, accounting of indirect or secondary emissions of wood products in use is wholly lacking. We believe that even the accounting methodology in version 3.0 Forest Protocols needs further refinement to better incorporate these uncertainties and emissions associated with the manufacture, transport and use of wood products. While some argue that it is better to over-estimate the continued stores in wood products so as to err on the side of conservative calculations of emissions reductions, we believe that accuracy in accounting should be improved to the greatest degree possible at the project level.

In version 3.0 of the Forest Protocols the potential additional transfer of some amount of carbon from harvested wood products into landfills after discard is included in the wood products accounting methodology only when less wood is being harvested in the project than in the baseline case. The rationale for this is to produce a more conservative estimate of emissions reductions. We are leery of including any estimate of long term stores in landfills given several factors: landfill data is of poor quality; the powerful methane emissions from landfills are not incorporated into the estimates of carbon stores to calculate net greenhouse gas emissions; there are issues of control and ownership of the carbon in landfills; and the fate of wood discarded after use is shifting rapidly due to public policies and programs promoting recycling, composting and biomass energy. This is an example of an instance where, the Reserve chose a methodology that produces a more conservative result, but which may also yield a less accurate one.

Inclusion of harvested wood products in the accounting for forest management projects is in most cases not likely to have a significant impact on long term emissions reductions calculated for most such projects, as described in more detail above. In most, even with a focus on conserving and restoring on-site carbon stocks through changed forest management intensity and timing, the primary change that the addition of wood products to baseline and project calculations tends to be to the timing of timber harvest and less to the volume. Therefore the timing of emissions reductions changes more than the volume, which may be minimized with the use of an averaged baseline.

7.5 Permanence

The range of risks to Permanence, combined with other project risks (market, regulatory, verification, measurement variability, etc.) are critical to acknowledge and seek to mitigate, especially considering the long-term nature of the project commitment. Since the Forest Protocols are young and project history extremely short, potential losses cannot be estimated reliably. Regardless of the requirements of the Forest Protocols, project owners are well served to hold back a loss reserve of at least 10% of annual registered emissions reductions, as either unobligated or not transferred to others, to self-insure against the range of risks to the permanence of registered emissions reductions (this would be prudent even if, under the risk assessment in version 3.0, a project were to have its Buffer Pool contribution calculated at a lower level)

We also note that the Permanence of a Project depends on ensuring consistency in Project activity during a very long period over which the likelihood of at least one ownership change grows substantially. Therefore, the use of multiple legal instruments to mitigate risks to permanence from ownership and management changes would provide the greatest assurances for the longevity of registered emissions reductions. In particular, in addition to the requirement of an explicit contract with the Reserve that provides for clear remedies for breach, as included in version 3.0 of the Forest Protocols, the use of a conservation easement has significant added value for prevention of over-harvesting or development-driven loss of carbon stocks in the event of involuntary transfers. As described above, conservation easements also ensure additional carbon stores are more likely to be retained in a genuinely permanent manner, above and beyond the 100-year Project Lifetime. Their grant to a conservation entity provides an independent, permanent level of monitoring of land use restrictions that form the basis of project activity in most forest management based projects.

7.6 Certification

One key aspect of project development under the Forest Protocols that is not addressed in this study is the Certification (*a.k.a.* verification) process. Therefore, we will simply note that this is the greatest on-going requirement and expense of Reserve projects. The independent certification process provides assurances to the Reserve, purchasers of emissions reductions and the public as to the reality of registered emissions reductions. The process also can provide helpful guidance for participating landowners and promote on-going improvements in the overall accounting system. However, it should be noted that certification represents a risk to landowners as well, as certifiers must sign off on project accounting prior to the Reserve's acceptance and registration of emissions reductions. Landowners could be subjected to expensive, burdensome certification processes and inconsistent interpretations of the Forest Protocol's requirements absent greater efforts to provide clear certification policies and procedures, as well as guidance for interpretation of the Forest Protocols. The new version of the Forest Protocols helps address some of these concerns, providing for field verification at 6-year intervals after the initial verification, and desk verification of annual stock change reports in intervening years, allowing for market delivery of verified emissions reductions in a more cost effective manner.

7.7 Entity Level Reporting

In addition to project level reporting, which has been the focus of this study, under version 2.1 of the Forest Protocols project developers are required to report their stocks at the entity level, which includes their biological and non-biological emissions, including project and non-project related activities alike. The intent of this requirement is to help entities to understand better their full greenhouse gas emissions profile, as well as to help prevent certain forms of activity-shifting leakage from occurring. If a project developer were to decrease harvest rates on some of his or her forestland as a part of planned carbon project activities but were to increase the rate of harvest on the remainder of his or her forestland, the emissions reductions reported for the project would be displaced by the increased emissions resulting from higher harvest rates on the project developers non-project land. Entity-level reporting would reveal the diminution of the project-level emissions reductions that would be caused by this form of leakage.

In the case of the Bascom Pacific Forest, entity-level reporting is rather simple due to two conditions. First, the project site constitutes the entire acreage of the lands owned by the entity that would be reporting and registering the project. As a result, entity-level biological stocks are identical to project-level stocks and would be reported as such. Second, the entity that owns the project site does not actually manage the land, nor does it own any equipment associated with management of the land, including logging equipment or mills. Rather, a forest management firm manages the land on behalf of the entity and the logs harvested from the project site are sold to a mill owned by a different entity. Thus, the project developer would not be required report any non-biological emissions as a part of entity-level reporting since all non-biological emissions associated with the project are owned, and would thus be reported by, a different entity.

Since these conditions exist for the entity that owns the Bascom Pacific Forest, only biological emissions (or carbon stocks in this case) for the project site would be required to be reported in order to fulfill entity-level reporting obligations.

7.8 Costs and Returns of Undertaking a Forest Project

When a landowner undertakes a project under the Forest Protocols, they are, in effect, entering a new business, producing certified emissions reductions. As with any forest product, emissions reductions have their costs and returns. Any landowner considering the development of a forest project should carefully consider the long-term commitment of resources, the current novel and unpredictable nature of the carbon market and the potential financial returns.

We conducted a pro forma financial analysis of the hypothetical Bascom Pacific project presented here and this analysis indicated an increase in net present value (NPV) from the net proceeds of the project of approximately $4 million or $435/acre.

The assumptions used in this analysis were:

1. Periodic emissions reductions were calculated using the "averaging" method to smooth out the fluctuations between reductions and reversals, so as to more accurately represent the results of how a final project would likely be developed for registration under either Protocol.[4]
2. 10% of emissions reductions were held back for a loss reserve or self-insurance
3. Emissions reductions were transacted at \$9/mtCO_2e (representative of with 2008 – 2009 market pricing) with this price held constant for the 100-year lifetime.
4. Verifications were estimated at $75,000/5-year period, incorporating one field verification and four desk reviews.
5. Other costs for initial project monitoring, Reserve documentation, and project management were estimated at $50,000 initially and $25,000 for subsequent periods
6. Cost of sales was estimated at 5% of sales receipts

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[4] We note that in the event that the Baseline was recast under version 2.1 as described on page 56, there would still be a period of reversals as the forest regenerated after the initial series of clear cuts. This would be handled, as is the case in the actual Van Eck Forest Project, by the landowner holding back a portion of the first 25 years' verified emissions reductions from the market to serve as a bank to fund the subsequent reversals. Regardless, the net emissions reductions at the end of 100 years are the same.

7. A discount rate of 15% was applied to the net earnings stream for the 100 years

Given the early stage of both the application of the Forest Protocols in actual projects and the carbon market, these assumptions are based on limited data and experience, and are therefore relatively speculative, as reflected in the discount rate applied. It is our hope that with wider application, and more efficiency gained throughout (but in particular in the certification process), these assumptions could prove conservative.

On balance, after reviewing the results of the hypothetical Bascom Pacific Forest project, and comparing them to other projects under the Forest Protocols with which we are familiar, we believe that the potential financial returns from such projects could provide an incentive for landowner participation, while fostering long term forest conservation and significant net gains from long term reduction of CO_2 emissions. We note that larger projects will likely have savings of scale as compared to smaller projects, especially in regard to project development and inventory costs. The Love Creek Forest is the smallest project developed under version 2.1 of the Forest Protocols with which we are familiar. It is about 350 acres and it, too, projects a modest but net positive financial return for the landowner under similar revenue and cost assumptions. Nonetheless, we believe that the Reserve should seek to develop a scheme whereby landowners of smaller properties could formally collaborate in registering projects, while still meeting the rigorous measurement and quantification requirements of the Forest Protocols.

In closing, we note that the Climate Action Reserve's Forest Protocols have been and will continue to evolve as developers, landowners, verifiers, the Reserve and policy makers apply them and learn from the results. Given the novel challenges presented by climate change and the urgent need for action to address them, we believe it is reasonable and appropriate to move ahead with emissions reduction projects under the prevailing state of the art with an understanding that it will incorporate improvements through an iterative public process, rather than wait for a theoretical perfect system before taking action.

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9.0 Glossary

C	Carbon
CACTOS	California Conifer Timber Output Simulator
CO_2	Carbon dioxide
DBH	Diameter at breast height
FIA	Forest Inventory and Analysis program of the USDA
GHG	Greenhouse gas
mt	Metric tons
MBF	Thousand board feet
PFT	Pacific Forest Trust
PIA	Project Implementation Agreement
WESTCARB	West Coast Regional Carbon Sequestration Partnership

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DEMONSTRATION OF THE CLIMATE ACTION RESERVE FORESTRY PROTOCOLS AT LATOUR DEMONSTRATION STATE FOREST

Timothy A. Robards and Doug Wickizer

California Department of Forestry and Fire Protection

DOE Contract No.: DE-FC26-05NT42593

Contract Period: October 1, 2005 - May 11, 2011

Arnold Schwarzenegger
Governor

DEMONSTRATION OF THE CLIMATE ACTION RESERVE FORESTRY PROTOCOLS AT LATOUR DEMONSTRATION STATE FOREST, WESTCARB FINAL REPORT

PIER FINAL PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
California Department of Forestry &
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September 2009
CEC-500-05-029

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Demonstration of the Climate Action Reserve Forestry Protocols at LaTour Demonstration State Forest, WESTCARB Final Report is the final report for the LaTour State Forest Carbon Registry Demonstration Project (contract number 500-05-029) conducted by the California Department of Forestry and Fire Protection. The information from this project contributes to PIER's Climate Change Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier or contact the Energy Commission at 916-654-5164.

Please cite this report as follows:

Robards, T.A. and D. Wickizer (California Department of Forestry and Fire Protection). 2009. Demonstration of the Climate Action Reserve Forestry Protocols at LaTour Demonstration State Forest, WESTCARB Final Report. California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-05-029.

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Acknowledgments

Thank you to the management and staff of LaTour Demonstration State Forest including Bruce Beck and Ben Rowe for assisting in implementing this project and associated treatments. Thanks to the summer field crews for climbing through the brush with us.

The invaluable assistance of Dr. E.M. (Ted) Bilek of the USDA Forest Service, Forest Products Laboratory, for guidance in modifying the CVal spreadsheet tool was greatly appreciated.

Demonstration of the Climate Action Reserve Forestry Protocols at LaTour Demonstration State Forest, WESTCARB Final Report

Timothy A. Robards and Doug Wickizer[1]

Abstract

This project provides two case studies of improved forest management and reforestation projects using version 3.1 of the Climate Action Reserve (CAR) forest protocol. Public and private lands are considered as separate scenarios. The baselines, project activity and Certified Reserve Tonnes (CRTs) were calculated for 100-year time periods. An economic analysis is provided for each scenario. A fire risk modeling analysis was also conducted.

The reforestation projects produced net CRTs of 118 to 216 tonnes per acre of CO2e, but were not economically feasible without subsidy. Buffer pools were 10% to 12% on private lands and 18% to 20% on public lands. The use of the improved forest management type on public lands was not feasible. The improved forest management projects produced net CRTs of from 162 to 178 tonnes per acre of CO2e.

An economic analysis showed that an improved forest management project, where the initial carbon stocks were well above the assessment area mean, yielded a net present value (NPV) of $617 per acre ($1,524 per hectare) at a $9/t price with no land purchase costs. At a price of $20/t the NPV value was $1,536 per acre ($3,794 per hectare). An improved forest management project with starting stocks just below the common practice yield NPVs of $65 ($159 per hectare) and $393 ($972 per hectare) for the $9/t and $20/t prices respectively. The wood products pool was a negligible factor in these analyses primarily because regenerated stands were not projected to grow at an improved growth rate over existing stands. Should this occur then additional CRTs will be realized over the life of the project. Reforestation projects produced more CRTs over the 100-year project life but improved forest management projects produce higher CRTs earlier without establishment costs, resulting in more favorable economic results.

The fire analysis showed that a strategically placed shaded fuel break bisecting the project area would likely provide a net benefit to carbon sequestration. There is currently no forestry protocol project type for fuel reduction and additional work needs to be done to quantify the carbon emission and sequestration tradeoff.

Keywords: sequestration, forest, reforestation, forest management, carbon offset, climate change, mitigation, Climate Action Reserve, protocol

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1.0 Overview of the Climate Action Reserve Forestry Protocols

The Climate Action Reserve (CAR) is a private non-profit national offsets program headquartered in Los Angeles that focuses on regulatory-quality emissions reporting and reductions. CAR also accredits and oversees independent project verifiers. Verified reduction credits, which are serialized and tracked by CAR, are called Certified Reserve Tonnes or CRTs.

A project that has CRTs may, as of this writing, sell them on the voluntary over-the-counter market or hold them for later trading in either a voluntary market or as offsets under emerging cap and trade market mechanisms. Cap and trade programs are proposed and in various stages of development, including already active, at the state (i.e. California), regional (i.e. Western Climate Initiative (WCI), Regional Greenhouse Gas Initiative (RGGI)), national and international levels. The Voluntary Carbon Standard Association (VCS), an international standards group focused on project-based voluntary GHG reductions, has recognized CAR offsets as meeting their criteria for protocols, verification and tracking. This allows CRTs to also be traded as Voluntary Carbon Units (VCUs).

Two CAR protocols exist that are related to trees and forests; the Forest Project Protocol (version 3.1) and the Urban Forest Project Protocol (version 1.1). These are reporting protocols for use by project developers. Each reporting protocol has an associated verification protocol that is used by the third-party verifier. The Urban Forest Project Protocol has only one project type, tree planting and maintenance. The Forest Project Protocol has three project types; they are:

- Improved Forest Management
- Reforestation
- Conservation

This demonstration project includes examples of the forest management and reforestation project types. A fuels treatment analysis, not related to the current CAR protocols, is also included in this report.

The CAR has recently undergone a major revision (version 3.1, approved by the CAR Board on September 1, 2009, adopted by the Cal. Air Resources Board on September 24, 2009) of the Forestry Project Protocols to address the following objectives.

- Allow greater landowner participation, particularly publicly-owned lands and industrial working forests.
- Make improvements that improve the protocol's clarity, accuracy, conservatism, environmental integrity, and cost-effectiveness (where doing so does not infringe on other principles).
- Design to allow use outside of California with minimal additional analysis.

The timing of the protocol revisions made it impossible to take this project through the verification process, as these revisions were necessary to have a valid project on public lands. Revision to the easement requirement and an appropriate baseline for public lands not subject to the California Forest Practice Act was required. However, the timing of this report and associated products coinciding with the release of the revised protocols provides an excellent opportunity to use this project as information for project developers. The rest of this section covers the specific guidelines for a reforestation and forest management project, data requirements, and permanence and leakage risk assessments.

The project start date may go back to 2001 if the project was initiated within one year of the revised protocol approval (September 1, 2009), otherwise it may go back one year before project filing with CAR. Since this project is initiating within one year of September 1, 2009 we can use 2005 as the starting year. Using the 2005 starting year was convenient based on the existing inventory database. A project implementation agreement must be executed between the project developer and the Reserve when the project is on private land. There is a native species test and a requirement to maintain or increase on-site live pool carbon stocks. A project assessment boundary must be identified and a secondary-effects (leakage) assessment performed. This is to ensure that the project is not causing an effect that counteracts the sequestration occurring directly from the project.

1.1. Reforestation Project Type

A reforestation project type may be defined as being out of forest cover (10% threshold) for at least ten years or as having sustained a catastrophic event in the last ten years. The project has to have been in forest cover in the past. This project uses the definition of being out of forest cover for over ten years. Both public and private lands may use this project type.

A baseline must be established for the project. The baseline uses the current conditions and projects those into the future for 100 years using a qualitative assessment as the guide. The qualitative assessment is based on the likely outcome in the absence of the project.

As with all forest projects the CRTs are accrued after they have occurred. Since stand biomass generally follows a sigmoidal curve, most CRTs will be realized after the initial "lag" phase of stand development. For this reason, inventories are likely not profitable or reasonable to expect until later in the life of the stand.

1.2. Improved Forest Management Project Type

This project type may apply to private or public lands. The use of native species with natural forest management, as defined by the protocol, is required. The forest may or may not be managed for timber. As with the reforestation project type, a 100-year baseline must be established. The following steps are required to construct the baseline for the private lands scenarios.

1. Determine the applicable forest type to look up the average stocking (common practice) from the provided tables (Appendix F).
2. Look up the average per acre live biomass carbon stocking, which was derived from the USDA Forest Service, Forest Inventory and Analysis (FIA) data.
3. Calculate the average per acre current carbon stocking for the live biomass in the project.
4. Decide if you are below or above the common practice (FIA average). How to calculate reductions will be based on this.
5. Check for additional constraints on management from legal, physical and economic feasibility perspectives. These may increase the baseline if they are more restrictive than current stocking levels or the FIA average. When the starting stocks are below the common practice, a high stocking reference will be used instead of the initial carbon stocks, if a look-back of 10 years indicates that stocks have decreased. In this case 80% of the highest stocking is used.
6. Model the baseline but do not drop below the legal, physical and economic limits or either the common practice or historical levels for the project area, depending on starting point. The baseline for the on-site and off-site dead wood (forest products) is averaged over the 100-year projection period and kept as separate values so that on-site carbon stocks cannot be reduced due to wood products.
7. If the average wood products landfill pool in the baseline is greater than the landfill pool for a given period then this difference of this amount is subtracted from allowable reductions.

The public lands baseline requires a more qualitative assessment up front before it can be quantified. Planning and budgets are part of this assessment.

1.3 Permanence Risk Analysis

Permanence is defined by the CAR as a period of 100 years from the date credits are issued. A risk analysis provides information to calculate a buffer pool requirement or alternatively, private insurance against reversals of CRTs. A separate risk assessment was conducted for both of the projects under a private and public lands scenario. Appropriate reductions in the form of a buffer pool will be applied and carried through the economic analysis.

1.4 Leakage Risk Analysis

There are separate leakage analyses for reforestation and forest management project types. For reforestation, an assessment of activity shifting leakage is required where crop lands or grazing is an issue. Using the flowchart provided it is quickly determined that the leakage risk is zero for reforestation. Decreases in harvest amounts over the 100-year period that are due to the project, relative to the baseline, are multiplied by 20% to derive the penalty for leakage on improved forest management projects. This is to account for market leakage or that the wood product demand will be partially met from other sources.

2.0 Demonstration Projects

Two contiguous areas within LaTour Demonstration State Forest (LDSF) were considered as separate projects for the purposes of this demonstration (Figure 1). The projects were treated as public and private lands in separate scenarios, so that the implications to CRTs and the economics could be compared. Figure 2 shows the locations of the project areas on the Forest. LDSF is located in Shasta County in the Southern Cascade Mountains. The Forest is at the headwaters of the South Cow Creek drainage, which eventually flows into the Sacramento River. White fir and mixed conifer are the primary forest types with some ponderosa/Jeffery pine types where planting has occurred.

The Forest was acquired in an essentially uncut condition in 1946 with single tree harvesting that focused on improving forest health commencing in the 1950s. Small group selection harvests were started in the 1990s to begin to regenerate mature forest and to address pest issues. A wildfire (Whitmore Fire) burned approximately 500 acres of the lower end on the west side in 1978 (figure 1). Salvage operations occurred at that time and the area was planted. Shrub competition severely retarded the growth of the regeneration, either slowing conifer growth or killing the trees (figure 3). Some portions of the Forest have been brush fields for as long as the State has had the property. Some of these are around McMullen Mountain and some of the area burned in 1978 was in brush.

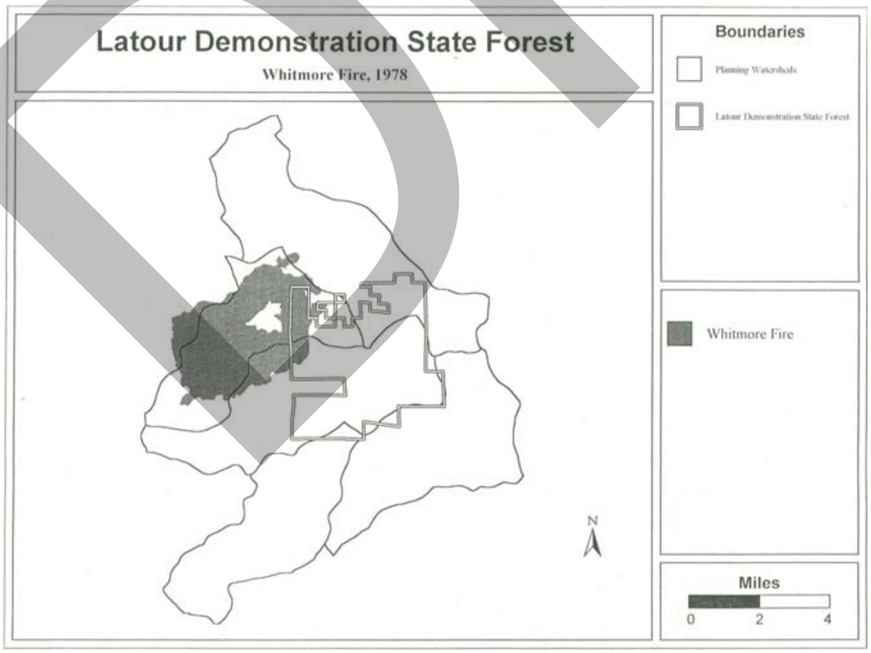


Figure 1. Whitmore (1978) fire boundary showing extent onto LDSF.

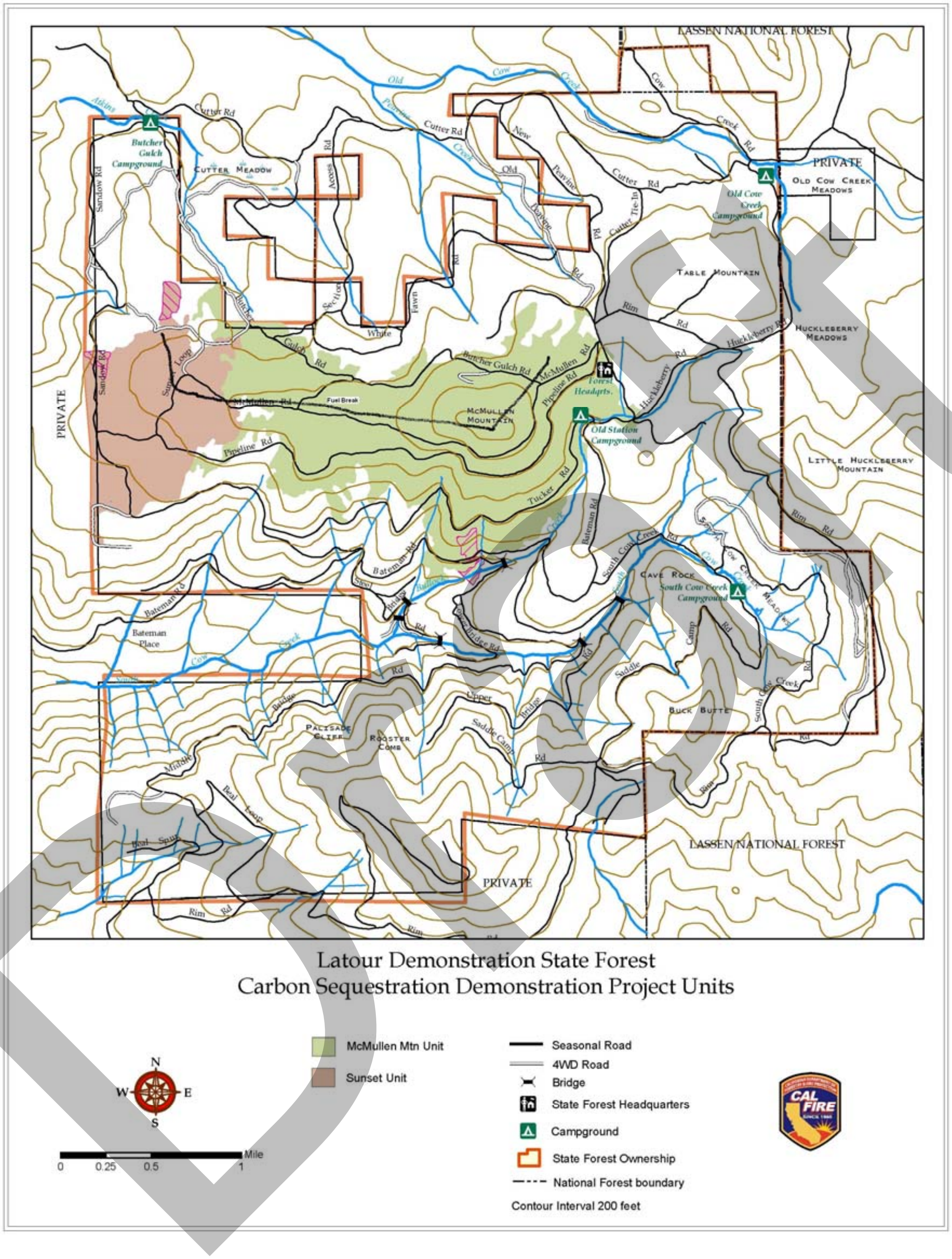


Figure 2. Map of LaTour Demonstration State Forest showing the two project areas.

Figure 3. Example of 1978 Whitmore burn in 2007 showing mix of survivor trees, planted pine regeneration, competing shrubs and naturally seeded white fir regeneration.

A number of areas were treated as part of this project (figure 4). Approximately 200 acres were treated (table 1). Units 2, 5 and a corner of 4 were the reforestation areas, but most of the treatments were improved forest management that fully occupied the sites with conifers and improved stand growth. These treatments were not necessary to have improved forest management projects, but aided in demonstrating reforestation. Initially, we estimated that more of the treated acres would be allocated to the reforestation project type, but subsequent measurements and analysis showed that the areas were appropriately considered as improved forest management.

Reforestation project eligibility was evaluated using Appendix E of the protocols where the project developer walks through a decision matrix to arrive at an eligibility determination. Site preparation costs were high due to the existing brush that was treated. The value of the harvested products was determined from looking up the Southern Cascade mixed conifer type in Appendix F, which gave a medium value. Rotation age was also taken from Appendix F and was 60 years. Site class was not needed as all projects in this category were eligible.

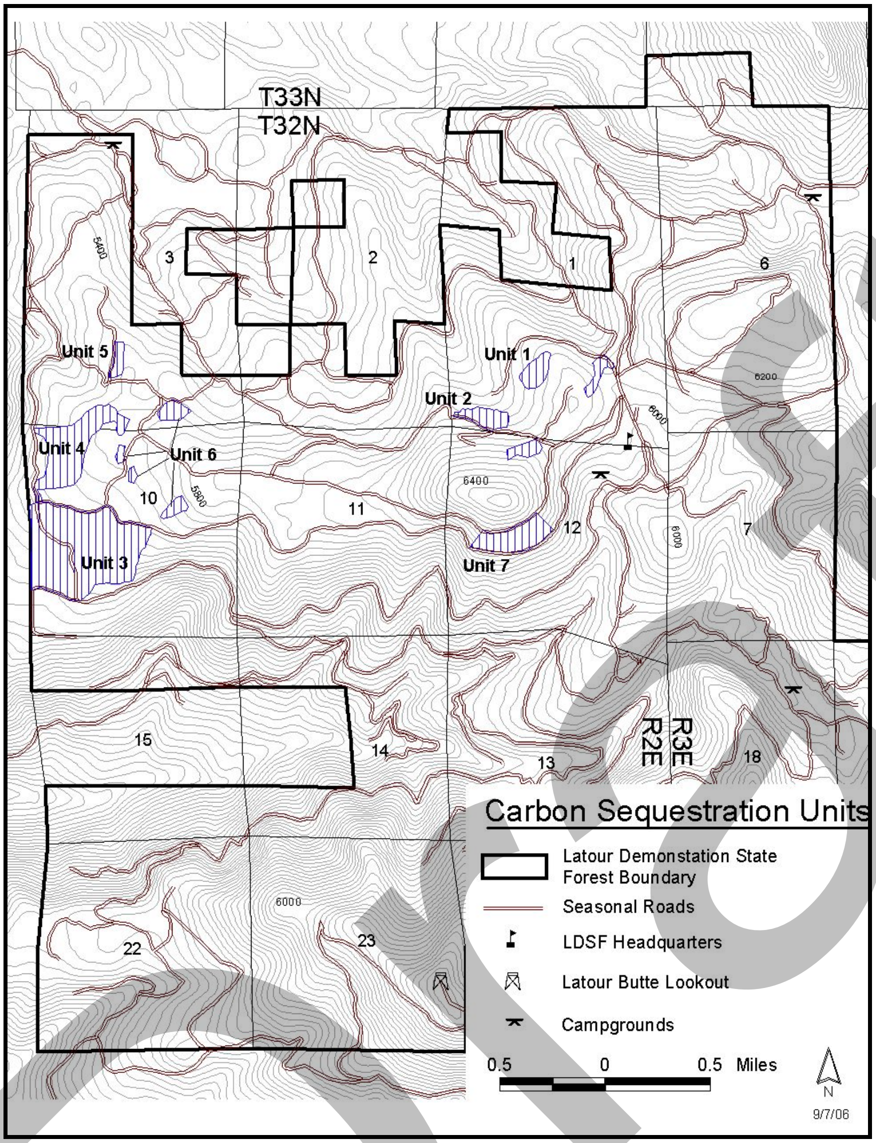


Figure 4. Treatment units, except unit 7 which was not installed. Units 2, 5, and part of 4 are the regeneration units.

Table 1. Treatment descriptions.

UNIT #	LOCATION	ACREAGE (APPROXIMATE)	TYPE OF WORK	SCHEDULE
1	OLD PEAVINE SPUR (SE/4Sec. 1)	20 acres	Brush piling, Spraying, Planting	June 2007 Spray spring 2008 Plant Fall 08/Spring09
2	UPPER BUTCHER GULCH ROAD (SW/4, Sec. 1)	20 acres	Brush Mastication, Spraying, Planting	June 2007 Spray spring 2008 Plant Fall 08/Spring09
3	SANDOW RD. TO PIPELINE RD (Sw/4, Dec. 10)	80 acres	Brush Release/Hand Spray	June to October 2007
4	BETWEEN SANDOW RD. AND SUNSET RD. (NW/4, Sec. 10)	35 to 40 acres	Release hand spray of 2000 Brush piled Unit	June to October 2007
5	SPUR ROAD OFF SANDOW RD.(NW/4 of SE/4, Sec. 10)	7 to 10 acres	Brush piling, Spraying, Planting	June 2007 Spray spring 2008 Plant Fall 08/Spring09
6	SCATTERED SMALL GROUPS OPENINGS BETWEEN McMULLEN RD. AND TUCKER RD.	20 to 25 acres	Hand spray	June 2007

2.1. Sunset Project Description

This unit is on the west side of the Forest, is about 428 acres (173 hectares) at 40.656° N and 121.743° W. The unit has an average elevation of 5,544 feet (1,690 m) with a range of 5,369 feet (1,636 m) to 5,749 feet (1,752 m) and has a relatively high ponderosa pine (*Pinus ponderosa*) component relative to the other mixed conifer species, partly due to the planting that occurred after the 1978 Whitmore Fire. The other dominant conifer species are sugar pine (*Pinus lambertiana*), incense-cedar (*Calocedrus decurrens*), white fir (*Abies concolor*), and red fir (*Abies magnifica*). The average climate (PRISM 2009) from 1971 through 2007 for this unit was 58.4 inches (148 cm) precipitation falling as rain and snow with an average January daily minimum temperature of 24.8° Fahrenheit (-4.0° C) and average July daily maximum temperature of 82.5° Fahrenheit (28.1° C). Table 2 shows the acres (table 3, hectares) by forest type and project type.

Table 2. Acres for each unit by forest type and project type.

	Sunset			McMullen Mtn.		
Forest Type	Reforestation	Management	Total	Reforestation	Management	Total
Ponderosa Pine	10.2	243.6	253.8	0.0	30.5	30.5
Mixed Conifer	0.0	7.8	7.8	8.5	104.4	112.9
White Fir	0.0	174.4	174.4	10.1	1,010.1	1,020.2
Red Fir	0.0	0.0	0.0	0.0	47.1	47.1
Total	**10.2**	**425.8**	**436.0**	**18.6**	**1,192.1**	**1,210.7**

Table 3. Hectares for each unit by forest type and project type.

	Sunset			McMullen Mtn.		
Forest Type	Reforestation	Management	Total	Reforestation	Management	Total
Ponderosa Pine	4.1	98.6	102.8	0.0	12.3	12.3
Mixed Conifer	0.0	3.2	3.2	3.4	42.3	45.7
White Fir	0.0	70.6	70.6	4.1	408.9	413.0
Red Fir	0.0	0.0	0.0	0.0	19.1	19.1
Total	**4.1**	**172.4**	**176.5**	**7.5**	**482.6**	**490.2**

2.2. McMullen Mountain Project Description

This unit (figures 5 - 7) is centered on McMullen Mountain in the north/center of the Forest, is about 1,211 acres (490 hectares) at 40.640° N and 121.703° W. The unit has an average elevation of 5,850 with a range of 4,970 feet (1,515 m) to 6,411 feet (1,954 m) and is dominated by white fir stands. The average climate (PRISM 2009) from 1971 through 2007 for this unit was 56.1 inches (142 cm) precipitation falling mostly as rain and snow with an average January daily minimum temperature of 23.8° Fahrenheit (-4.6° C) and average July daily maximum temperature of 81.4° Fahrenheit (27.4° C). Table 2 shows the acres (table 3, hectares) by forest type and project type.

Figure 5. White fir stand that grew up through shrubs through natural succession over many decades; shrub “skeletons” are visible on ground.

Figure 6. Before mastication treatment of reforestation unit on McMullen Mountain. Evidence of past burning in unit, which may explain lack of advanced regeneration.

Figure 7. Post treatment of reforestation unit on McMullen Mountain showing mastication and planted seedling.

3.0 Sunset Project GHG Analysis: Private Land Scenario

This project is mostly a forest management project (tables 2 and 3). The protocols specify that the required carbon pools for a forest management project are the above- and below-ground living biomass, standing and down dead biomass (note that down dead biomass was changed to optional in the final version), and off-site dead biomass. The optional pools are shrubs and herbaceous understory, litter, and soil carbon. Only the required pools will be included in this analysis. The reforestation unit in this project requires that shrubs and herbaceous understory also be estimated. The above- and below-ground live tree biomass is required for reforestation, where they exist. They are rarely present for this unit and will be tracked at future inventory periods (figures 8 to 10).

Figure 8. Reforestation unit in Sunset Project, pre-treatment.

Figure 9. Reforestation unit in Sunset Project showing dead brush and exposed mineral soil with planted conifers, post-treatment.

Figure 10. Reforestation unit in Sunset Project showing grove of residual trees near road, post-treatment.

3.1. Inventory Description and Results

The inventory design and calculation methods are described in appendix I. Table 4 shows the starting carbon inventory estimate for the project along with the sampling error. The sampling error was calculated as 1.645 times the standard error estimate. The protocol calls for a reduction in CRTs where percent sampling errors are between 5% and 20%. This is calculated on the above and below ground live tree carbon. The result was a percent sampling error of 7.9%, which would give a 7.9% reduction to CRTs.

Table 4. Starting carbon inventory for forest management on the Sunset project.

Attribute	Reforestation	Forest Management
No. of Plots	3	141
Mean Trees per Acre	0	95.60
Mean Trees per Hectare	0	236.14
Mean Bole Cubic Feet per Acre (ground to tip)	0	614.41
Mean Bole Cubic Meters per Hectare (ground to tip)	0	1,517.58
Mean Bole C per Acre (tonnes)	0	18.96
Mean Bole C per Hectare (tonnes)	0	46.84
Mean Bark C per Acre (tonnes)	0	8.97
Mean Bark C per Hectare (tonnes)	0	22.15
Mean Crown Branches C per Acre (tonnes)	0	4.17
Mean Crown Branches C per Hectare (tonnes)	0	10.29
Mean Tree Live Aboveground C per Acre (tonnes)	0	32.10
Mean Tree Live Aboveground C per Hectare (tonnes)	0	79.28
Mean Tree Live Belowground C per Acre (tonnes)	0	11.10
Mean Tree Live Belowground C per Hectare (tonnes)	0	27.42
Mean Tree Live C per Acre (tonnes)	0	43.21
Mean Tree Live C per Hectare (tonnes)	0	106.72
Acres	10.2	425.8
Hectares	4.1	172.4
Total Live Tree C (tonnes)	0	18,099.80
Total Lying Dead C (tonnes)	0.04	0.89
Total Standing Dead C (tonnes)	0.14	3.37
Total C (tonnes)	0.18	18,104.05
Standard Error C (tonnes)	na	871.74
Sampling Error (tonnes)	na	1,434.02
Sampling Error (%)	na	7.92%
Mean Shrub Aboveground C per Acre (tonnes)	14.60	na
Mean Shrub Aboveground C per Hectare (tonnes)	36.06	na
Mobile Combustion C per Acre (tonnes)	0.12	na
Mobile Combustion C per Hectare (tonnes)	0.29	na
Total Shrub Aboveground C (tonnes)	148.92	na
Total Reforestation C (tonnes)	150.29	na

3.2. Baseline Calculations

The baseline for the reforestation project type is the existing aboveground shrub carbon, which will be assumed to be a steady stock for the 100-year projection period. In this case it is 148.92 tonnes of C, which is 14.6 tonnes C per acre (36.1 t/h). No dead wood is assumed since the area was a brush field and no large dead wood was accumulating. No harvests were simulated. The reforestation unit is a brushfield that will undergo a slow natural succession process if left undisturbed. Given the fire frequency for the area and the high fuel load and combustion potential of this fuel type, a high-severity disturbance would be likely in a 100-year timeframe, therefore natural reforestation was not assumed. There are no legal requirements to reforest this unit.

The baseline for forest management project types bifurcates depending on whether the starting stocks of carbon are above or below the average for the applicable assessment area (common practice), based on the FIA average. LDSF is located in the Sierra Nevada

– Southern Cascades assessment area, which is 39 tonnes per acre in above- and below-ground live trees for private ownerships (CAR 2009, Appendix F). Since the inventory shows 43.57 tonnes per acre in total live tree carbon, the forest management baseline shall be based on a steady flow from the FIA mean of 39 tonnes per acre. The current inventory will be the starting condition, which is 2005 in this case since that is when the project starts. The resulting baseline will have to be shown to be economically and legally feasible, which it is, given that there are not significant constraints to management of the unit. Economic feasibility is demonstrated by the historic and continued timber sales to local mills from the project area. The area is well roaded, of low to moderate steepness, at the upper end of watersheds and not in habitat that significantly constrains management. The legal constraints are primarily the California Forest Practice Act and associated regulations, which the property has successfully operated under since the creation of the Act. The application of the Maximum Sustained Production of High Quality Timber Products (MSP) constraint could be a significant factor depending on landowner status. In this scenario we consider the project to be private land operated by a non-industrial owner, which allows us to use the MSP option C safe-harbor rules. The management of LDSF has shown a steady increase in inventory over time, including the last 10 year, which may be verified from the permanent plots and periodic management reports. The resulting average stocks over a 100-year period must be at or above the common practice figure of 39 tonnes per acre C.

If a harvest schedule uses optimization, such as a linear program, and the carbon yields are incorporated into it, then the baseline may be easily modeled by changing the optimization function to match the FIA baseline figure. Otherwise, and this is the case here, modeling the harvest schedule must be done by trial and error to approach the FIA figure but end at or above it. The trial and error approach is time consuming unless the project is very small; we recommend optimization or other operations research approaches given the complexity of the carbon accounting rules. This complexity is increased when financial accounting of carbon and timber is included.

A mix of small group clearings and clearcuts along with commercial thinnings from below were used. These silvicultural prescriptions are consistent with current practices on the Forest and produce wood products that may be utilized for dimensional lumber and peelers for plywood, both of which are in demand in the area. In general, the clearfelling, whether as small group selections less than or equal to 2.5 acres (1 hectare) or clearcuts up to 20 acres (8 hectares) in size, was moved up in time and commercial thinnings with a residual basal area of 100 ft^2/acre (22.9 m^2/h) were used to maintain the stocking over time. These opening sizes and residual stocking meet the minimum requirements of the California forest practice regulations. Where clearcuts were implemented, the minimum age requirements of the rules were met. Table 5 shows a summary of the silvicultural treatments simulated for the baseline.

Table 5. Acres of silvicultural prescriptions for the baseline simulation of the Sunset Unit for private lands forest management.

	Year											
Treatment	2005	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	*Total Acres*
Clearfell (Group Selection and Clearcut)	69.7	12.3	6.4	34.9	69.5	0.0	16.0	2.0	203.4	10.9	0.0	*425.1*
Commercial Thin with 100 sq. ft. Residual Basal Area	0.0	14.1	0.0	57.2	252.9	261.0	269.3	312.4	144.2	166.2	31.1	*1,508.4*
Commercial Thin with 120 sq. ft. Residual Basal Area	0.0	0.0	0.0	9.5	0.0	0.0	0.0	0.0	22.0	0.0	0.0	*31.5*
Commercial Thin with 140 sq. ft. Residual Basal Area	0.0	65.6	22.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	*88.1*
Commercial Thin with 160 sq. ft. Residual Basal Area	0.0	4.5	0.0	22.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	*26.5*
Single Tree Selection with 70% Basal Area Retention	0.0	0.0	0.0	117.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	*117.0*
Sanitation and Salvage	0.0	52.7	0.0	44.8	0.0	18.9	0.0	6.2	0.0	0.0	0.0	*122.6*
Shaded Fuel Break with 50 sq. ft. Basal Area Retention	0.0	0.0	0.0	19.1	0.0	19.1	0.0	19.1	0.0	19.1	0.0	*76.4*
Total Acres	*69.7*	*149.2*	*28.9*	*304.5*	*322.4*	*299.0*	*285.3*	*339.7*	*369.6*	*196.2*	*31.1*	*2,395.6*

The amount of carbon associated with the live and dead wood, on-site and off-site, for the baseline is shown in table 6. Note that the project portion of table 6 is explained in the next section, but is presented here so the two may be viewed together for comparison. The landfill pool is not used for reductions calculations unless the baseline average exceeds the project pool, but it is always required to report it. Figures 11 and 12 show the on-site and off-site baseline estimates for the 100-year planning period. Note that the year 2010 is the only 5-year reporting with the rest being 10-year periods. When averaging the baseline only the 10-year periods were used.

Table 6. Tonnes per acre of carbon in the baseline and project activity projections for the Sunset Unit forest management scenario.

	Baseline									**Project**					
Year	On-site Live Tree Baseline	On-site Dead Wood Baseline	On-site Live Tree Average Baseline	FIA Live Tree Average	On-site Live and Dead C Baseline	On-site Live and Dead C Avg Baseline	Off-site Dead C (Wood Products)	Off-site Dead C (Wood Products) for Period	Off-site Dead C (Landfill)	On-site Live Tree Project Activity	On-site Dead Wood Project Activity	Sum of On-site Live and Dead C Project Activity	Off-site Dead C (Wood Products)	Off-site Dead C (Wood Products) for Period	Off-site Dead C (Landfill)
2005	42.86	3.33	40.88	39.00	46.19	43.21	1.03	0.68	0.17	42.86	4.13	46.98	0.00	0.00	0.00
2010	31.23	2.78	40.88	39.00	34.01	43.21	1.82	0.68	0.29	33.31	3.46	36.78	1.10	1.10	0.18
2015	38.16	2.91	40.88	39.00	41.07	43.21	2.22	1.36	0.36	48.42	3.46	51.88	1.53	0.44	0.25
2025	54.68	4.16	40.88	39.00	58.85	43.21	4.30	1.36	0.69	66.46	4.18	70.64	3.41	1.88	0.55
2035	53.25	3.77	40.88	39.00	57.02	43.21	6.58	1.36	1.06	68.51	3.84	72.35	3.71	0.30	0.60
2045	41.50	2.69	40.88	39.00	44.19	43.21	7.60	1.36	1.22	88.79	3.37	92.17	6.16	2.45	0.99
2055	45.25	3.02	40.88	39.00	48.27	43.21	8.70	1.36	1.40	75.37	3.41	78.78	6.44	0.27	1.03
2065	50.29	3.33	40.88	39.00	53.62	43.21	9.74	1.36	1.56	93.63	3.55	97.19	8.56	2.12	1.37
2075	53.60	4.36	40.88	39.00	57.96	43.21	12.70	1.36	2.04	85.22	3.97	89.18	8.83	0.27	1.42
2085	18.91	1.74	40.88	39.00	20.65	43.21	13.41	1.36	2.15	102.02	4.49	106.51	11.05	2.21	1.77
2095	19.38	1.77	40.88	39.00	21.15	43.21	13.49	1.36	2.17	90.40	4.41	94.80	11.28	0.23	1.81
2105	31.80	3.72	40.88	39.00	35.52	43.21	13.63	1.36	2.19	104.93	4.47	109.41	11.39	0.11	1.83

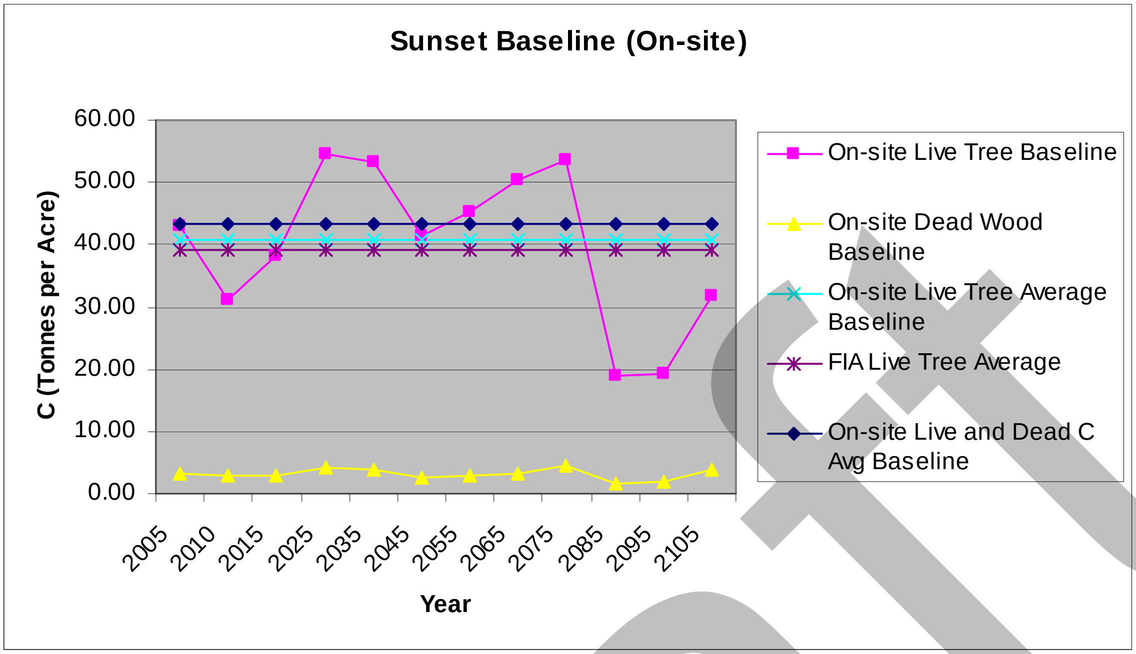


Figure 11. Sunset unit on-site baseline for private lands forest management scenario.

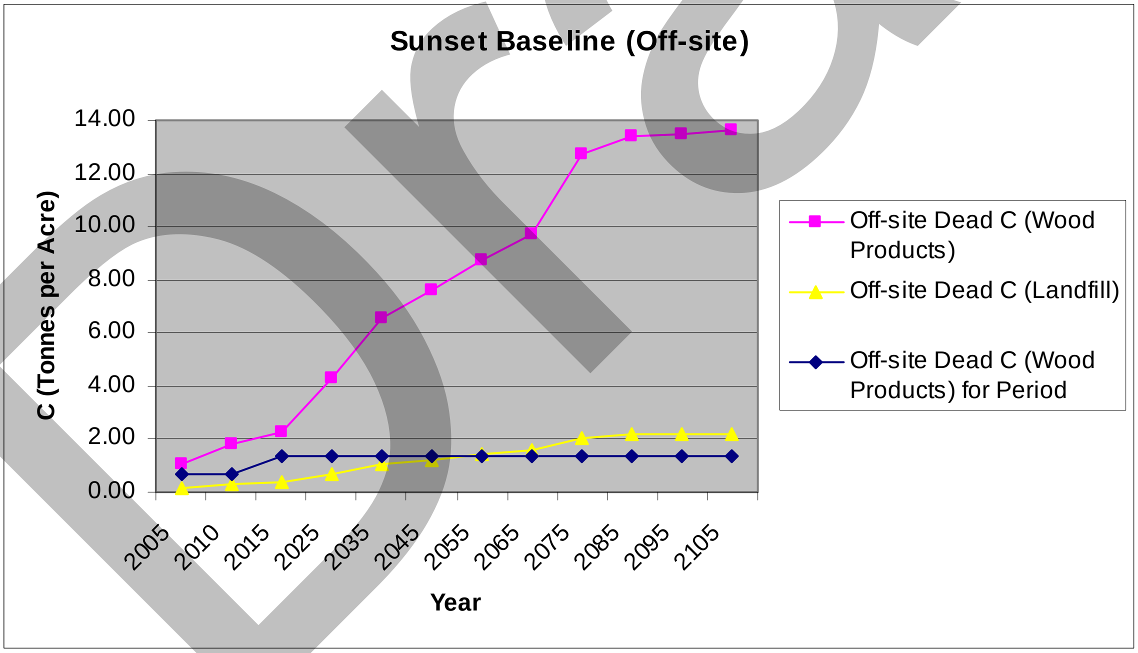


Figure 12. Sunset unit off-site baseline for private lands forest management scenario.

The results of the forest management baseline analysis were that the average on-site stocking was 40.88 tonnes of C per acre (100.97 tonnes C per hectare). Off-site wood products storage (based on 100-year storage in-use) increased over time and had an average over the period of 0.136 tonnes/acre/year C. This equated to a total of 3,765 thousand cubic feet (106,600 m³) of timber over the 100-year period. Assuming six board feet per cubic foot, this equates to 22,590 MBF total or 531 board feet per acre per year over the 100-year period.

3.3. Project Activity Calculations

The project activity for the reforestation project type was modeled as a 10x10 foot spacing of 1-0 planted seedlings of a pine and fir mix, which resulted in 436 trees per acre (1,077 trees/h). Commercial thinnings from below leaving a residual basal area of 120 ft2/ac (27.5 m2/h) were simulated in 2050, 2070, and 2090. The result of the project activity was to increase on-site carbon stocks to 76.3 tonnes C per acre (188.5 t/h) after 100 years (table 7). The total wood products pool (figure 13) projected over the 100-year period was 11.9 tonnes C per acre (29.4 t/h), which was 7.8 thousand cubic feet (MCF) per acre (546 m3/h). Note that no shrub carbon was assumed for the project activity, a conservative assumption.

Table 7. Tonnes per acre of carbon in the baseline and project activity projections for the Sunset Unit reforestation scenario.

	Baseline					**Project**					
Year	On-site Live Tree Baseline	On-site Dead Wood Baseline	On-site Live Tree Average Baseline	Off-site Dead C (Wood Products)	Off-site Dead C (Landfill)	On-site Live Tree Project Activity	On-site Dead Wood Project Activity	Sum of On-site Live and Dead C Project Activity	Off-site Dead C (Wood Products)	Off-site Dead C (Wood Products) for Period	Off-site Dead C (Landfill)
2005	14.60	0.00	14.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2010	14.60	0.00	14.60	0.00	0.00	0.00	0.20	0.20	0.00	0.00	0.00
2015	14.60	0.00	14.60	0.00	0.00	0.00	0.20	0.20	0.00	0.00	0.00
2025	14.60	0.00	14.60	0.00	0.00	19.31	4.40	23.71	0.00	0.00	0.00
2035	14.60	0.00	14.60	0.00	0.00	47.76	4.40	52.16	0.00	0.00	0.00
2045	14.60	0.00	14.60	0.00	0.00	61.13	4.40	65.53	0.00	0.00	0.00
2055	14.60	0.00	14.60	0.00	0.00	49.78	2.80	52.58	4.02	4.02	0.64
2065	14.60	0.00	14.60	0.00	0.00	72.19	2.80	74.99	4.02	0.00	0.64
2075	14.60	0.00	14.60	0.00	0.00	55.56	2.80	58.36	8.84	4.83	1.42
2085	14.60	0.00	14.60	0.00	0.00	69.59	5.80	75.39	8.84	0.00	1.42
2095	14.60	0.00	14.60	0.00	0.00	60.12	5.80	65.92	11.92	3.08	1.91
2105	14.60	0.00	14.60	0.00	0.00	70.50	5.80	76.30	11.92	0.00	1.91

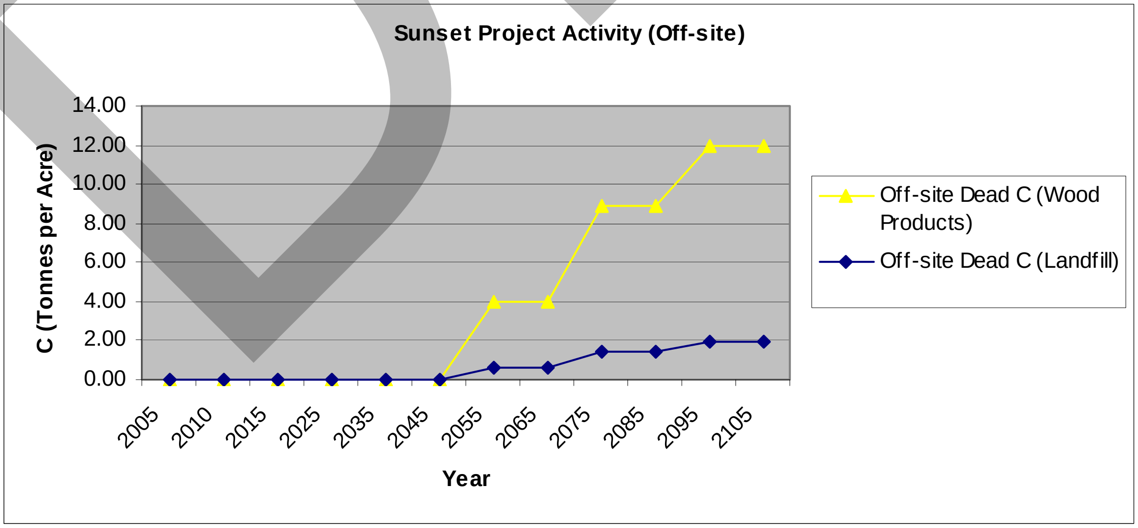


Figure 13. Reforestation project activity projections of off-site dead wood pools.

The project activity for the forest management project type was projected using the stand level treatments identical to the long-term harvest schedule approved by the State of California under 14 CCR 933.11(a), also known as an "option a" plan. The modeling was done using a stand level projection of treatments over a 100-year period that was then summarized across the Forest. Adjustments were made to some stands to meet regulatory requirements for long-term planning. The overall goal was to move over-mature stands to younger age classes over time to create a balance of stand ages. Dead wood was modeled using the mortality functions of FVS with an assumed decay rate of 10% per year. Table 8 shows the silvicultural prescriptions. The project proposes less intensive treatments and fewer acres treated relative to the baseline.

Table 8. Acres of silvicultural prescriptions for the project activity simulation of the Sunset Unit for private lands forest management.

	Year											
Treatment	2005	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	*Total Acres*
Clearfell (Group Selection and Clearcut)	0.0	90.4	6.4	21.7	6.5	21.8	6.4	17.1	6.3	11.9	3.3	*191.8*
Commercial Thin with 100 sq. ft. Residual Basal Area	0.0	13.1	0.0	15.8	0.0	60.7	0.0	39.1	0.0	61.2	0.0	*189.9*
Commercial Thin with 120 sq. ft. Residual Basal Area	0.0	0.0	0.0	0.0	0.0	6.9	0.0	6.9	0.0	6.9	0.0	*20.7*
Commercial Thin with 140 sq. ft. Residual Basal Area	0.0	0.0	25.8	70.5	27.8	58.1	27.8	84.3	28.0	69.1	31.1	*422.5*
Commercial Thin with 160 sq. ft. Residual Basal Area	0.0	4.5	0.0	22.0	0.0	22.0	0.0	22.0	0.0	22.0	0.0	*92.5*
Commercial Thin with 180 sq. ft. Residual Basal Area	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.7	0.0	*5.7*
Commercial Thin with 200 sq. ft. Residual Basal Area	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	0.0	0.0	0.0	*2.7*
Single Tree Selection with 70% Basal Area Retention	0.0	20.3	0.0	143.1	0.0	143.1	0.0	137.3	0.0	143.1	0.0	*586.9*
Sanitation and Salvage	0.0	65.5	0.0	59.7	0.0	31.7	0.0	37.5	0.0	31.7	0.0	*226.1*
Shaded Fuel Break with 50 sq. ft. Basal Area Retention	0.0	0.0	0.0	19.1	0.0	19.1	0.0	19.1	0.0	19.1	0.0	*76.4*
Total Acres	*0.0*	*193.8*	*32.2*	*351.9*	*34.3*	*363.4*	*34.2*	*366.0*	*34.3*	*370.7*	*34.4*	*1,815.2*

The results of the C stocking may be seen in table 6 under "Project". Notice that there is a near-term decrease in carbon stocks, which is a reflection of the near-term harvesting that has occurred in this unit as per the existing harvest schedule. An approximate 20-year cutting cycle is implemented on LDSF. This will have an effect on the reductions calculation that is shown below.

The result of the project activity projection was to increase on-site carbon stocks from an average of 42.86 tonnes/acre (105.9 tonnes/hectare) to 104.93 tonnes/acre (259.2 tonnes/hectare) at the end of the 100-year period. Off-site wood products storage grew to 11.93 tonnes/acre C (29.5 t/h), which was 12 percent less than the 13.63 tonnes/acre C (33.7 t/h) in the baseline. The harvest is projected to total 3,146 MCF (89,088 m3) of timber over the 100-year period. Figures 14 and 15 show the project activity for the on-site and off-site carbon over time.

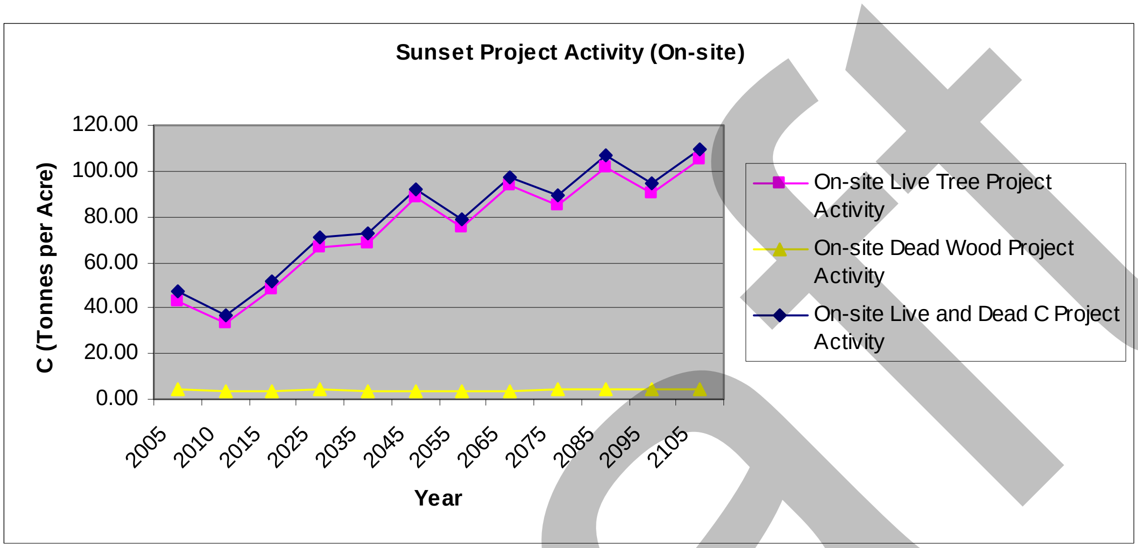


Figure 14. Sunset unit on-site project activity for the forest management project type.

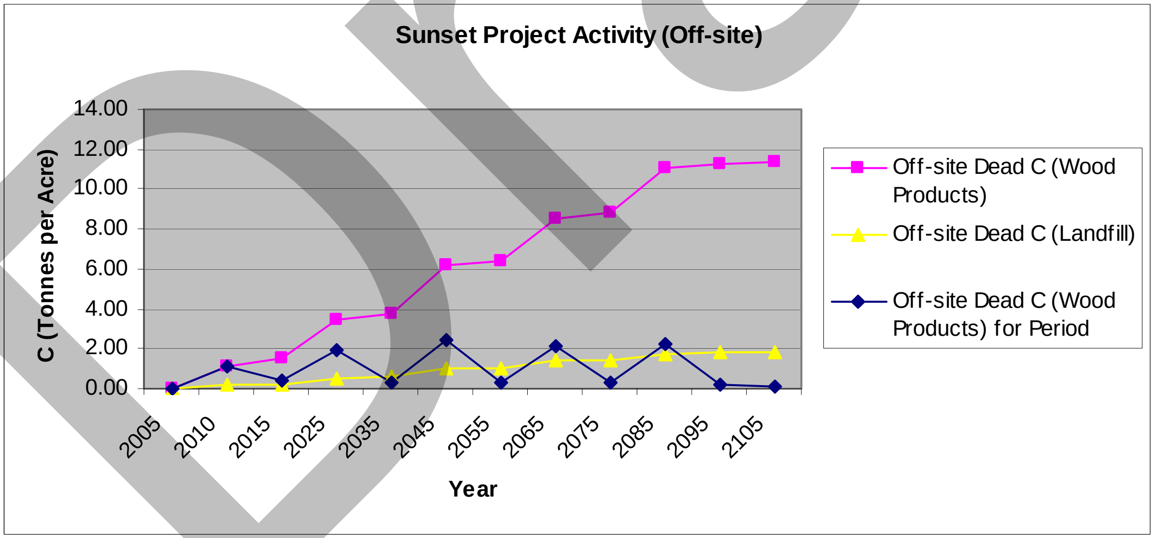


Figure 15. Sunset unit off-site project activity for the forest management project type.

3.4. Gross Biological Reductions

The difference between the project activity and baseline projections is the gross reduction, which is shown in tables 9 and 10 for the 100-year planning period and the two project types. Figures 16 and 17 show the gross reductions and the "smoothed" reductions whereby a reversal due to near-term harvests does not occur. For example, if 100 CRTs were created in decade 2 but due to harvest cycles there were -10 CRTs in decade 3, then only 90 CRTs would be claimed for decade 2. This leads to an estimate of the decadal gross new CRTs, before any deductions for inventory precision, permanence or leakage.

Table 9. Tonnes of carbon in gross reductions before deductions, deductions, and net reductions; for the Sunset Unit reforestation scenario.

	Gross Additionality						**Deductions**			**Net Reductions**			
Year	On-Site Reductions	Off-site Dead C Reductions (Wood Products)	Sum of On and Off-site Reductions	Total Marginal Reductions	Non-reversed Cumulative CRTs	New CRTs	Secondary Effects	Inventory Confidence Deduction	Buffer Pool Deduction	New Net CRTs	Total Net CRTs	Buffer Contribution	Total Buffer
2005	-14.60	0.00	-14.60	-14.60	0.00	0.00	-0.12	0.00	0.00	0.00	0.00	0.00	0.00
2010	-14.40	0.00	-14.40	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2015	-14.40	0.00	-14.40	-14.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2025	9.11	0.00	9.11	23.71	9.11	9.11	0.00	0.00	1.82	7.29	7.29	1.82	1.82
2035	37.56	0.00	37.56	13.85	37.56	28.45	0.00	0.00	5.69	22.76	30.05	5.69	7.51
2045	50.93	0.00	50.93	37.08	42.00	4.44	0.00	0.00	0.89	3.55	33.60	0.89	8.40
2055	37.98	4.02	42.00	4.92	42.00	0.00	0.00	0.00	0.00	0.00	33.60	0.00	8.40
2065	60.39	0.00	64.41	59.49	52.60	10.61	0.00	0.00	2.12	8.49	42.08	2.12	10.52
2075	43.76	4.83	52.60	-6.89	52.60	0.00	0.00	0.00	0.00	0.00	42.08	0.00	10.52
2085	60.79	0.00	69.63	76.52	63.24	10.64	0.00	0.00	2.13	8.51	50.59	2.13	12.65
2095	51.32	3.08	63.24	-13.28	63.24	0.00	0.00	0.00	0.00	0.00	50.59	0.00	12.65
2105	61.70	0.00	73.62	86.90	73.62	10.38	0.00	0.00	2.08	8.30	58.90	2.08	14.72

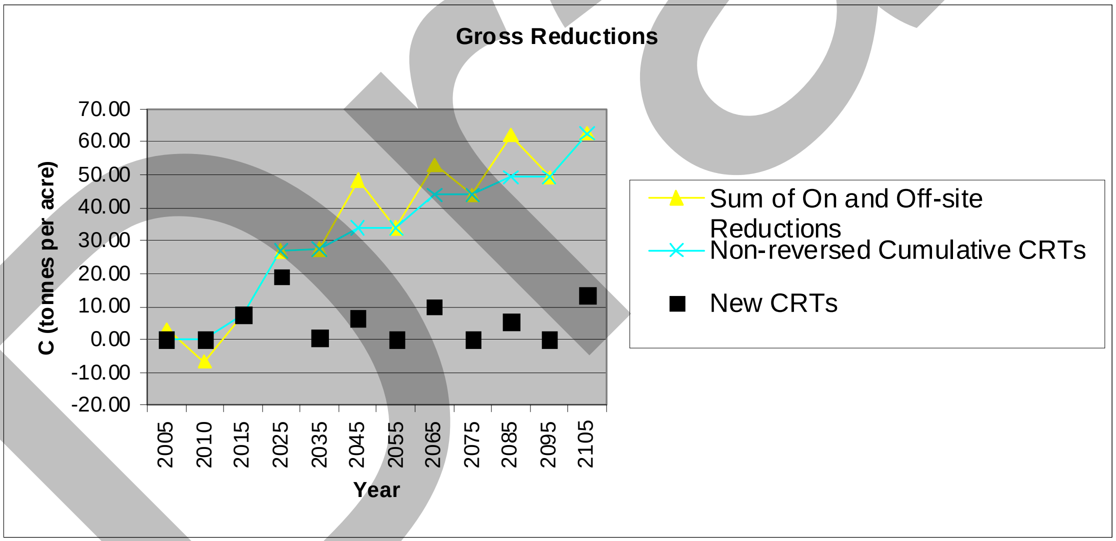


Figure 16. Reforestation, Sunset unit gross reductions and CRTs.

Table 10. Tonnes of carbon in the gross reductions before deductions, deductions, and net reductions; for the Sunset Unit forest management scenario.

	Gross Reductions						Deductions			Net Reductions			
Year	On-Site Reductions	Off-site Dead C Reductions (Wood Products)	Sum of On and Off-site Reductions	Total Marginal Reductions	Non-reversed Cumulative CRTs	New CRTs	Secondary Effects	Inventory Confidence Deduction	Buffer Pool Deduction	New Net CRTs	Total Net CRTs	Buffer Contribution	Total Buffer
2005	3.78	-0.68	3.10	3.10	0.00	0.00	-0.08	0.00	0.00	0.00	0.00	0.00	0.00
2010	-6.43	0.42	-6.70	-9.79	0.00	0.00	-0.08	0.00	0.00	0.00	0.00	0.00	0.00
2015	8.68	-0.93	7.48	17.28	7.48	7.48	-0.16	0.59	1.50	5.24	5.24	1.50	1.50
2025	27.43	0.52	26.76	9.48	26.76	19.27	-0.16	1.52	3.85	13.74	18.97	3.85	5.35
2035	29.14	-1.06	27.40	17.92	27.40	0.64	-0.16	0.05	0.13	0.30	19.27	0.13	5.48
2045	48.96	1.09	48.31	30.39	33.84	6.44	-0.16	0.51	1.29	4.48	23.76	1.29	6.77
2055	35.57	-1.09	33.84	3.45	33.84	0.00	-0.16	0.00	0.00	0.00	23.76	0.00	6.77
2065	53.98	0.76	53.00	49.55	43.91	10.07	-0.16	0.80	2.01	7.10	30.86	2.01	8.78
2075	45.98	-1.09	43.91	-5.65	43.91	0.00	-0.16	0.00	0.00	0.00	30.86	0.00	8.78
2085	63.30	0.85	62.08	67.73	49.24	5.34	-0.16	0.42	1.07	3.69	34.55	1.07	9.85
2095	51.60	-1.13	49.24	-18.49	49.24	0.00	-0.16	0.00	0.00	0.00	34.55	0.00	9.85
2105	66.20	-1.25	62.59	81.08	62.59	13.35	-0.16	1.05	2.67	9.47	44.01	2.67	12.52

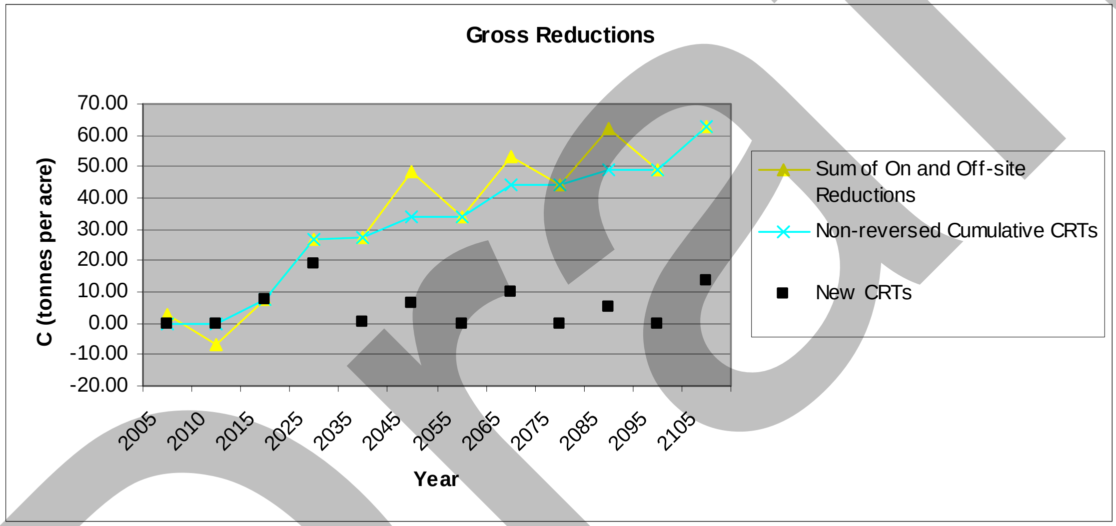


Figure 17. Forest management, Sunset unit gross reductions and CRTs.

3.5. Permanence Analysis

This is a risk analysis, with the details provided in appendix D of the protocol. The analysis is identical for the reforestation and improved forest management project types.

Financial Risk: The financial risk for this private lands scenario assumes a PIA only and no conservation easement, which requires a 5% buffer contribution.

Management Risk: Management risk consists of three types of risks. Illegal removals are given a 0% risk for property in the United States. Conversion to an alternate land use is a function of whether development rights are encumbered by an easement or deed restriction, which is not the case here, incurring a 2% deduction. Overharvesting is the final management risk and is also a function of having a legal restriction on harvesting, which is not the case here and therefore incurs a 2% deduction.

Social Risk: This is a flat 2% for the United States.

Natural Disturbance Risk: There are three components to this risk category. Wildfire risk is a function of fire frequency and burn severity, which may be reduced using specified categories of fuels treatment activity. Default values will be given in Appendix F of the protocols for the assessment areas, but are not yet provided. In this case the risk is given as 3% and is based on the location of the unit on the "front country" where significant fires occur down elevation to the west every 10 years or so and present a risk of expansion into the unit, as occurred in the 1978 Whitmore Fire. While shaded fuel breaks are planned and the treatments that occurred as part of this project provide tie-in points for that break, it does not yet constitute a large enough percentage on the landscape to merit a deduction in risk.

Disease or insect outbreak is given a blanket 3% risk rating. Other episodic catastrophic events are given a default value of 3%.

The total permanence risk deduction is 20% (table 11).

Table 11. Risk deductions for the Sunset unit, private lands forest management scenario.

Risks	Deduction
Financial	5.0%
Management	4.0%
Social	2.0%
Natural Dist.	9.0%
Total	20.0%

3.6. Leakage Analysis

The leakage analysis is also referred to as secondary effects analysis and is covered in section 6.2.6 for forest management project types. Note that a leakage analysis is conducted each year based on actual harvest relative to the modeled average baseline harvest. If the total harvest level is reduced in the project activity relative to the baseline, then 20% of the difference between the two is the reduction applied to the carbon reductions. The value is provided on an annual and per acre basis. Table 12 shows the effect for the Sunset unit forest management scenario, which is 0.02 tonnes per acre per year. Note that while the baseline is calculated once and is fixed for the project life, leakage is calculated each year based on actual harvest.

Table 12. Secondary effects (SE) for Sunset unit, private lands forest management scenario. Units are in tonnes of C.

Project Harvested	17,268.36
Baseline Harvested	20,666.09
Gross Total Effect	3,397.74
Secondary Effect	679.55
Annual SE	-6.80
Annual SE (per acre)	-0.02

For the reforestation project type the secondary effects are specified in table 6.1 of the protocol (mobile combustion emissions for reforestation projects) and are a function of three categories of brush cover. We used the heavy category and converted the CO2e to C to keep the units consistent at this stage of the analysis. This resulted in a one-time secondary effect of 0.12 tonnes per acre (0.3 t/h) of C that is applied the first year and carries over until there are CRTs to deduct it from.

3.7. Net Biological Reductions

The three types of deductions are shown in tables 9 and 10, as is the resulting net reductions and buffer contributions. Figures 18 and 19 illustrate the resulting marketable CRTs and the buffer pool over the project period. For the forest management project type there is a substantial salable amount of CRTs in 2025 with the first salable CRTs in 2015. The reforestation project type is surprisingly similar, on a per acre basis, with a large amount of CRTs available in 2035 and beginning in 2025.

The forest management project has two factors that make it a questionable project without modification. First, the stocking levels are just above the FIA mean. Second, the project activity plan was for harvesting between 2005 and 2015 that reduced on-site stocking. An evaluation should be made to determine whether it would be more beneficial to the landowner to delay project initiation. The requirement in the protocol to maintain or increase on-site carbon stocks over time allows for the case where a long-term management plan decreases stocks temporarily.

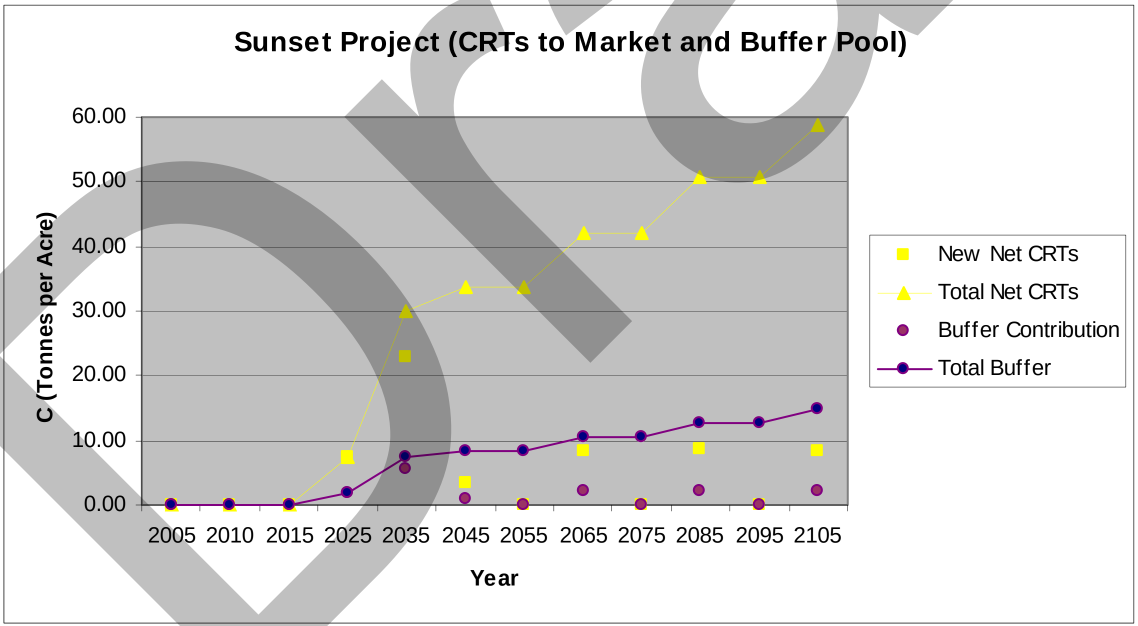


Figure 18. Net CRTs and buffer pool contributions for the Sunset unit, reforestation.

Over the 100-year life of this project the off-site long-term wood products contribution to salable gross CRTs was -3.6 tonnes per acre for the forest management type. The amount is negative because more wood products were produced in the baseline than in the project activity. There is also a reduction for this in the secondary effects calculation. The effect of the -3.6 tonne reduction from long-term wood product storage was about 1% of the total gross reductions. For the reforestation project type, projected wood products contribution to the total CRTs products was only 3.2%. The inventory deduction of 7.9% was applied to estimated CRTs for the entire 100-year period. However, if the sampling error were reduced to 5% or less in a future inventory then the deducted reductions could be recouped.

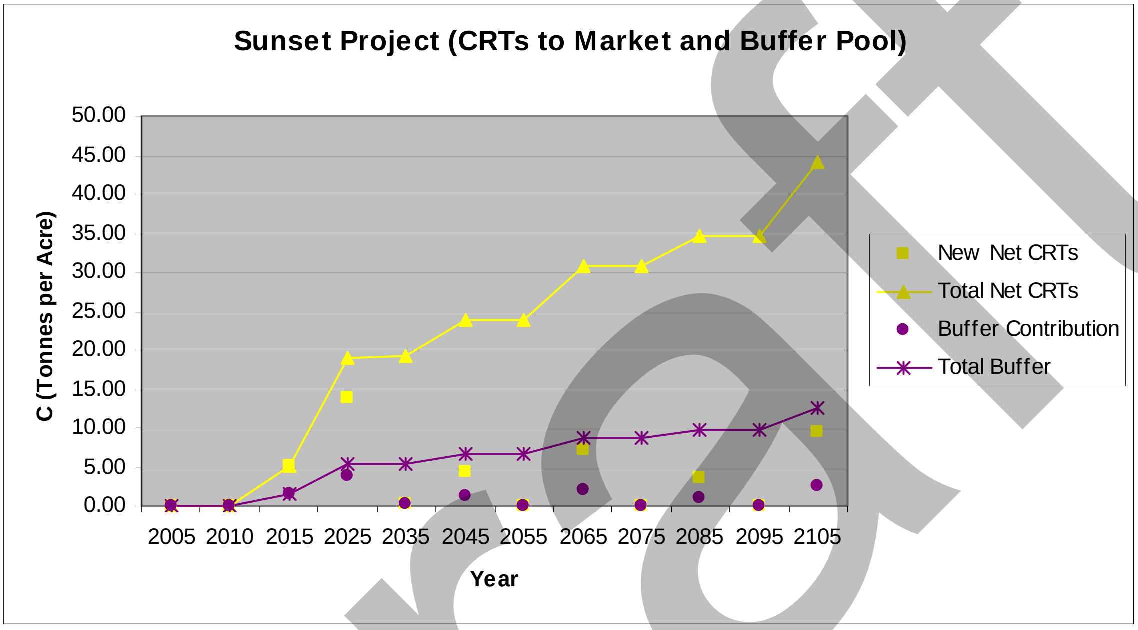


Figure 19. Net CRTs and buffer pool contributions for the Sunset unit, forest management.

4.0 Sunset Project GHG Analysis: Public Land Scenario

Projects are allowed on public lands for the first time with version 3 of the protocols. There is a requirement that the project be approved by the managing agency and that Congressional approval for carbon projects be in place for federal lands. In this case we will use LDSF as it is, a demonstration state forest. In this case the approval for a project rests with the California Department of Forestry and Fire Protection (CAL FIRE) under a management plan approved by the California Board of Forestry and Fire Protection. CAL FIRE, as the forest manager, would have to decide to implement the project.

The project activity and baseline for a public lands reforestation project are the same as for a private lands project. Refer to the private lands scenario for reforestation (above) for the baseline, project activity and projected reductions. There are some differences to the buffer pool contribution from the risk analysis. The financial risk is 1% instead of 5%, conversion risk is 0% rather than 2%, and overharvesting risk is 0% rather than 2%. This results in a buffer contribution that is 12% for a public land project, reduced from 20% for the private lands project (table 13). Table 14 shows the net reductions for the project.

Table 13. Risk deductions for the Sunset unit, public lands reforestation scenario.

Risks	Deduction
Financial	1.0%
Management	0.0%
Social	2.0%
Natural Dist.	9.0%
Total	12.0%

Table 14. Tonnes of carbon in the gross reductions before deductions, deductions, and net reductions; for the Sunset Unit reforestation public lands scenario.

	Gross Reductions						Deductions			Net Reductions			
Year	On-Site Reductions	Off-site Dead C Reductions (Wood Products)	Sum of On and Off-site Reductions	Total Marginal Reductions	Non-reversed Cumulative CRTs	New CRTs	Secondary Effects	Inventory Confidence Deduction	Buffer Pool Deduction	New Net CRTs	Total Net CRTs	Buffer Contribution	Total Buffer
2005	-14.60	0.00	-14.60	-14.60	0.00	0.00	-0.12	0.00	0.00	0.00	0.00	0.00	0.00
2010	-14.40	0.00	-14.40	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2015	-14.40	0.00	-14.40	-14.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2025	9.11	0.00	9.11	23.71	9.11	9.11	0.00	0.00	1.09	8.02	8.02	1.09	1.09
2035	37.56	0.00	37.56	13.85	37.56	28.45	0.00	0.00	3.41	25.04	33.05	3.41	4.51
2045	50.93	0.00	50.93	37.08	42.00	4.44	0.00	0.00	0.53	3.90	36.96	0.53	5.04
2055	37.98	4.02	42.00	4.92	42.00	0.00	0.00	0.00	0.00	0.00	36.96	0.00	5.04
2065	60.39	0.00	64.41	59.49	52.60	10.61	0.00	0.00	1.27	9.34	46.29	1.27	6.31
2075	43.76	4.83	52.60	-6.89	52.60	0.00	0.00	0.00	0.00	0.00	46.29	0.00	6.31
2085	60.79	0.00	69.63	76.52	63.24	10.64	0.00	0.00	1.28	9.36	55.65	1.28	7.59
2095	51.32	3.08	63.24	-13.28	63.24	0.00	0.00	0.00	0.00	0.00	55.65	0.00	7.59
2105	61.70	0.00	73.62	86.90	73.62	10.38	0.00	0.00	1.25	9.13	64.79	1.25	8.83

The improved forest management project type for public lands has a baseline characterization that is different from private lands. The initial inventory is to be projected for 100 years by extrapolating from historical trends and anticipating how current and future public policy will affect onsite carbon stocks. Trends for the last ten years have been for increasing stocks, which then requires that stands free of harvest for 60 years be used as a guide. Policy on state forests is to maximize timber yields, which implies operating near culmination of mean annual increment, to use an even-aged indicator. Considering that this baseline scenario will likely be near the project activity scenario, there is little or no biological reductions to be realized from a public lands scenario on LDSF. Therefore, this scenario will not be analyzed further.

5.0 McMullen Project GHG Analysis: Private Land Scenario

Like the Sunset project, this project is mostly a forest management project (tables 2 and 3). The protocols specify that the required carbon pools for a forest management project are the above- and below-ground living biomass, standing and down dead biomass (note that down dead biomass was changed to optional in the final version), and off-site dead biomass. The optional pools are shrubs and herbaceous understory, litter, and soil carbon. Only the required pools will be included in this analysis. The reforestation unit in this project also requires that shrubs and herbaceous understory be estimated. The above- and below-ground live tree biomass is required for reforestation where they exist. They are rarely present for this unit and will be tracked at future inventory periods (figures 6 and 7).

There is an assumption here that it is permissible to stratify a project into reforestation and improved forest management types and apply the appropriate carbon pools to each. If this is not permissible then the shrub and herbaceous pools would have to be included with the improved forest management inventory or the project types would have to be separate projects.

5.1. Inventory Description and Results

The inventory design and calculation methods are described in appendix I. Table 15 shows the starting carbon inventory estimate for the project along with the percent sampling error. The protocol specifies that a reduction in CRTs occur for percent sampling errors between 5% and 20%. This is calculated on the above and below ground live tree carbon. Since the percent sampling error is less than 5% there are no deductions.

Table 15. Starting carbon inventory for forest management on the McMullen Mountain project.

Attribute	Reforestation	Forest Management
No. of Plots	0	459
Mean Trees per Acre	0	141.00
Mean Trees per Hectare	0	348.27
Mean Bole Cubic Feet per Acre (ground to tip)	0	925.08
Mean Bole Cubic Meters per Hectare (ground to tip)	0	2,284.95
Mean Bole C per Acre (tonnes)	0	30.24
Mean Bole C per Hectare (tonnes)	0	74.69
Mean Bark C per Acre (tonnes)	0	13.33
Mean Bark C per Hectare (tonnes)	0	32.92
Mean Crown Branches C per Acre (tonnes)	0	6.49
Mean Crown Branches C per Hectare (tonnes)	0	16.02
Mean Tree Live Aboveground C per Acre (tonnes)	0	50.05
Mean Tree Live Aboveground C per Hectare (tonnes)	0	123.62
Mean Tree Live Belowground C per Acre (tonnes)	0	17.36
Mean Tree Live Belowground C per Hectare (tonnes)	0	42.88
Mean Tree Live C per Acre (tonnes)	0	67.41
Mean Tree Live C per Hectare (tonnes)	0	166.51
Acres	18.6	1192.1
Hectares	7.5	482.6
Total Live Tree C (tonnes)	0	80,364.30
Total Lying Dead C (tonnes)	0.00	0.89
Total Standing Dead C (tonnes)	4.86	3.37
Total C (tonnes)	4.86	80,368.55
Standard Error C (tonnes)	na	1,748.36
Sampling Error (tonnes)		2,876.05
Sampling Error (%)	na	3.58%
Mean Shrub Aboveground C per Acre (tonnes)	14.46	na
Mean Shrub Aboveground C per Hectare (tonnes)	35.71	na
Mobile Combustion C per Acre (tonnes)	0.12	na
Mobile Combustion C per Hectare (tonnes)	0.29	na
Total Shrub Aboveground C (tonnes)	268.90	na
Total Reforestation C (tonnes)	275.94	na

There is an assumption here that it is permissible to stratify a project into reforestation and improved forest management types and apply the appropriate carbon pools to each. If this is not permissible then the shrub and herbaceous pools would have to be included with the improved forest management inventory or the project types would have to be separate projects.

5.2. Baseline Calculations

The baseline for the reforestation project type is the existing aboveground shrub carbon, which will be assumed to be a steady stock for the 100-year projection period. In this case it is 268.9 tonnes of C, which is 14.5 tonnes C per acre (35.7 t/h). No dead wood is assumed since the area was a brush field and no large dead wood was accumulating. No harvests were simulated. The reforestation unit is a brushfield that will undergo a slow natural succession process if left undisturbed. Given the fire frequency for the area and the high fuel load and combustion potential of this fuel type, a high-severity disturbance would be likely in a 100-year timeframe, therefore natural reforestation was not assumed. There are no legal requirements to reforest this unit.

The baseline for forest management project types bifurcates depending on whether the starting stocks of carbon are above or below the average for the applicable assessment area (common practice), based on the FIA average. LDSF is located in the Sierra Nevada – Southern Cascades assessment area, which is 39 tonnes per acre in above- and below-ground live trees for private ownerships (CAR 2009, Appendix F). Since the inventory shows 67.41 tonnes per acre in total live tree carbon, the forest management baseline shall be based on a steady flow from the FIA mean of 39 tonnes per acre. The current inventory will be the starting condition, which is 2005 in this case since that is when the project starts. The resulting baseline will have to be shown to be economically and legally feasible, which it is, given that there are not significant constraints to management of the unit. Economic feasibility is demonstrated by the historic and continued timber sales to local mills from the project area. The area is well roaded, of low to moderate steepness, at the upper end of watersheds and not in habitat that significantly constrains management. The legal constraints are primarily the California Forest Practice Act and associated regulations, which the property has successfully operated under since the creation of the Act. The application of the Maximum Sustained Production of High Quality Timber Products (MSP) constraint could be a significant factor depending on landowner status. In this scenario we consider the project to be private land operated by a non-industrial owner, which allows us to use the MSP option C safe-harbor rules. The resulting average stocks over a 100-year period must be at or above the common practice figure of 39 tonnes per acre C.

If a harvest schedule uses optimization, such as a linear program, and the carbon yields are incorporated into it then the baseline may be easily modeled by changing the optimization function to match the FIA baseline figure. Otherwise, and this is the case here, modeling the harvest schedule must be done by trial and error to approach the FIA figure but end at or above it. The trial and error approach is time consuming unless the project is very small; we recommend optimization or other operations research approaches given the complexity of the carbon accounting rules. This complexity is increased when financial accounting of carbon and timber is included.

A mix of small group clearings and clearcuts along with commercial thinnings from below were used. These silvicultural prescriptions are consistent with current practices on the Forest and produce wood products that may be utilized for dimensional lumber and peelers for plywood, both of which are in demand in the area. In general, the clearfelling, whether as small group selections less than or equal to 2.5 acres (1 hectare) or clearcuts up to 20 acres (8 hectares) in size, was moved up in time and commercial thinnings with a residual basal area of 100 ft^2/acre (22.9 m^2/h) were used to maintain the stocking over time. These opening sizes and residual stocking meet the minimum requirements of the California forest practice regulations. Where clearcuts were implemented the minimum age requirements of the rules were met. Table 16 shows a summary of the silvicultural treatments simulated for the baseline.

Table 16. Acres of silvicultural prescriptions for the baseline simulation of the McMullen Mtn Unit for private lands forest management.

	Year										
Treatment	2005	2010	2030	2040	2050	2060	2070	2080	2090	2100	*Total Acres*
Clearfell (Group Selection and Clearcut)	0.0	273.8	221.4	0.0	224.2	0.0	228.1	0.0	186.3	0.0	*1,133.8*
Commercial Thin with 100 sq. ft. Residual Basal Area	0.0	563.2	671.7	0.0	14.1	0.0	0.0	0.0	0.0	0.0	*1,249.0*
Commercial Thin with 140 sq. ft. Residual Basal Area	0.0	285.2	0.0	0.0	265.4	0.0	404.3	0.0	742.7	0.0	*1,697.6*
Shaded Fuel Break with 50 sq. ft. Basal Area Retention	0.0	54.6	16.1	39.6	16.1	39.6	16.1	39.6	16.1	35.2	*273.0*
Total Acres	*0.0*	*1,176.8*	*909.2*	*39.6*	*519.8*	*39.6*	*648.5*	*39.6*	*945.1*	*35.2*	*4,353.4*

The amount of carbon associated with the live and dead wood, on-site and off-site, for the baseline is shown in table 17. Note that the project portion of table 17 is explained in the next section but is presented here so the two may be viewed together for comparison. The landfill pool is not used for reductions calculations unless the baseline average exceeds the project pool, but it is always required to report it. Figures 20 and 21 show the on-site and off-site baseline estimates for the 100-year planning period. Note that the year 2010 is the only 5-year reporting with the rest being 10-year periods. When averaging the baseline only the 10-year periods were used.

Table 17. Tonnes per acre of carbon in the baseline and project activity projections for the McMullen Mtn Unit forest management scenario.

	Baseline									**Project**					
Year	On-site Live Tree Baseline	On-site Dead Wood Baseline	On-site Live Tree Average Baseline	FIA Live Tree Average	On-site Live and Dead C Baseline	On-site Live and Dead C Avg Baseline	Off-site Dead C (Wood Products)	Off-site Dead C (Wood Products) for Period	Off-site Dead C (Landfill)	On-site Live Tree Project Activity	On-site Dead Wood Project Activity	Sum of On-site Live and Dead C Project Activity	Off-site Dead C (Wood Products)	Off-site Dead C (Wood Products) for Period	Off-site Dead C (Landfill)
2005	67.41	2.79	39.47	39.00	70.20	41.96	0.00	0.73	0.00	67.41	2.80	70.21	0.00	0.00	0.00
2010	31.16	2.72	39.47	39.00	33.89	41.96	4.79	0.73	0.77	65.24	2.75	67.98	0.76	0.76	0.12
2015	31.16	2.79	39.47	39.00	33.96	41.96	4.79	1.46	0.77	71.80	2.81	74.61	2.45	1.69	0.39
2025	43.46	3.14	39.47	39.00	46.60	41.96	7.59	1.46	1.22	69.35	3.13	72.49	2.83	0.38	0.45
2035	28.77	3.70	39.47	39.00	32.47	41.96	7.65	1.46	1.23	77.92	3.45	81.37	4.94	2.11	0.79
2045	37.60	3.69	39.47	39.00	41.29	41.96	9.20	1.46	1.48	79.16	3.71	82.87	5.27	0.33	0.84
2055	34.28	3.36	39.47	39.00	37.64	41.96	9.22	1.46	1.48	94.27	3.66	97.93	5.75	0.49	0.92
2065	44.54	3.37	39.47	39.00	47.90	41.96	11.86	1.46	1.90	97.73	3.98	101.71	6.08	0.33	0.98
2075	31.34	2.84	39.47	39.00	34.18	41.96	11.88	1.46	1.91	109.89	3.86	113.75	7.23	1.14	1.16
2085	42.12	3.29	39.47	39.00	45.41	41.96	14.40	1.46	2.31	101.95	3.79	105.74	7.49	0.26	1.20
2095	31.03	3.30	39.47	39.00	34.33	41.96	14.41	1.46	2.31	111.19	4.01	115.20	7.83	0.34	1.26
2105	42.49	3.15	39.47	39.00	45.64	41.96	14.55	1.46	2.34	109.42	4.04	113.47	7.91	0.08	1.27

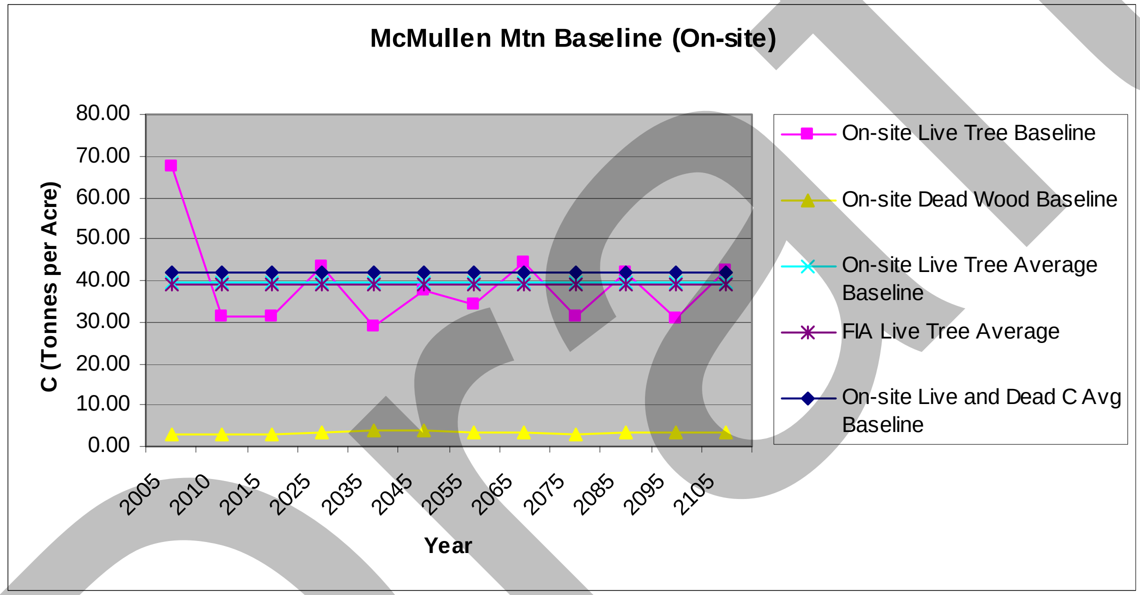


Figure 20. McMullen Mtn unit on-site baseline for private lands forest management scenario.

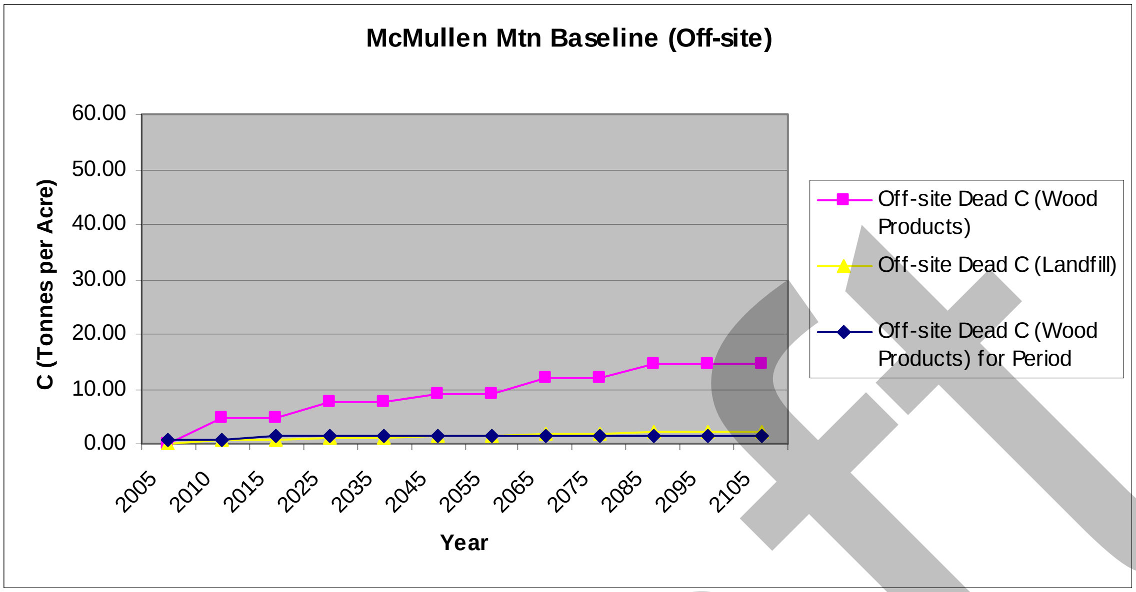


Figure 21. McMullen Mtn unit off-site baseline for private lands forest management scenario.

The results of the forest management baseline analysis were that the average on-site stocking was 39.47 tonnes of C per acre (97.5 tonnes C per hectare). Off-site wood products storage (based on 100-year storage in-use) increased over time and had an average over the period of 0.079 tonnes/acre/year C. This equated to a total of 11,257 thousand cubic feet (318,759 m^3) of timber over the 100-year period. Assuming six board feet per cubic foot, this equates to 67,541 MBF total or 567 board feet per acre per year over the 100-year period.

5.3. Project Activity Calculations

The project activity for the reforestation project type was modeled as a 10x10 foot spacing of 1-0 planted seedlings of a pine and fir mix, which resulted in 436 trees per acre (1,077 trees/h). Commercial thinnings from below leaving a residual basal area of 120 ft^2/ac (27.5 m^2/h) were simulated in 2050, 2070, and 2090. The result of the project activity was to increase on-site carbon stocks to 45.4 tonnes C per acre (112.1 t/h) after 100 years (table 18). This is a substantially reduced projection of carbon stocks relative to the Sunset reforestation unit due to the site quality, which is 55 feet (16.8 m) high at base age 50 at McMullen relative to 110 feet (33.5 m) high at Sunset. The total wood products pool (figure 22) projected over the 100-year period was 6.7 tonnes C per acre (16.5 t/h), which was 4.4 thousand cubic feet (MCF) per acre (305 m^3/h).

Table 18. Tonnes per acre of carbon in the baseline and project activity projections for the McMullen Unit reforestation scenario.

	Baseline					Project					
Year	On-site Live Tree Baseline	On-site Dead Wood Baseline	On-site Live Tree Average Baseline	Off-site Dead C (Wood Products)	Off-site Dead C (Landfill)	On-site Live Tree Project Activity	On-site Dead Wood Project Activity	Sum of On-site Live and Dead C Project Activity	Off-site Dead C (Wood Products)	Off-site Dead C (Wood Products) for Period	Off-site Dead C (Landfill)
2005	14.60	0.00	14.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2010	14.60	0.00	14.60	0.00	0.00	0.00	0.20	0.20	0.00	0.00	0.00
2015	14.60	0.00	14.60	0.00	0.00	0.00	0.20	0.20	0.00	0.00	0.00
2025	14.60	0.00	14.60	0.00	0.00	2.65	0.20	2.85	0.00	0.00	0.00
2035	14.60	0.00	14.60	0.00	0.00	19.20	2.50	21.70	0.00	0.00	0.00
2045	14.60	0.00	14.60	0.00	0.00	36.04	4.42	40.46	0.00	0.00	0.00
2055	14.60	0.00	14.60	0.00	0.00	29.58	4.42	34.00	2.13	2.13	0.34
2065	14.60	0.00	14.60	0.00	0.00	43.64	4.42	48.06	2.13	0.00	0.34
2075	14.60	0.00	14.60	0.00	0.00	33.93	4.42	38.36	4.64	2.50	0.74
2085	14.60	0.00	14.60	0.00	0.00	44.68	3.55	48.23	4.64	0.00	0.74
2095	14.60	0.00	14.60	0.00	0.00	37.39	2.82	40.21	6.66	2.02	1.07
2105	14.60	0.00	14.60	0.00	0.00	45.39	2.82	48.20	6.66	0.00	1.07

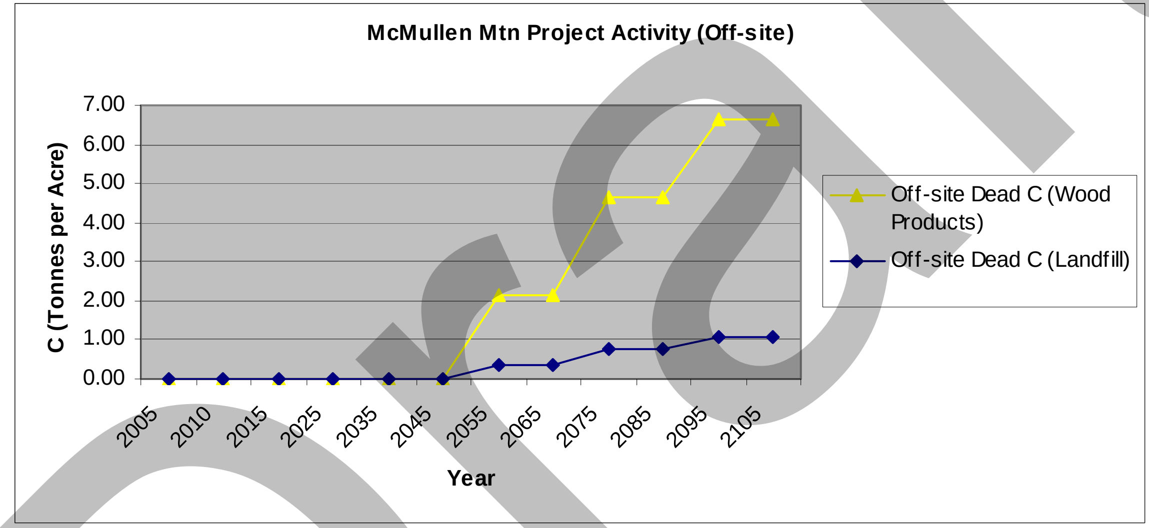


Figure 22. Reforestation project activity projections of off-site dead wood pools for McMullen reforestation project.

The project activity for the forest management project type was projected using the stand level treatments identical to the long-term harvest schedule approved by the State of California under 14 CCR 933.11(a), also known as an “option a” plan. Table 19 shows the silvicultural prescriptions. The modeling was done using a stand level projection of treatments over a 100-year period that was then summarized across the Forest. Adjustments were made to some stands to meet regulatory requirements for long-term planning. The overall goal was to move over-mature stands to younger age classes over time to create a balance of stand ages. Dead wood was modeled using the mortality functions of FVS with an assumed decay rate of 10% per year. The silvicultural prescriptions for the proposed project activity use substantially less intensive management and harvest far fewer acres over the 100-year period.

The results of the C stocking may be seen in table 17 under “Project”. Notice that there is a small near-term decrease in carbon stocks, which is a reflection of the near-term harvesting that has occurred in this unit as per the existing harvest schedule. An approximate 20-year cutting cycle is implemented on LDSF. This will have an effect on the reductions calculation that is shown below, but because the starting stocks are well above the FIA mean the effect will not be nearly as severe as was the case with the Sunset unit.

Table 19. Acres of silvicultural prescriptions for the project activity simulation of the McMullen Mtn Unit for private lands forest management.

	Year										
Treatment	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	*Total Acres*
Clearfell (Group Selection and Clearcut)	30.4	193.2	30.3	180.5	30.1	29.4	30.7	75.0	14.2	14.1	*627.9*
Commercial Thin with 100 sq. ft. Residual Basal Area	0.0	0.0	4.4	0.0	10.3	0.0	0.0	0.0	0.0	0.0	*14.7*
Commercial Thin with 140 sq. ft. Residual Basal Area	84.8	0.0	59.6	42.9	77.0	42.9	81.8	42.9	102.8	65.4	*600.1*
Commercial Thin with 160 sq. ft. Residual Basal Area	0.0	0.0	0.0	0.0	0.0	0.0	0.0	22.5	0.0	0.0	*22.5*
Single Tree Selection with 70% Basal Area Retention	42.5	0.0	81.8	0.0	14.1	0.0	0.0	0.0	0.0	0.0	*138.4*
Shaded Fuel Break with 50 sq. ft. Basal Area Retention	55.7	0.0	16.1	42.5	16.1	42.5	16.1	42.6	16.1	38.1	*285.8*
Total Acres	*213.4*	*193.2*	*192.2*	*265.9*	*147.6*	*114.8*	*128.6*	*183.0*	*133.1*	*117.6*	*1,689.4*

The result of the project activity projection was to increase on-site carbon stocks from an average of 67.41 tonnes/acre (166.5 tonnes/hectare) to 109.42 tonnes/acre (270.3 tonnes/hectare) at the end of the 100-year period. Off-site wood products storage grew to 7.91 tonnes/acre C (19.5 t/h), which was 46 percent less than the 14.55 tonnes/acre C (35.9 t/h) in the baseline. The harvest was projected to total 6,118 MCF (173,251 m^3) of timber over the 100-year period. Figures 23 and 24 show the project activity for the on-site and off-site carbon over time.

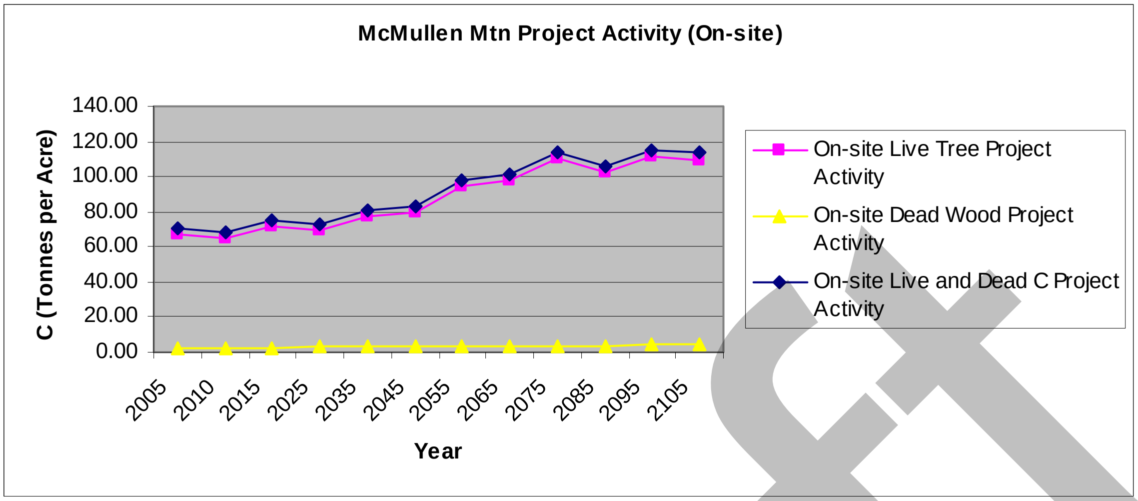


Figure 23. McMullen Mtn unit on-site project activity for the forest management project type.

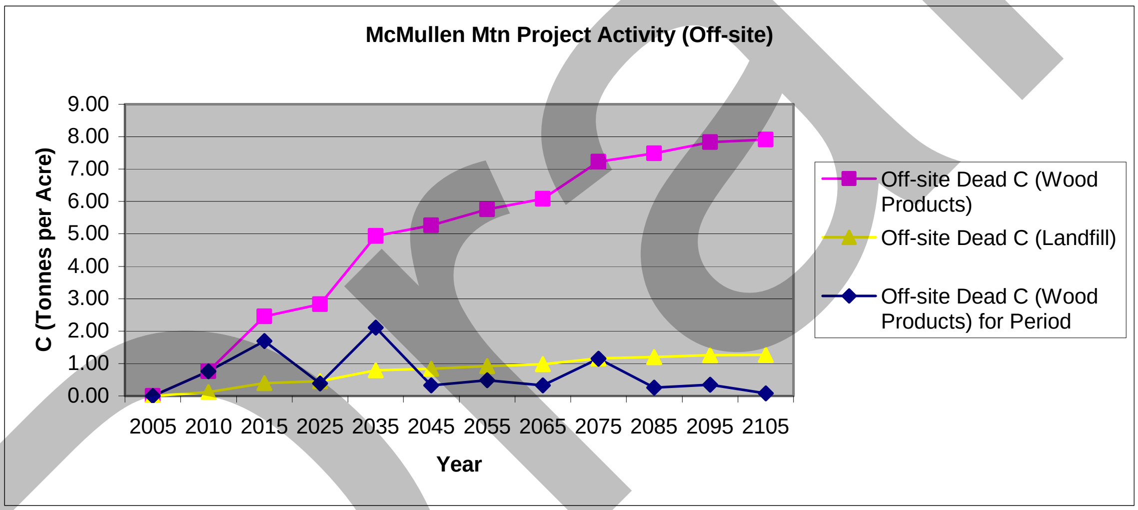


Figure 24. McMullen Mtn unit off-site project activity for the forest management project type.

5.4. Gross Biological Reductions

The difference between the project activity and baseline projections is the gross reduction, which is shown in tables 20 and 21 for the 100-year planning period and the two project types. Figures 25 and 26 show the gross reductions and the "smoothed" reductions whereby a reversal due to near-term harvests does not occur. For example, if 100 CRTs were created in decade 2 but due to harvest cycles there were -10 CRTs in decade 3, then only 90 CRTs would be claimed for decade 2. This leads to an estimate of the decadal gross new CRTs, before any deductions for inventory precision, permanence or leakage.

Table 20. Tonnes of carbon per acre in the gross reductions before deductions, deductions, and net reductions; for the McMullen Mtn Unit reforestation scenario.

	Gross Reductions						**Deductions**			**Net Reductions**			
Year	On-Site Reductions	Off-site Dead C Reductions (Wood Products)	Sum of On and Off-site Reductions	Total Marginal Reductions	Non-reversed Cumulative CRTs	New CRTs	Secondary Effects	Inventory Confidence Deduction	Buffer Pool Deduction	New Net CRTs	Total Net CRTs	Buffer Contribution	Total Buffer
2005	-14.60	0.00	-14.60	-14.60	0.00	0.00	-0.12	0.00	0.00	0.00	0.00	0.00	0.00
2010	-14.40	0.00	-14.40	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2015	-14.40	0.00	-14.40	-14.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2025	-11.75	0.00	-11.75	2.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2035	7.10	0.00	7.10	4.25	7.10	7.10	0.00	0.00	1.42	5.68	5.68	1.42	1.42
2045	25.86	0.00	25.86	21.61	21.54	14.43	0.00	0.00	2.89	11.55	17.23	2.89	4.31
2055	19.40	2.13	21.54	-0.07	21.54	0.00	0.00	0.00	0.00	0.00	17.23	0.00	4.31
2065	33.46	0.00	35.60	35.67	28.40	6.86	0.00	0.00	1.37	5.49	22.72	1.37	5.68
2075	23.76	2.50	28.40	-7.27	28.40	0.00	0.00	0.00	0.00	0.00	22.72	0.00	5.68
2085	33.63	0.00	38.27	45.54	32.26	3.87	0.00	0.00	0.77	3.09	25.81	0.77	6.45
2095	25.61	2.02	32.26	-13.28	32.26	0.00	0.00	0.00	0.00	0.00	25.81	0.00	6.45
2105	33.60	0.00	40.26	53.54	40.26	8.00	0.00	0.00	1.60	6.40	32.21	1.60	8.05

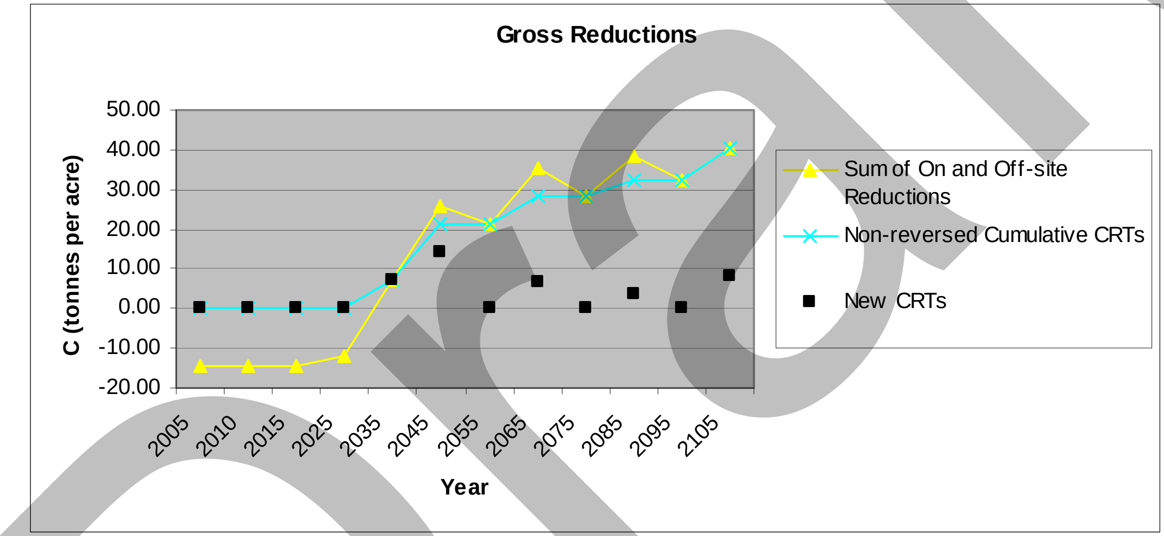


Figure 25. Reforestation, McMullen Mtn unit gross reductions and CRTs.

Table 21. Tonnes of carbon per acre in the gross reductions before deductions, deductions, and net reductions; for the McMullen Mtn Unit forest management scenario.

	Gross Reductions						**Deductions**			**Net Reductions**			
Year	On-Site Reductions	Off-site Dead C Reductions (Wood Products)	On and Off-site Reductions	Total Marginal Reductions	Non-reversed Cumulative CRTs	New CRTs	Secondary Effects	Inventory Confidence Deduction	Buffer Pool Deduction	New Net CRTs	Total Net CRTs	Buffer Contribution	Total Buffer
2005	28.25	-0.73	27.52	27.52	25.33	25.33	-0.24	0.00	4.56	20.53	20.53	4.56	4.56
2010	26.02	0.03	25.33	-2.20	25.33	0.00	-0.24	0.00	0.00	0.00	20.53	0.00	4.56
2015	32.65	0.24	32.19	34.38	28.99	3.67	-0.47	0.00	0.66	2.53	23.06	0.66	5.22
2025	30.53	-1.07	28.99	-5.39	28.99	0.00	-0.47	0.00	0.00	0.00	23.06	0.00	5.22
2035	39.41	0.65	38.53	43.92	38.53	9.54	-0.47	0.00	1.72	7.35	30.41	1.72	6.94
2045	40.92	-1.13	38.90	-5.02	38.90	0.37	-0.47	0.00	0.07	0.00	30.41	0.00	6.94
2055	55.97	-0.97	52.99	58.01	52.99	14.09	-0.47	0.00	2.54	11.08	41.49	2.54	9.47
2065	59.75	-1.12	55.64	-2.36	55.64	2.65	-0.47	0.00	0.48	1.70	43.19	0.48	9.95
2075	71.79	-0.31	67.38	69.74	58.17	2.52	-0.47	0.00	0.45	1.60	44.79	0.45	10.40
2085	63.78	-1.19	58.17	-11.57	58.17	0.00	-0.47	0.00	0.00	0.00	44.79	0.00	10.40
2095	73.24	-1.11	66.52	78.09	63.41	5.24	-0.47	0.00	0.94	3.83	48.61	0.94	11.35
2105	71.51	-1.38	63.41	-14.68	63.41	0.00	-0.47	0.00	0.00	0.00	48.61	0.00	11.35

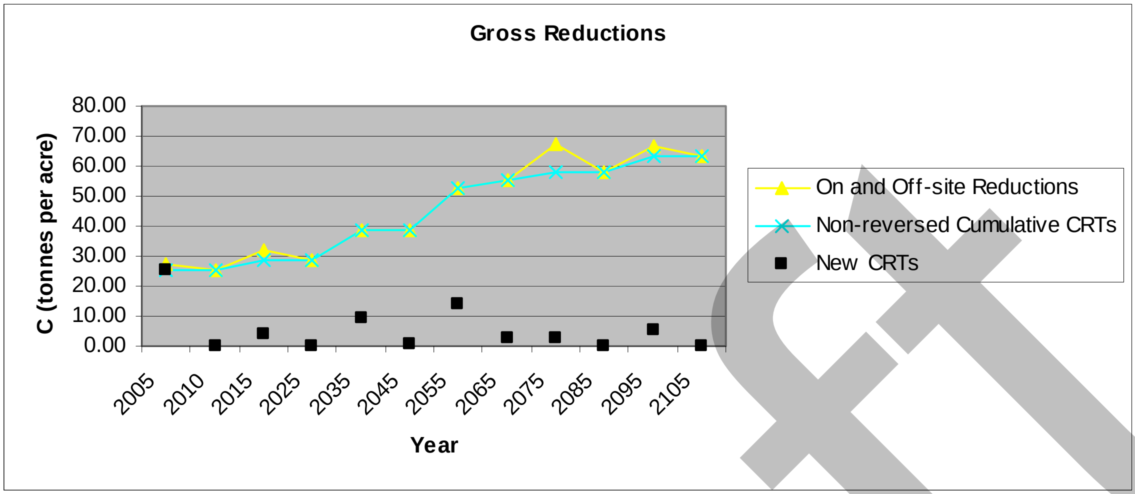


Figure 26. Forest management, McMullen Mtn unit gross reductions and CRTs.

5.5. Permanence Analysis

This is a risk analysis with the details provided in appendix D of the protocol. The analysis is identical for the reforestation and improved forest management project types.

Financial Risk: The financial risk for this private lands scenario assumes a PIA only and no conservation easement, which requires a 5% buffer contribution.

Management Risk: Management risk consists of three types of risks. Illegal removals are given a 0% risk for property in the United States. Conversion to an alternate land use is a function of whether development rights are encumbered by an easement or deed restriction, which is not the case here, incurring a 2% deduction. Overharvesting is the final management risk and is also a function of having a legal restriction on harvesting, which is not the case here and therefore incurs a 2% deduction.

Social Risk: This is a flat 2% for the United States.

Natural Disturbance Risk: There are three components to this risk category. Wildfire risk is a function of fire frequency and burn severity, which may be reduced using specified categories of fuels treatment activity. Default values will be given in Appendix F of the protocols for the assessment areas, but are not yet provided. In this case the risk is given as 1%. This is less frequent than the Sunset unit and is based on the location of the unit at a higher elevation centered on McMullen Mountain where ridgetop firelines would increase the probability of halting fire spread. While shaded fuel breaks are planned and the treatments that occurred as part of this project provide tie-in points for that break, it does not yet constitute a large enough percentage on the landscape to merit a deduction in risk.

Disease or insect outbreak is given a blanket 3% risk rating. Other episodic catastrophic events are given a default value of 3%.

The total permanence risk deduction is 18% (table 22).

Table 22. Risk deductions for the McMullen Mtn unit, private lands forest management scenario.

Risks	Deduction
Financial	5.0%
Management	4.0%
Social	2.0%
Natural Dist.	7.0%
Total	18.0%

5.6. Leakage Analysis

The leakage analysis is also referred to as secondary effects analysis and is covered in section 6.2.6 of the protocol for forest management project types. Note that a leakage analysis is conducted each year based on actual harvest relative to the modeled average baseline harvest. If the total harvest level is reduced in the project activity relative to the baseline then 20% of the difference is the reduction applied to the carbon reductions. The value is provided on an annual and per acre basis. Table 23 shows the effect for the McMullen Mtn unit forest management scenario, which is 0.05 tonnes per acre per year.

Table 23. Secondary effects (SE) for McMullen Mtn unit, private lands forest management scenario. Units are in tonnes of C.

Project Harvested	33,582.21
Baseline Harvested	61,786.94
Gross Total Effect	28,204.73
Secondary Effect	5,640.95
Annual SE	-56.41
Annual SE (per acre)	-0.05

For the reforestation project type the secondary effects are specified in table 6.1 of the protocol (mobile combustion emissions for reforestation projects) and are a function of three categories of brush cover. We used the heavy category and converted the CO2e to C to keep the units consistent at this stage of the analysis. This resulted in a one-time secondary effect of 0.12 tonnes per acre (0.3 t/h) of C that is applied the first year and carries over until there are CRTs to deduct it from.

5.7. Net Biological Reductions

The three types of deductions are shown in tables 20 and 21 as is the resulting net reductions and buffer contributions. Figures 27 and 28 illustrate the resulting marketable CRTs and the buffer pool over the project period. For the forest management project type there is a substantial salable amount of CRTs immediately with substantial amounts also in 2035 and 2065. The reforestation project type is similar to the Sunset reforestation project at a lower level and a decade later, on a per acre basis, with a large amount of CRTs available in 2045 and beginning in 2035.

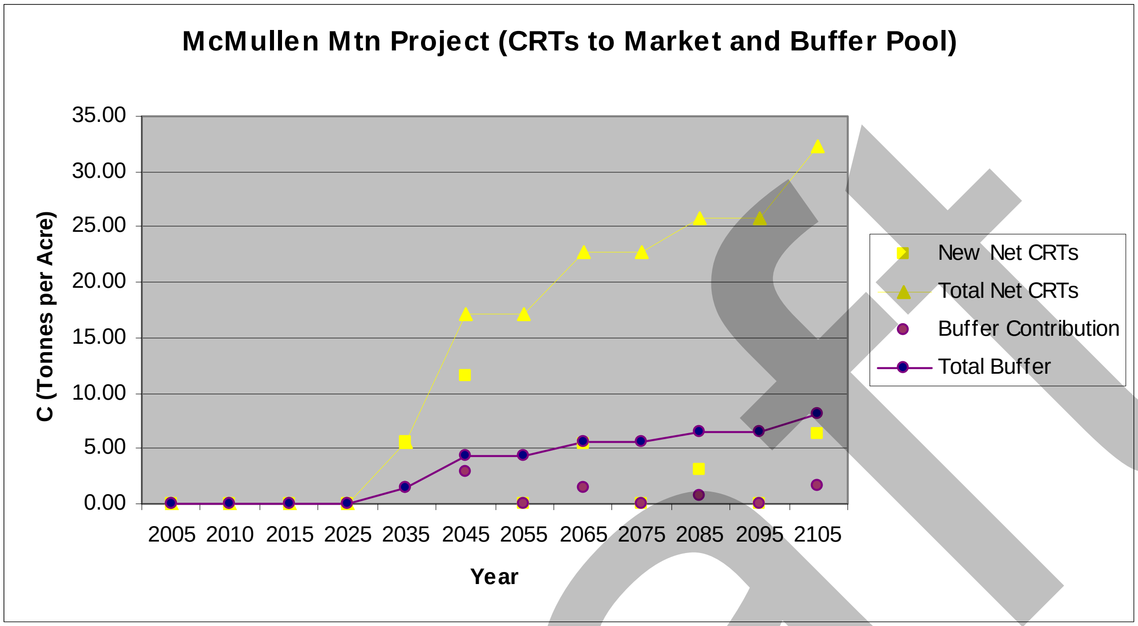


Figure 27. Net CRTs and buffer pool contributions for the McMullen Mtn unit, reforestation.

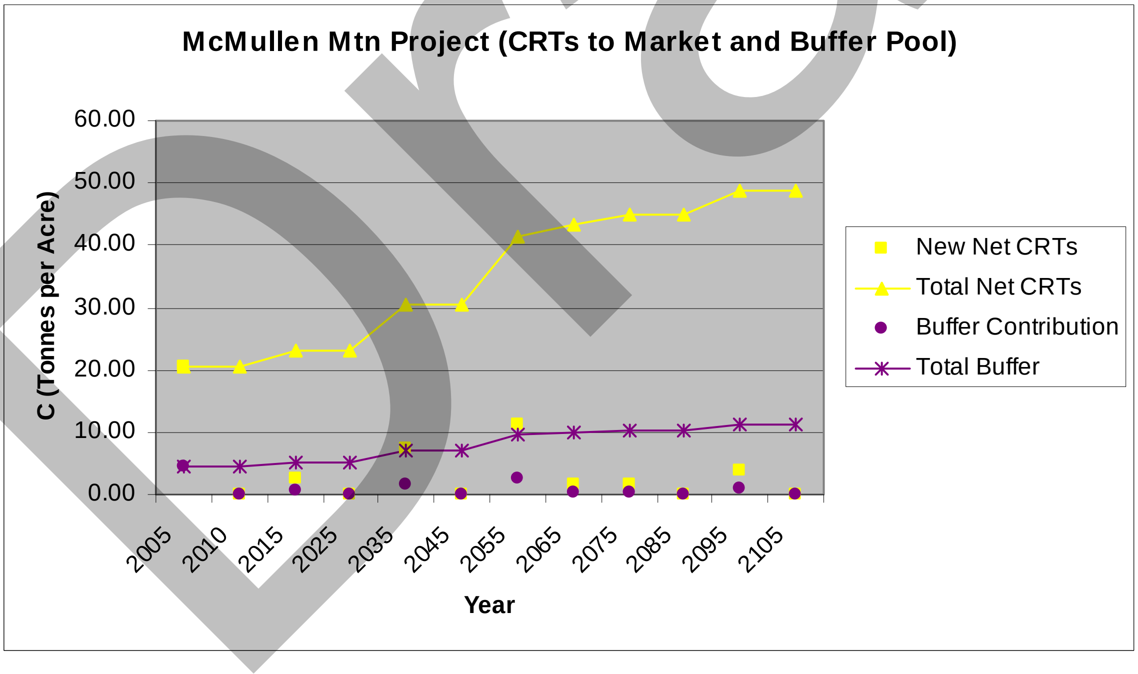


Figure 28. Net CRTs and buffer pool contributions for the McMullen Mtn unit, forest management.

Over the 100-year life of this project the off-site long-term wood products contribution to salable gross CRTs was -8.1 tonnes per acre for the forest management type. The amount is negative because more wood products were produced in the baseline than in the project activity. There is also a reduction for this in the secondary effects calculation. The effect of the -8.1 tonne reduction from long-term wood product storage was about 13% of the total gross reductions. For the reforestation project type, projected wood products contribution to the total CRTs products was only 4.5%.

6.0 McMullen Project GHG Analysis: Public Land Scenario

Projects are allowed on public lands for the first time with version 3 of the protocols. There is a requirement that the project be approved by the managing agency and that Congressional approval for carbon projects be in place for federal lands. In this case we will use LDSF as it is, a demonstration state forest. In this case the approval for a project rests with the California Department of Forestry and Fire Protection (CAL FIRE) under a management plan approved by the California Board of Forestry and Fire Protection. CAL FIRE, as the forest manager, would have to decide to implement the project.

The project activity and baseline for a public lands reforestation project are the same as for a private lands project. Refer to the private lands scenario for reforestation (above) for the baseline, project activity and projected reductions. There are some differences to the buffer pool contribution from the risk analysis. The financial risk is 1% instead of 5%, conversion risk is 0% rather than 2%, and overharvesting risk is 0% rather than 2%. This results in a buffer contribution that is 10% for a public land project, reduced from 18% for the private lands project (table 24). Table 25 shows the net reductions for the project.

Table 24. Risk deductions for the McMullen Mtn unit, public lands reforestation scenario.

Risks	Deduction
Financial	1.0%
Management	0.0%
Social	2.0%
Natural Dist.	7.0%
Total	10.0%

Table 25. Tonnes of carbon in the gross reductions before deductions, deductions, and net reductions; for the McMullen Mtn Unit reforestation public lands scenario.

	Gross Reductions						Deductions			Net Reductions			
Year	On-Site Reductions	Off-site Dead C Reductions (Wood Products)	On and Off-site Reductions	Total Marginal Reductions	Non-reversed Cumulative CRTs	New CRTs	Secondary Effects	Inventory Confidence Deduction	Buffer Pool Deduction	New Net CRTs	Total Net CRTs	Buffer Contribution	Total Buffer
2005	-14.60	0.00	-14.60	-14.60	0.00	0.00	-0.12	0.00	0.00	0.00	0.00	0.00	0.00
2010	-14.40	0.00	-14.40	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2015	-14.40	0.00	-14.40	-14.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2025	-11.75	0.00	-11.75	2.85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2035	7.10	0.00	7.10	4.25	7.10	7.10	0.00	0.00	0.71	6.39	6.39	0.71	0.71
2045	25.86	0.00	25.86	21.61	21.54	14.43	0.00	0.00	1.44	12.99	19.38	1.44	2.15
2055	19.40	2.13	21.54	-0.07	21.54	0.00	0.00	0.00	0.00	0.00	19.38	0.00	2.15
2065	33.46	0.00	35.60	35.67	28.40	6.86	0.00	0.00	0.69	6.17	25.56	0.69	2.84
2075	23.76	2.50	28.40	-7.27	28.40	0.00	0.00	0.00	0.00	0.00	25.56	0.00	2.84
2085	33.63	0.00	38.27	45.54	32.26	3.87	0.00	0.00	0.39	3.48	29.04	0.39	3.23
2095	25.61	2.02	32.26	-13.28	32.26	0.00	0.00	0.00	0.00	0.00	29.04	0.00	3.23
2105	33.60	0.00	40.26	53.54	40.26	8.00	0.00	0.00	0.80	7.20	36.23	0.80	4.03

The improved forest management project type for public lands has a baseline characterization that is different from private lands. The initial inventory is to be projected for 100 years by extrapolating from historical trends and anticipating how current and future public policy will affect onsite carbon stocks. Trends for the last ten years have been for increasing stocks, which then requires that stands free of harvest for 60 years be used as a guide. Policy on state forests is to maximize timber yields, which implies operating near culmination of mean annual increment, to use an even-aged indicator. Considering that this baseline scenario will likely be near the project activity scenario, there is little or no biological reduction to be realized from a public lands scenario on LDSF. Therefore, this scenario will not be analyzed further.

7.0 Economic Analysis

This section provides costs and revenue estimates, provides a spreadsheet tool to evaluate the economics of the reforestation and improved forest management project types using these projects as examples, and shows the economic feasibility of these projects. The CVal spreadsheet program (Bilek et al. 2009), originally developed for Chicago Climate Exchange (CCX) forestry protocols, was adapted for the CAR forestry protocols, version 3.1.

7.1. Costs of the Projects

Project costs for the two project areas, forest management and reforestation are shown in tables 26-29. These tables are taken directly from the modified CVal spreadsheet (Bilek et al. 2009). Many of these costs will vary substantially from project to project and will depend on if an acceptable inventory already exists, the size of the project and whether aggregating with other landowners. The reforestation projects assume a $600 per acre site preparation, planting and competing vegetation treatment cost. The verification costs were set at a fixed cost of $10,000 plus a variable cost of $0.50 per acre. The periodic inventory costs for the smaller reforestation projects were set at a fixed cost of $500 plus a variable cost of $30 per acre. The larger improved forest management periodic inventories were set at a $1,000 fixed cost and $20 per acre. The periodic inventory and verification costs are assumed to be every 6 years. Annual reporting requires third party verifier review and is estimated at $1,500 per year for the larger projects and $200 for the smaller reforestation projects.

A total initial cost estimate for the Sunset improved forest management was $20,520 assuming an inventory and management plan that included baseline and project activity characterization was needed. The McMullen Mountain improved forest management total initial cost was $35,840 with the same assumptions. The Sunset and McMullen Mountain reforestation projects initial costs were $7,120 and $12,400, respectively.

Table 26. Sunset improved forest management costs.

Tract size	**426**	acres	Initial inventory cost	**$ 9,520**	per tract
Year 1 carbon sequestration rate	**-**	tonnes CO_2e/ac/yr	Management plan cost	**$ 10,000**	per tract
Sequestration rate is…	**Variable**	*Fill in rates in table below.*	Other up-front costs	**$ 1,000**	per tract
Carbon reserve pool factor	**10%**		Contract year (Year that up-front costs occur)	**1**	(counter year)
Initial carbon price	**$ 9.00**	per tonne CO_2e	Periodic verification cost	**$ 10,213**	per tract
Carbon price is…	**Constant**		Periodic inventory cost	**$ 9,520**	per tract
Aggregator's fee	**0%**		End of project costs	**$ 1,000**	per tract
Annual reporting cost	**$ 1,500.00**	per tonne CO_2e	Hurdle rate	**5.0%**	
Trading fee	**$ 0.20**	per tract	Finance rate	**5.0%**	
Other annual costs	**$ 1.00**	per tonne CO_2e	Count pre-contract carbon?	**No**	
Up-front costs sensitivity factor	**0%**		End-of-project year	**2104**	
Annual costs sensitivity factor	**0%**				
End-of-project costs sensitivity factor	**0%**		Total up-front costs	**$ 20,520**	per tract
Periodic costs sensitivty factor	**0%**		Total end-of-project costs	**$ 1,000**	per tract

Table 27. McMullen Mountain improved forest management costs.

Tract size	**1,192**	acres	Initial inventory cost	**$ 24,840**	per tract
Year 1 carbon sequestration rate	**-**	tonnes CO_2e/ac/yr	Management plan cost	**$ 10,000**	per tract
Sequestration rate is…	**Variable**	*Fill in rates in table below.*	Other up-front costs	**$ 1,000**	per tract
Carbon reserve pool factor	**10%**		Contract year (Year that up-front costs occur)	**1**	(counter year)
Initial carbon price	**$ 9.00**	per tonne CO_2e	Periodic verification cost	**$ 10,596**	per tract
Carbon price is…	**Constant**		Periodic inventory cost	**$ 24,840**	per tract
Aggregator's fee	**0%**		End of project costs	**$ 1,000**	per tract
Annual reporting cost	**$ 1,500.00**	per tonne CO_2e	Hurdle rate	**5.0%**	
Trading fee	**$ 0.20**	per tract	Finance rate	**5.0%**	
Other annual costs	**$ 1.00**	per tonne CO_2e	Count pre-contract carbon?	**No**	
Up-front costs sensitivity factor	**0%**		End-of-project year	**2104**	
Annual costs sensitivity factor	**0%**				
End-of-project costs sensitivity factor	**0%**		Total up-front costs	**$ 35,840**	per tract
Periodic costs sensitivty factor	**0%**		Total end-of-project costs	**$ 1,000**	per tract

Table 28. Sunset reforestation costs.

Tract size	10	acres	Initial inventory cost	$ -	per tract
Year 1 carbon sequestration rate	-	tonnes CO_2e/ac/yr	Management plan cost	$ -	per tract
Sequestration rate is…	**Variable**	*Fill in rates in table below.*	Other up-front costs	**$ 7,120**	per tract
Carbon reserve pool factor	**10%**		Contract year (Year that up-front costs occur)	**1**	(counter year)
Initial carbon price	**$ 9.00**	per tonne CO_2e	Periodic verification cost	**$ 10,005**	per tract
Carbon price is…	**Constant**		Periodic inventory cost	**$ 806**	per tract
Aggregator's fee	**0%**		End of project costs	**$ 1,000**	per tract
Annual reporting cost	**$ 200.00**	per tonne CO_2e	Hurdle rate	**5.0%**	
Trading fee	**$ 0.20**	per tract	Finance rate	**5.0%**	
Other annual costs	**$ 1.00**	per tonne CO_2e	Count pre-contract carbon?	**No**	
Up-front costs sensitivity factor	**0%**		End-of-project year	**2104**	
Annual costs sensitivity factor	**0%**				
End-of-project costs sensitivity factor	**0%**		Total up-front costs	**$ 7,120**	per tract
Periodic costs sensitivty factor	**0%**		Total end-of-project costs	**$ 1,000**	per tract

Table 29. McMullen Mountain reforestation costs.

Tract size	19	acres	Initial inventory cost	$ -	per tract
Year 1 carbon sequestration rate	-	tonnes CO_2e/ac/yr	Management plan cost	$ -	per tract
Sequestration rate is…	**Variable**	*Fill in rates in table below.*	Other up-front costs	**$ 12,400**	per tract
Carbon reserve pool factor	**10%**		Contract year (Year that up-front costs occur)	**1**	(counter year)
Initial carbon price	**$ 109.69**	per tonne CO_2e	Periodic verification cost	**$ 10,010**	per tract
Carbon price is…	**Constant**		Periodic inventory cost	**$ 1,070**	per tract
Aggregator's fee	**0%**		End of project costs	**$ 1,000**	per tract
Annual reporting cost	**$ 200.00**	per tonne CO_2e	Hurdle rate	**5.0%**	
Trading fee	**$ 0.20**	per tract	Finance rate	**5.0%**	
Other annual costs	**$ 1.00**	per tonne CO_2e	Count pre-contract carbon?	**No**	
Up-front costs sensitivity factor	**0%**		End-of-project year	**2104**	
Annual costs sensitivity factor	**0%**				
End-of-project costs sensitivity factor	**0%**		Total up-front costs	**$ 12,400**	per tract
Periodic costs sensitivty factor	**0%**		Total end-of-project costs	**$ 1,000**	per tract

7.2. Carbon and Timber Revenues

This analysis only considers the carbon revenues in the financial analysis and does not include timber revenues, which may be added in as an additional analysis. In fact, if timber revenues are forgone or delayed, there may be significant costs and therefore reductions in net present value. Two CO2e prices were considered, the current prevailing over the counter price for voluntary market CAR project CRTs of $9.00/tonne and a realistic long-term compliance CRT price of $20.00/tonne. There is an assumed 10% holdback in addition to required buffer pools since this is common practice in OTC voluntary transactions.

7.3. Direct Benefits of the Four Scenarios

A 5% hurdle rate is assumed. Neither of the reforestation projects produced a positive NPV at $9.00/t or at $20.00/t. The Sunset improved forest management project, at $9.00/t, produced a positive NPV of $27,500, which was $64.55/acre ($159.45/h). At $20.00/t, the Sunset forest management project produced a NPV of $167,585 or $393.39/acre ($971.68/h). The McMullen Mountain improved forest management project had initial carbon stocks well above the FIA mean so there were immediate CRTs produced. This resulted in a NPV, at $9.00/t, of $735,235, which was $616.81/acre ($1,523.52/h). At the $20.00/t price the NPV was $1,830,926 or $1,536.01/acre ($3,793.95/h).

7.4. Sensitivity Analysis

The carbon price was varied to determine the break even point for the four project scenarios. The Sunset reforestation project required a price of $68.88/t CO2e to break even. The McMullen Mountain reforestation project required a price of $109.69/t CO2e to break even. The difference in price is due to the lower site productivity of the later unit, which results in lower and later CRTs.

The break even CRT price for the Sunset improved forest management project was $6.85/t. The McMullen Mountain forest management project had a break even price of $1.62/t. The improved forest management projects were much more lucrative due to not having the large up front costs the reforestation entails and because CRTs may be realized earlier. Where timber is a competing income stream to carbon the timber values associated with the carbon project activity versus the baseline scenario could be computed to determine the optimum mix of commodities. This could be analyzed for different costs and revenue points.

8.0 Fuels Treatment Analysis

The impact of fuels treatments on the carbon accounting of the treated and surrounding stands is an area of current research and policy debate. Version 3 of the CAR protocols acknowledges the utility of fuel treatments on the landscape by providing a risk reduction for different treatment categories of none, low, medium and high, which are not quantitatively defined. These can reduce the annual probability of the fire multiplier by 0%, 17.4%, 33.6%, and 50% respectively. For example, a return interval of 10 years would produce an annual probability of fire of 10%. With no treatments this would remain a 10% deduction. A high level of treatments would reduce it by one half so that a 5% risk deduction would apply. Note that risk is defined by the protocols (appendix D.4) as the annual probability of occurrence. This may not match other definitions of risk that multiply the probability of occurrence by the biomass lost, which is a function of burn severity.

This section simulates the planned implementation of a shaded fuel break that ties in with the treatments implemented as part of this project (figure 4). The fire break runs along a ridge from the Sunset unit generally east to the top of McMullen Mountain and then down to treatment areas to the northeast (figure 1). Pre and post fire simulations are performed and assumptions are made about the benefits of risk reduction for neighboring stands. The carbon benefits are then estimated. This analysis is separate from the current forestry protocols and is intended to assist the discussion around the carbon benefits of fuel treatments in forested landscapes.

8.1. Fuel Treatments

The proposed shaded fuel break on LDSF will be 300 feet in width, retain a post-harvest basal area of 50 ft^2/acre (11.5 m^2/h), and reduce ground and ladder fuels. Table 30 shows the stands that are part of the shaded fuel break, which total 75 acres (30 hectares). Pre and post treatment conditions are shown. These are in addition to the units treated as part of the reforestation and improved forest management. An example depiction of a treatment is shown in figure 29. This shows the thinning of the trees, but the ground fuels are also reduced by either piling and burning or chipping and hauling to a biomass plant. We are assuming here that the understory is piled and burned because current market conditions do not allow for hauling from LDSF to a biomass facility. The pre and post harvest condition was matched to the most appropriate fuel model (table 30) for fire behavior simulation.

Table 30. Summary of stands in the proposed shaded fuel break.

			Pre-Treatment						Post-Treatment				
Stand	Acres	WHR Class	Trees per Acre	Basal Area (sq. ft./ac.)	Quadratic Mean Diameter (inches)	Fuel model (Photo series)	Fuel model (FB-Model 2005)	Fuel Load, Biomass (tons/ac)	Trees per Acre	Basal Area (sq. ft./ac.)	Fuel model (Photo series)	Fuel model (FB-Model 2005)	Fuel Load, Biomass (tonnes/ac)
STAND_105_BREAK	13.9	WFR4D	117.7	236	19.2	PNW-95/2-TF-4-PC True Fir, size class 4, partial cut	TL04	24.7	36.1	50	PNW-95/2-TF-4-RC True Fir, Size Class 4, Regeneration Cut	TL01	6.9
STAND_106	2.2	WFR4D	179.5	177	14.7	PNW-95/2-TF-4-PC True Fir, size class 4, partial cut	TL04	24.7	43.2	50	PNW-95/2-TF-4-RC True Fir, Size Class 4, Regeneration Cut	TL01	6.9
STAND_118_BREAK	2.7	WFR4D	108	216	19.2	PNW-95/2-TF-4-PC True Fir, size class 4, partial cut	TL04	24.7	22.7	50	PNW-95/2-TF-4-RC True Fir, Size Class 4, Regeneration Cut	TL01	6.9
STAND_123_BREAK	1.8	WFR4M	44.7	65	16.4	PNW-95/1-TF-4-PC True Fir, size class 4, partial cut	TL01	17.6	28.2	50	PNW-95/2-TF-4-RC True Fir, Size Class 4, Regeneration Cut	TL01	6.9
STAND_155	5.5	WFR4D	117.7	236.01	19.2	PNW-95/2-TF-4-PC True Fir, size class 4, partial cut	TL04	24.7	22.9	50	PNW-95/2-TF-4-RC True Fir, Size Class 4, Regeneration Cut	TL01	6.9
STAND_156	14.1	KMC4M	141.1	127.2	12.9	PNW-95/3-MC-4-PC Mixed Conifer, size class 4, partial cut	TL01	28.6	47.9	50	PNW-95/2-TF-4-RC True Fir, Size Class 4, Regeneration Cut	TL01	6.9
STAND_158	5.9	KMC4M	67.4	94.2	16	PNW-95/3-MC-4-PC Mixed Conifer, size class 4, partial cut	TL01	28.6	32.2	50	PNW-95/2-TF-4-RC True Fir, Size Class 4, Regeneration Cut	TL01	6.9
STAND_164_BREAK	1.8	KMC4D	159.9	271.7	17.7	PNW-95/4-MC-4-PC Mixed Conifer, size class 4, partial cut	TL07	38.2	26.7	50	PNW-95/2-TF-4-RC True Fir, Size Class 4, Regeneration Cut	TL01	6.9
STAND_390_BREAK	7.8	KMC4D	111.7	186.6	17.5	PNW-95/4-MC-4-PC Mixed Conifer, size class 4, partial cut	TL07	38.2	27.3	50	PNW-95/2-TF-4-RC True Fir, Size Class 4, Regeneration Cut	TL01	6.9
S129_BREAK	19.1	KMC2P	314.57	50.62	5.4	PNW-105/1-PP-1 Ponderosa pine, size class 1, natural	TL-08	10	116.66	50	PNW-52/4-PP-1-TH Ponderosa pine, size class 1, thinned, assume pile and burn slash	TL07	2.7

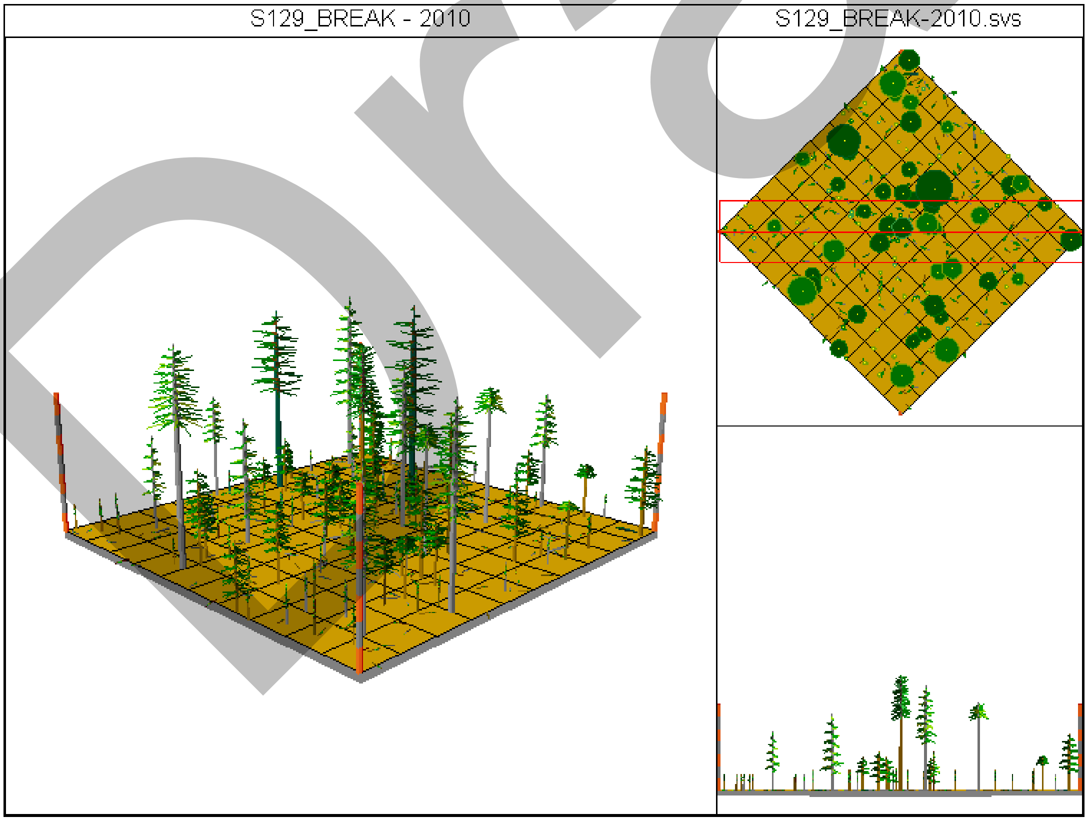


Figure 29. Stand 129 shaded fuel break in 2010 showing removal of small trees.

8.2. Fire Simulations in Treated Stands

Fire behavior was simulated using Fuels Management Analyst Plus version 3 (FMA 2009). The FVS tree list files for each of the stands were input directly into FMA. Weather conditions for the categories of moderate, high and extreme were derived from local RAWS stations using Fire Family Plus version 4 (Bradshaw and Brittain 2008) from the ten year period 1999-2008. The fire weather categories for LDSF are shown in table 31. Burning index was used as the parameter to determine the fire weather categories. Moderate weather has a 75% climatological probability, high severity weather a 7% probability and extreme a 3% probability. This probability covers the fire season, which is defined as May 1 to October 31.

Table 31. Fire weather for LDSF.

		Condition Category		
		Moderate	High	Extreme
Fuel Moisture (percent)	1-hour dead	4.86	3.31	2.86
	10-hour dead	6.12	4.31	3.81
	100-hour dead	10.08	7.56	7.45
	1000-hour dead	12.11	9.31	8.85
	Herbaceous live	11.56	3.49	2.86
	Woody live	81.77	72.19	70.41
Wind (mph)	20-foot wind speed	4	5.84	6.83

Figure 30 shows a profile of the crown density of a stand. FMA is sensitive to ground and canopy fuel interactions, which is ideal for analyzing the effects of fuel treatments. Tables 32-34 show the results of the modeling for the moderate, high and extreme weather conditions. In general both treated and untreated stands were surface fires with little or no crown scorching or tree mortality, the exception being the small tree stand 129. The primary benefit of the treatments was to decrease the rate of spread in many of the stands. Given that the 300 foot width is 4.5 chains (one chain is 66 feet) and the maximum fire spread is reduced from 3.2 to 1.7 chains per hour under extreme weather conditions, this allows more than two hours for resources to respond or hold the line at the fuel break. In all cases the flame lengths are below 4 feet, which is a rule of thumb for where hand crews must transition to dozers due to heat intensity. Therefore, all resources may be brought to bear at this location under all the weather scenarios.

The weather scenarios are likely conservative in that the winds may be higher than modeled because of the ridge-top location. The weather station that supplied the fire weather data was not in such an exposed location. Based on this modeling a shaded fuel break would not be necessary as it would not be beneficial to separate tree crowns because the ground fire would not reach the crowns even under extreme weather conditions. If this could be reliably determined then an understory biomass harvest would be beneficial, which would retain most of the carbon on site. Since a shaded fuel break can allow more light and wind to the ground, creating hotter and drier understory conditions, all of these factors should be considered in total.

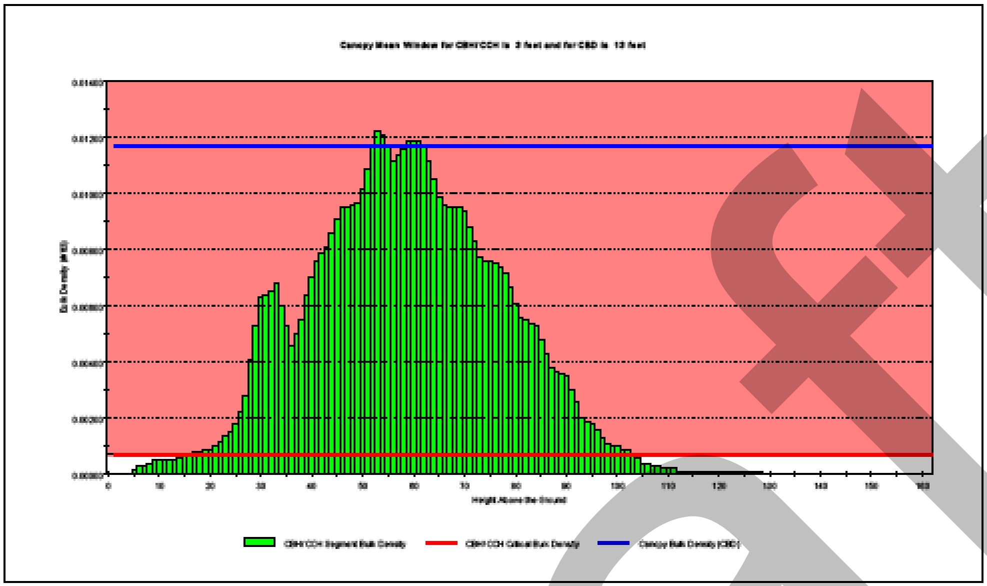


Figure 30. Canopy density for stand 105, used for fire modeling.

Table 32. Fire modeling results for moderate weather conditions.

Stand	Fire Type		Flame Length (feet)		Rate of Spread (ch/hr)		Probability of Ignition (%)		Spotting Distance from Torching Tree (mi)		Percent Mortality		Average Crown Scorch (%)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
STAND_105_BREAK	Surface	Surface	0.8	0.3	0.7	0.3	65	68	0.10	0.10	16.1	16.1	0.0	0.0
STAND_106	Surface	Surface	0.8	0.3	0.7	0.3	67	67	0.10	0.10	17.9	17.9	0.0	0.0
STAND_118_BREAK	Surface	Surface	0.8	0.3	0.7	0.3	67	67	0.11	0.11	11.0	11.0	0.0	0.0
STAND_123_BREAK	Surface	Surface	0.3	0.3	0.3	0.3	67	67	0.10	0.10	11.2	11.2	0.0	0.0
STAND_155	Surface	Surface	0.8	0.3	0.7	0.3	67	67	0.11	0.12	12.5	12.5	0.0	0.0
STAND_156	Surface	Surface	0.3	0.3	0.3	0.3	67	67	0.10	0.10	18.1	18.1	0.0	0.0
STAND_158	Surface	Surface	0.3	0.3	0.3	0.3	67	67	0.10	0.10	16.7	16.7	0.0	0.0
STAND_164_BREAK	Surface	Surface	1.2	0.3	0.9	0.3	67	67	0.11	0.10	10.8	10.8	0.0	0.0
STAND_390_BREAK	Surface	Surface	1.2	0.3	0.9	0.3	67	67	0.10	0.10	11.7	11.7	0.0	0.0
S129_BREAK	Surface	Surface	1.9	1.2	1.7	0.9	67	67	0.10	0.08	29.8	25.5	25.5	0.1

Table 33. Fire modeling results for high weather conditions.

Stand	Fire Type		Flame Length (feet)		Rate of Spread (ch/hr)		Probability of Ignition (%)		Spotting Distance from Torching Tree (mi)		Percent Mortality		Average Crown Scorch (%)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
STAND_105_BREAK	Surface	Surface	1.0	0.4	1.1	0.4	81	84	0.15	0.15	16.1	16.1	0.0	0.0
STAND_106	Surface	Surface	1.0	0.4	1.1	0.4	82	82	0.15	0.15	17.9	17.9	0.0	0.0
STAND_118_BREAK	Surface	Surface	1.0	0.4	1.1	0.4	82	82	0.16	0.16	11.0	11.0	0.0	0.0
STAND_123_BREAK	Surface	Surface	0.4	0.4	0.4	0.4	82	82	0.15	0.15	11.2	11.2	0.0	0.0
STAND_155	Surface	Surface	1.0	0.4	1.1	0.4	82	82	0.16	0.16	12.5	12.5	0.0	0.0
STAND_156	Surface	Surface	0.4	0.4	0.4	0.4	82	82	0.14	0.14	18.1	18.1	0.0	0.0
STAND_158	Surface	Surface	0.4	0.4	0.4	0.4	82	82	0.15	0.15	16.7	16.7	0.0	0.0
STAND_164_BREAK	Surface	Surface	1.6	0.4	1.5	0.4	82	82	0.16	0.16	10.8	10.8	0.0	0.0
STAND_390_BREAK	Surface	Surface	1.6	0.4	1.5	0.4	82	82	0.16	0.16	11.7	11.7	0.0	0.0
S129_BREAK	Surface	Surface	2.5	1.6	2.7	1.5	82	82	0.14	0.12	32.9	35.2	39.5	29.7

Table 34. Fire modeling results for extreme weather conditions.

Stand	Fire Type		Flame Length (feet)		Rate of Spread (ch/hr)		Probability of Ignition (%)		Spotting Distance from Torching Tree (mi)		Percent Mortality		Average Crown Scorch (%)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
STAND_105_BREAK	Surface	Surface	1.1	0.5	1.3	0.5	86	89	0.18	0.17	16.1	16.1	0.0	0.0
STAND_106	Surface	Surface	1.1	0.5	1.3	0.5	88	88	0.17	0.17	17.9	17.9	0.0	0.0
STAND_118_BREAK	Surface	Surface	1.1	0.5	1.3	0.5	88	88	0.19	0.19	11.0	11.0	0.0	0.0
STAND_123_BREAK	Surface	Surface	0.5	0.5	0.5	0.5	88	88	0.18	0.18	11.2	11.2	0.0	0.0
STAND_155	Surface	Surface	1.1	0.5	1.3	0.5	88	88	0.19	0.19	12.5	12.5	0.0	0.0
STAND_156	Surface	Surface	0.5	0.5	0.5	0.5	88	88	0.17	0.17	18.1	18.1	0.0	0.0
STAND_158	Surface	Surface	0.5	0.5	0.5	0.5	88	88	0.18	0.18	16.7	16.7	0.0	0.0
STAND_164_BREAK	Surface	Surface	1.7	0.5	1.7	0.5	88	88	0.18	0.18	10.8	10.8	0.1	0.0
STAND_390_BREAK	Surface	Surface	1.7	0.5	1.7	0.5	88	88	0.18	0.18	10.8	10.8	0.0	0.0
S129_BREAK	Surface	Surface	2.7	1.7	3.2	1.7	88	88	0.17	0.14	36.0	36.2	43.6	31.9

8.3. Carbon and Fire Risk Tradeoff Analysis

The carbon reduction from the shaded fuel break treatments reduces stocks from approximately 48.6 tonnes of live (above and below ground) carbon per acre (120.0 t/h) to 20.4 t/a (49.4 t/h) for a reduction of 28.2 t/a (69.7 t/h) total. In five years this recovers to 24.7 t/a (61.0 t/h). Considering just the treated acres and based on the fire modeling, there was not a net benefit to the thinning from a carbon standpoint. Significant carbon was removed and the site occupancy will be maintained over time at this lower level. Some of this will be recovered in long-term wood products storage and if prices for biomass improve, over time there will be higher utilization of the understory thinning material. The pre versus post treatment fire behavior modeling does not change significantly in this case.

Since the proposed fuel break divides the two project areas in half approximately, consider the fuel break as protecting one half of the total carbon stocks over a 100-year project period. Such an assumption may be optimistic on average, but given the topographic layout and good access this is not an unreasonable assumption. What would the expected average value be given these assumptions? Equation 1 provides a way to quantify the estimate of the value of the shaded fuel break where it is assumed to protect one half of the project carbon. Growth is not included in (1) because we are assuming that the fuel break will be maintained over time and only replacement trees will be allowed to grow to maturity.

$$CVS = LTL + \sum_{t} (PF_t \times PC_t) \times FREQ_t \times (EL_t \times EP_t + HL_t \times HP_t + ML_t \times MP_t) + RECAP \qquad (1)$$

Where *CVS* = carbon value saved by implementing project,

LTL = long-term loss from fuel break treatment,

PF = protection factor (what proportion of project is protected),

PC = project carbon on site,

FREQ = average long-term fire frequency as an annual probability,

EL = extreme weather loss of carbon as a proportion,

EP = extreme weather probability (annual),

HL = high severity weather loss of carbon as a proportion,

HP = high severity weather probability (annual),

ML = moderate weather loss of carbon as a proportion,

MP = moderate weather probability (annual),

$RECAP$ = recapture of site given incident (in carbon), and

t = time, which is 100 years in this case but may be in 5 or 10-year increments.

The following is an example of using equation (1). Several examples are shown in table 35 that illustrate that CVS may be positive or negative depending on the parameters and assumptions. $RECAP$ may be complex in that reforestation or natural succession would have to be modeled. Alternatively, a persistent brush field may occur, especially on non-industrial private lands where there is no legal requirement and it is often common not to reforest after a catastrophic fire. In this example we assume that is the case and $RECAP$=0.

Table 35. Example calculations of carbon tonnes protected by shaded fuel break under different assumptions.

	Example			
Parameter	Expected	More Severe Fire outside Fuel Break	Increased Frequency	Less Protection
LTL	-2,109.4	-2,109.4	-2,109.4	-2,109.4
PF	0.50	0.50	0.50	0.20
PC	98,616.9	98,616.9	98,616.9	98,616.9
FREQ	0.03	0.03	0.10	0.03
EL	0.30	0.60	0.30	0.30
EP	0.03	0.03	0.03	0.03
HL	0.20	0.40	0.20	0.20
HP	0.07	0.07	0.07	0.07
ML	0.10	0.20	0.10	0.10
MP	0.75	0.75	0.75	0.75
RECAP	0.0	0.0	0.0	0.0
CVS	12,387.3	26,884.0	46,212.9	3,689.3

The frequency of fire ($FREQ$), or the return interval, and the weather category characteristics may change over the 100-year period due to fuel changes in the fire-shed, climate change, fire prevention and protection measures. They are held constant in this example. We have made a simple assumption regarding loss of carbon outside the fuel break but in the project area, which is 30% loss for an extreme fire event, 20% loss for a high severity fire, and 10% loss for a moderate event. These are low figures for areas with steeper slopes or lower in elevation where weather is more severe on average.

In all cases examined (table 35) the fuel break provided a positive carbon benefit. Holding other things constant it would take a fire frequency of .435% a year to reach a break even point between the carbon lost in the fuel break treatment and that theoretically saved. These are conservative estimates because the carbon saved used the beginning period carbon stocks, which increases over time.

9.0 Discussion and Conclusions

Harvest scheduling for the improved forest management project type can be complex, even for smaller properties. This is due to trying to optimize reductions by simulating the baseline close to the FIA mean or starting inventory, depending on starting point. If you are conducting an economic analysis, such as maximizing NPV, then a flexible optimizing harvest schedule is even more desirable. Therefore, we recommend using an optimizing harvest schedule for improved forest management project types, such as a linear or dynamic program.

The inclusion of harvested wood products in the baseline accounted for reductions in harvest over the 100-year projection period. The secondary effects calculation applied an additional penalty of 20% of the reduced harvest to account for market leakage. The risk assessment analysis produced what appear to be reasonable results, but will have to be monitored over time to match long-term results by geographic region.

The contribution of wood products was relatively small or even negative for the scenarios presented. This might have been different if there was more harvesting, especially over a larger area with a mix of age classes where harvests could be offset with on-site growth and not cause a reduction in CRTs. Improvements in stand growth could also change the contribution of the harvested wood products pool. Both the baseline and project activity were projected using growth calibrations from the native lightly managed stands. Where group selections or clearcuts occur that create rapidly growing thrifty stands, wood products contributions could increase. This would be captured over time with inventories and would ultimately be reflected in CRTs. Therefore, the CRT projections for these scenarios are conservative.

The application of the reforestation project type was found to be appropriate for both private and public lands, but not economically viable without subsidy. The improved forest management project type was not found to be appropriate for these projects on public lands, as the baseline could not be shown to differ from the project activity. Improved forest management project types on private lands had economic returns (NPV) of $65 and $617 per acre ($159 and $1,524 per hectare) for the two demonstration project areas assuming a price of $9.00 a tonne CO2e. At $20.00 a tonne CO2e the NPVs were $393 and $1,536 per acre ($972 and $3,794 per hectare). The higher value resulted from the starting inventory being substantially above the common practice for the assessment area, which resulted in CRTs being immediately created.

The use of CVal (Bilek et al. 2009) rapidly produces an economic analysis of a project based on carbon income and project costs. This software provides an excellent example of the type of analytic tools needed to build rational ecosystem services markets.

The analysis of the effects of a fuel reduction project showed that the project appeared beneficial to carbon management when carbon benefits from avoided fire to adjacent acres was included in the calculation. More work is needed in this area as it is the application of stochastic landscape disturbances to project specific areas. Quantification necessarily involves estimates of disturbance and weather probabilities from historical records and local knowledge, along with estimates of fire severity for both treated and untreated conditions.

Appendix I: LDSF Inventory, Biomass Calculations and Growth Projections

Inventory and projection methods will be discussed below with results provided in the appropriate sections in the main body of the report. A description of the inventory, biomass calculations, carbon conversions and growth projection methodologies will be provided here since they apply uniformly to both project areas and the private as well as the public scenarios.

Inventory

LDSF maintains two inventories across the entire Forest. The first is a continuous forest inventory (CFI) that consists of 221 permanent plots or approximately one plot per 40 acres. These plots were established in 1964/5 and have been measured, with one exception, every five years. The second inventory consists of temporary plots and is called the timber atlas inventory (TAI). These two data sets provide a level of information and intensity that is not typical for most forestlands, but provide useful data for a demonstration and research forest such as this.

CFI Overview

The CFI is based on 221 permanent plots on a systematic grid across the Forest. The plots are probability proportional to size (the larger the tree the larger the probability of inclusion on the plot, at a given distance from plot center) and use a basal area factor (BAF) of 15 ft^2/acre (3.44 m^2/hectare). Tree species, diameter at breast height (dbh) to the nearest 0.1 inch (0.25 cm), crown ratio, and condition are recorded for each measured tree. A subsample of total tree height is collected. The data is stored in a Microsoft Access database.

TAI Overview

The TAI inventory is a multi-resource inventory that evolved over time from an inventory originally designed for timber and tax purposes in the 1960s. There are approximately 3,600 current plots across the forest, on a 16-plot systematic grid within 40-acre (16.2 h) units called lots. The plots are probability proportional to size and use a basal area factor (BAF) of 20 ft^2/acre (4.59 m^2/hectare). Tree species, dbh to the nearest 2.0 inches (5.08 cm), and crown ratio were recorded for each measured tree. A subsample of total tree height, breast height age, and crown radius was collected. A small tree subplot was sampled. Shrub species, height and cover; standing dead and lying dead wood was estimated with dimensions and decay class variables. An estimate of canopy cover was made by taking a sighting tube shot at each plot center and between each plot, recording the tree canopy intersections. Shrub information was also collected at each intermediate plot. Other wildlife habitat information was collected for each plot. The data was stored in a Microsoft Access database.

Inventory Workup

The TAI inventory was used in conjunction with a type map to provide the carbon estimates and growth projections for both projects. For the above-ground live carbon pool, each tree record's data was input into the FIA standard biomass functions. Only trees 5 inches (12.7 cm) dbh and above were included in the analysis. The steps and appropriate functions for the most common species present are shown below.

Step 1, calculate the bole volume: The bole volume calculation is shown for each species using a 20-inch (50.80 cm) dbh tree and a total height (THT) of 80 feet (24.4 m). The volume assumes a ground to tip bole, no stump or tip deduction. These equations, cubic volume total stem (CVTS), are from the document *Volume estimation for the PNW-FIA Integrated Database* (dated 13 May 2009).

Ponderosa pine (Equation #5): CVTS(DBH=20 in.,THT=80 ft.) = 64.5787 ft^3.

White fir (Equation #23): CVTS(DBH=20 in.,THT=80 ft.) = 60.5337 ft^3.

Incense-cedar (Equation #19): CVTS(DBH=20 in.,THT=80 ft.) = 50.8788 ft^3.

Douglas-fir (Equation #3): CVTS(DBH=20 in.,THT=80 ft.) = 60.0552 ft^3.

Black oak (Equation #41): CVTS(DBH=20 in.,THT=80 ft.) = 115.4407 ft^3.

Step 2, calculate the biomass of the bole: The bole, or stem or trunk, biomass is the volume of the wood multiplied by the wood density. Wood density is variable and average densities are reported by species or species groups. The wood densities below are from *the Regional biomass equations used by FIA to estimate bole, bark and branches* (dated 13 May 2009).

Ponderosa pine: 64.5787 ft^3 X 23.71 lbs/ft^3 X (1 lb./2.204622 kg) = 694.5237 kg

White fir: 60.5337 ft^3 X 23.09 lbs/ft^3 X (1 lb./2.204622 kg) = 633.9972 kg

Incense-cedar: 50.8788 ft^3 X 21.84 lbs/ft^3 X (1 lb./2.204622 kg) = 504.0288 kg

Douglas-fir: 60.0552 ft^3 X 28.7 lbs/ft^3 X (1 lb./2.204622 kg) = 781.8048 kg

Black oak: 115.4407 ft^3 X 34.94 lbs/ft^3 X (1 lb./2.204622 kg) = 1,829.5637 kg

Step 3, calculate the biomass of the bark: The bark biomass is estimated directly from the tree DBH, THT and wood density although some species equations only use DBH. These functions may be found in the *Regional biomass equations used by FIA to estimate bole, bark and branches* (dated 13 May 2009).

Ponderosa pine (Equation #9): BB(DBH=50.80 cm, THT=24.4m) = 79.5466 kg

White fir (Equation #1): BB(DBH=50.80 cm) = 369.0422 kg

Incense-cedar (Equation #12): BB(DBH=50.80 cm) = 124.5344 kg

Douglas-fir (Equation #8): BB(DBH=50.80 cm) = 187.6330 kg

Black oak (Equation #30): BB(DBH=50.80 cm, THT=24.4m, Density) = 167.7698 kg

Step 4, calculate the biomass of the live crown branches: The live crown branches are computed from tree DBH and THT although some species equations only use DBH. These functions may be found in the *Regional biomass equations used by FIA to estimate bole, bark and branches* (dated 13 May 2009).

Ponderosa pine (Equation #7): BB(DBH=50.80 cm, THT=24.4m) = 178.3803 kg

White fir (Equation #1): BB(DBH=50.80 cm, THT=24.4m) = 91.0286 kg

Incense-cedar (Equation #10): BB(DBH=50.80 cm, THT=24.4m) = 239.9483 kg

Douglas-fir (Equation #6): BB(DBH=50.80 cm) = 110.4461 kg

Black oak (Equation #16): BB(DBH=50.80 cm) = 289.3839 kg

Step 5, sum the aboveground live tree biomass: The bole, bark and live branches are summed. The leaves or needles are not estimated here. Technically, much of the bole and bark is dead as much of the live portions are at the intersection of the two, but we lump these pools into the live component as the organism is alive.

Ponderosa pine: (694.5237 kg + 79.5466 kg + 178.3803 kg)/1,000 kg/tonne = 0.95 tonne

White fir: (633.9972 kg + 369.0422 kg + 91.0286 kg)/1,000 kg/tonne = 1.09 tonne

Incense-cedar: (504.0288 kg + 124.5344 kg + 239.9483 kg)/1,000 kg/tonne = 0.87 tonne

Douglas-fir: (781.8048 kg + 187.6330 kg + 110.4461 kg)/1,000 kg/tonne = 1.08 tonne

Black oak: (1,829.5637 kg + 167.7698 kg + 289.3839 kg)/1,000 kg/tonne = 2.29 tonne

Step 6, convert biomass to carbon estimate: The carbon content of biomass is approximately ½ or 50%.

Ponderosa pine: 0.95 tonnes biomass X 0.5 = 0.476 tonnes C

White fir: 1.09 tonnes biomass X 0.5 = 0.547 tonnes C

Incense-cedar: 0.87 tonnes biomass X 0.5 = 0.434 tonnes C

Douglas-fir: 1.08 tonnes biomass X 0.5 = 0.540 tonnes C

Black oak: 2.29 tonnes biomass X 0.5 = 1.143 tonnes C

Step 7, estimate below-ground carbon: The below-ground carbon was estimated using the protocol suggested reference by Cairns et al. (1997). The function is:

$$BBD = e^{-0.7747+0.8836*\ln(ABD)}$$

where *ABD* = above-ground biomass density in tonnes per hectare,

BBD = below-ground biomass density in tonnes per hectare.

This estimate is made for each plot so that it may be incorporated into the plot-level standard error estimates. The carbon is estimated by multiplying *BBD* by 0.5.

Step 8, estimate standing and lying dead wood for both project types: The TAI inventory provides estimates for both of these carbon pools. The specifications of the inventory are as follows.

- Minimum size of 10 inches (25.4 cm) diameter for snags, 8 inches (20.3 cm) diameter for down wood
- Species coded for snags where identifiable
- Decay classes of sound and rotten for both snag and down wood, down wood also has an intermediate class
- Length, small diameter and large diameter for down wood, dbh for snags.

The volume of the aboveground wood was estimated and then multiplied by a density factor that varied by species and decay class. The frustum of a parabaloid formula (1.2) was used to calculate volume for down wood (Husch et al. 1993). A neiloid formula (1.3) was used for snags, since only one measurement was taken (dbh) and that was near the base.

$$V = \frac{h}{2}(A_b + A_u) \tag{0.2}$$

$$V = \frac{1}{4}(A_b h) \tag{0.3}$$

where, A_b = cross-sectional area at the base,

A_u = cross-sectional area at the top, and

H = height or length.

The wood density used for snags was the same as that for the standing live trees, where the wood was sound. Where species was not identified for snags, white fir density was used as it was the most common species on LDSF. Rotten snags received a density of 0.202 g/cm^3, which was the decay class 3 for down white fir in the Sierra Nevada according to Harmon and Sexton (1996). Since snag height was not measured the height was estimated using the LDSF height-diameter functions used for live trees.

No estimates for bark biomass were made. The wood density for down wood used the white fir estimates for the Sierra Nevada from Harmon and Sexton (1996, see table 4). This was translated to be 0.340 g/cm^3 for sound logs, 0.333 g/cm^3 for intermediate logs, and 0.185 g/cm^3 for rotten logs. Biomass estimates from dead wood was converted to carbon tonnes as in previous steps.

Step 9, calculate the standard error and sampling error of the carbon estimate: The standard error is a common statistical parameter used to express the variability of an estimate. The protocols require an estimate of the confidence bound using a 90% level of confidence. This is calculated by multiplying the standard error by the t-value of 1.645. The standard error formula will be a function of the sampling design, which could be systematic with random start (treated as random), stratified, multi-stage, double, combinations of the above or other design. In this case we have a systematic grid of plots that have been overlaid on a type map yielding a stratified random sample. Each stand was treated as a separate stratum. The total and standard error formula are as follows (Husch et al. 1993).

Mean (live and dead tree carbon per acre) per stand or stratum: $\overline{x}_j = \dfrac{\sum_{i=1}^{n_j} x_{ij}}{n_j}$, where x_{ij} is the above- and below-ground live tree and above-ground standing and lying tree carbon from the ith tree on the jth plot and n_j are the number of plots in the jth stratum.

Mean (live and dead tree carbon) per project: $\overline{x} = \dfrac{\sum_{j=1}^{M} N_j \overline{x_j}}{N} = \sum_{j=1}^{M} P_j \overline{x_j}$,

where M is the number of strata (or stands), N_j is the number of sampling units in the jth stratum, N is total number of sampling units in the population, and P_j is the proportion of the total forest area in the jth stratum (N_j/N).

Total (live and dead tree carbon) per project: $\hat{X} = N\overline{x}$

Each stand or stratum stand variance (standard deviation squared) is calculated using the simple random sampling formula.

Variance of the mean per acre estimate for a stratum: $s_j^2 = \dfrac{\sum_{i=1}^{n_j} (X_{ij} - \overline{x}_j)^2}{n_j - 1}$

The variance estimate for the mean of the project, or population, assumes that the sample is small relative to the population so that the finite population correction may be ignored (a more conservative estimate).

Variance of the mean per acre estimate for project: $s_{\bar{x}}^2 = \sum_{j=1}^{M} P_j^2 \frac{s_j^2}{n_j}$

Variance of the carbon estimate for project: $s_X^2 = N^2 s_{\bar{x}}^2$

The standard error of the total is the square root of s_x^2.

Step 10, estimate shrub carbon for reforestation units: The carbon contained in the vegetation removed from a site when conducting a reforestation project type must be estimated. This was done by using shrub biomass estimates from Martin et al. (1981) for live and dead aboveground material. Two species were available from this paper, greenleaf manzanita (*Arctostaphylos patula*) and snowbrush (*Ceanothus velutinus*). To be conservative, other species used the manzanita estimates since they were the larger of the two. The biomass estimates were provided by percent cover in 10% classes. Cover estimates from field plots that were installed pre-treatment were used to estimate the biomass.

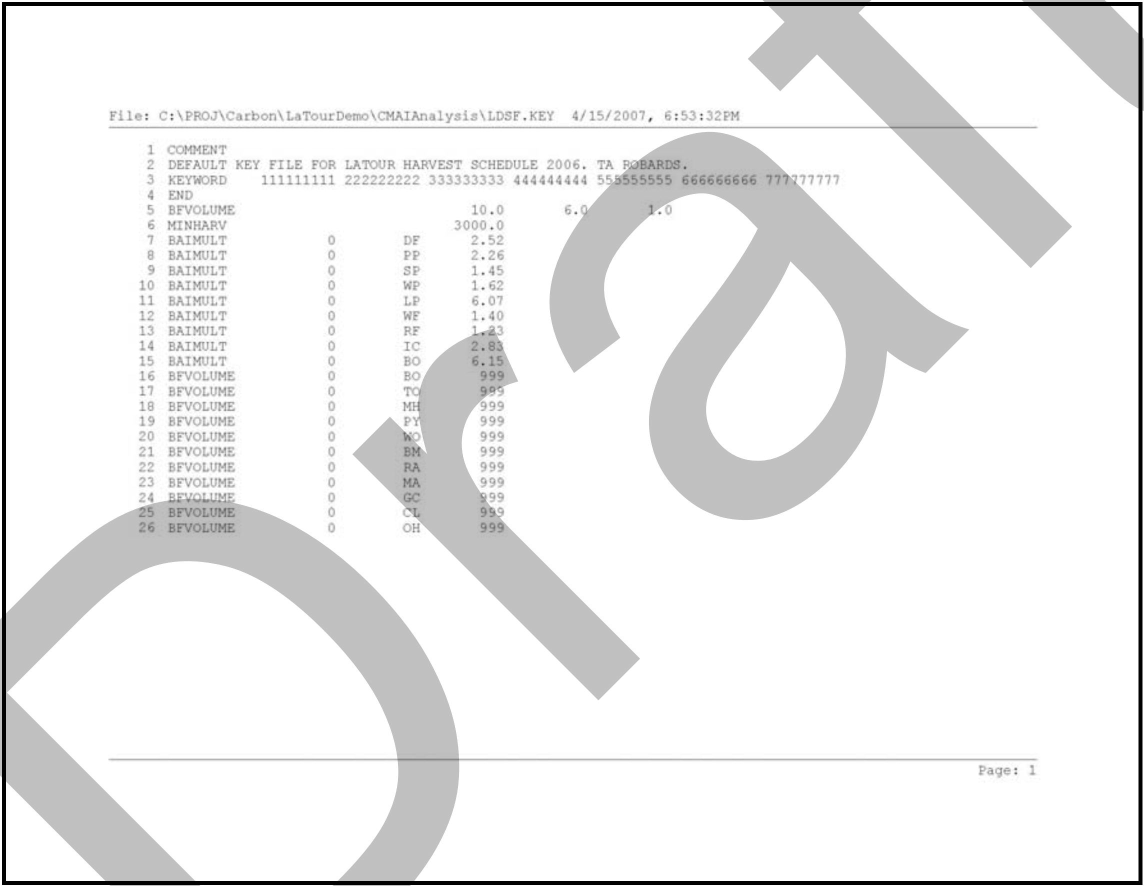
Herbaceous cover is also required but is rare, in a carbon inventory sense, in these brushfields. Indirect estimations of emissions from mobile combustion preparing and planting the site are taken from the protocols (FPP table 6.1). The reforestation in the McMullen Mountain project was in heavy brush using mastication to clear it; therefore a heavy emission is appropriate, given as 0.429 tonnes per acre CO2e. This equates to 0.117 tonnes per acre C. The reforestation unit in the Sunset project was sprayed, brush raked, and piled. Since the brush was also dense and large the heavy emission amount of 0.117 tonnes per acre C will also apply. No emissions from shifting from croplands occurred.

The results of this analysis are shown in tables 4 and 15 for the Sunset and McMullen Mountain projects respectively. The reforestation components did not have any aboveground live tree components; therefore the tree calculations were not performed for that project type. Shrub carbon removed was estimated for the reforestation types only. The biomass functions used for the projections of both baseline and project activity were the same as the FIA functions.

Growth Projections

The growth projections used the same modeling methods as for the LDSF option-A plan (CCR 933.13), which is a state-approved long-term (100 years) harvest schedule to demonstrate sustained yield. The project activity projections are the same as that presented in the option-A plan; for both the private and public lands scenarios.

Growth data from the CFI plots was used to calibrate the diameter growth component of the Forest Vegetation System (FVS) variant ICASCA (Dixon 1999), by species. This growth simulator was used within the Landscape Management System (LMS) version 2.0.46 (Robards and Smith 2006). LMS provided an integrated system for growth projections, harvest simulation, statistical reports, stand visualization and carbon yield reporting. Figure 1 shows the key file that was used with every simulation in this report. The BFVOLUME keyword sets the merchantable volume at a minimum 10-inch dbh, 6 inch top and 1 foot stump. At least 3,000 board feet per acre must be available to harvest economically. The BAIMULT keyword is the LDSF growth calibration factors. The BFVOLUME keyword sets hardwood species to zero board foot volume.



```
File: C:\PROJ\Carbon\LaTourDemo\CMAIAnalysis\LDSF.KEY  4/15/2007, 6:53:32PM

COMMENT
DEFAULT KEY FILE FOR LATOUR HARVEST SCHEDULE 2006. TA ROBARDS.
KEYWORD    111111111 222222222 333333333 444444444 555555555 666666666 777777777
END
BFVOLUME                            10.0       6.0       1.0
MINHARV                           3000.0
BAIMULT            0        DF      2.52
BAIMULT            0        PP      2.26
BAIMULT            0        SP      1.45
BAIMULT            0        WP      1.62
BAIMULT            0        LP      6.07
BAIMULT            0        WF      1.40
BAIMULT            0        RF      1.23
BAIMULT            0        IC      2.83
BAIMULT            0        BO      6.15
BFVOLUME           0        BO       999
BFVOLUME           0        TO       999
BFVOLUME           0        MH       999
BFVOLUME           0        PY       999
BFVOLUME           0        WO       999
BFVOLUME           0        BM       999
BFVOLUME           0        RA       999
BFVOLUME           0        MA       999
BFVOLUME           0        GC       999
BFVOLUME           0        CL       999
BFVOLUME           0        OH       999

                                                                                Page: 1
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Figure 31. FVS key file used in the simulations.

While carbon pool estimates were available from within LMS, based primarily on Jenkins et al. (2003), we used the FIA biomass functions for both baseline and project activity projections. This was done by post-processing the inventory data files by 5-year periods using the custom-made California Forest Carbon Processor program (Robards 2009). This accounted for both above-ground and below-ground carbon. Dead wood was simulated using the LMS defaults for dead wood decay over time, but were found to estimate very little down or standing dead wood over time. Since this would cause an underestimation in the baseline and therefore an overestimation in additionality over time, an average down wood component was estimated from published fuel loading for down dead wood that was 3.1 inches (7.9 cm) or larger (Blonski and Schramel 1981; FMA 2009). Table 36 shows the default values that were used by forest type and size class. The ratio of long-term average projected snag to down wood biomass was assumed to be 1:1.

Table 36. Default down wood density by forest type and size class (class 2: 5-11" (12.7-28.0 cm) dbh, class 3: 12-20" (30.5-50.8 cm) dbh, 4: >20" (50.8 cm) dbh).

Forest Type	**Size Class**	**DDW 3.1"+ (tons biomass per acre)**	**DDW 3.1"+ (tonnes C per acre)**
Ponderosa pine	2	4.9	2.2
Ponderosa pine	3	3.2	1.4
Ponderosa pine	4	6.5	2.9
White fir	2	2.2	1.0
White fir	3	6.7	3.0
White fir	4	7.8	3.5
Red fir	3, 4	1.8	0.8
Lodgepole pine	2	2.2	1.0
Lodgepole pine	3	6.1	2.8
Mixed Conifer, Fir	4	6.6	3.0
Mixed Conifer, Pine	4	5.2	2.4

The wood products estimates for the baseline require that a volume estimate be obtained from the simulations, which was taken from LMS. Then the merchantable cubic foot volumes were multiplied by the density factor of 24.59 lbs/ft^3 and then converted to tonnes of C by multiplying by ½ and dividing by 2,204.6 pounds. The wood product class was estimated to be 70% softwood plywood and 30% softwood lumber based on the last two timber sales from the Forest (Ben Rowe, CAL FIRE, personal communication). Therefore, a .470 factor for softwood lumber and a 0.490 factor for softwood plywood were applied for in-use. A 0.294 and a 0.283 factor were applied for landfills, respectively.

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WEST
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CARBON MARKETS INVESTMENT CRITERIA FOR BIOCHAR PROJECTS

Weisberg, Peter, Matt Delaney and Janet Hawkes.

The Climate Trust

The
Climate
Trust

DOE Contract No.: DE-FC26-05NT42593

Contract Period: October 1, 2005 - May 11, 2011

ABSTRACT

The Climate Trust conducted an assessment of biochar to determine its appropriateness as a terrestrial carbon sequestration offset project. Biochar is an inert residue created by pyrolysis with the potential to rapidly sequester large amounts of carbon. This report describes what types of biochar projects can most readily qualify as high-quality greenhouse gas offsets for carbon market buyers and investors. The offset quality criteria outlined by the Offset Quality Initiative (2008) are applied to the biochar project type as a whole and to a pilot project at the Thompson Timber log yard in Philomath, Oregon. This report finds that attractive projects must meet the following three criteria. First, projects must use waste biomass that, in the absence of a project, would be left to decompose. Second, projects must produce at least 25,000 metric tons of biochar over 10 years. Third, projects must be able to account for, track, and monitor where all the produced biochar is incorporated into the soil. When applying these criteria to the pilot project in Philomath, this report finds that the pilot project could be an attractive offset project if it were to scale up to use all available waste biomass and apply it to a limited number of landscapes.

Keywords: Terrestrial carbon sequestration, biochar, pyrolysis, climate change, carbon markets, greenhouse gas offsets, biomass, West Coast Regional Carbon Sequestration Partnership, WESTCARB

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EXECUTIVE SUMMARY

Introduction

The West Coast Regional Carbon Sequestration Partnership (WESTCARB), led by the California Energy Commission, is one of seven U.S. Department of Energy regional partnerships working to evaluate, validate, and demonstrate ways to sequester carbon dioxide (CO_2) and reduce emissions of greenhouse gases (GHGs) linked to global warming. The nascent carbon offset market offers a venue for directing funds to innovative terrestrial sequestration project concepts. However, such innovative projects must be validated against a set of criteria that are commonly used to determine the appropriateness and viability of the project concept in the carbon offset market.

Heating organic material without oxygen in a process called pyrolysis thermo-chemically transforms biomass into a stable char residue that resists decomposition, while also producing oil and gas. This residue is called biochar when it is incorporated into soils as an agricultural amendment (Driver and Gaunt 2010; Lehmann 2007; Roberts et al. 2010).

Biochar could provide a major contribution to the global effort to reduce GHG emissions; some estimates suggest it could mitigate as much as one-eighth of global GHG emissions (Woolf et al. 2010). Given the substantial timber resources in the region, many of the WESTCARB states (Alaska, Arizona, California, Nevada, Oregon, and Washington) are suitable candidates to host biochar projects.

Biochar production reduces GHG emissions through the following pathways:

1. *Sequestering carbon in biochar*. Photosynthesis sequesters carbon in biomass as it grows. When this biomass decomposes, the carbon is released back to the atmosphere. If the biomass is instead converted through pyrolysis into biochar, the carbon originally sequestered in the biomass will be stored for a much longer time because much of the carbon in the biochar will not decompose for hundreds or thousands of years (Lehmann 2007). Biochar can slow the basic carbon cycle to sequester carbon for long periods of time, because it is significantly more inert than the original feedstock that created it.
2. *Displacing fossil fuel energy with renewable energy*. Pyrolysis also produces oils and gases that can be combusted to generate renewable energy. When biomass instead of fossil fuels create energy—and it is harvested in a manner that does not increase land-use emissions— it can avoid CO_2 emissions.
3. *Diverting waste from generating methane*. Many biomass feedstocks that could be pyrolyzed currently decompose in the absence of oxygen under water or in landfills. Rice residues, green waste, and manure, for example, are commonly left to decompose in rice paddies, landfills, or lagoons (Woolf et al. 2010). This anaerobic decomposition

releases methane (CH_4). Pyrolysis of these feedstocks prevents this anaerobic decomposition and avoids these CH_4 emissions.

Through these pathways, biochar has the potential to provide a material contribution to efforts to reduce the build-up of greenhouse gases in the atmosphere. Globally, it is estimated that, at its maximum sustainable potential, biochar could annually reduce 1.8 gigatons of carbon dioxide equivalent emissions (CO_2e), or 12% of the world's GHG emissions (Woolf et al. 2010). In the United States, pyrolyzing 40% of unused agricultural and forestry residues could reduce 230 million metric tons of CO_2e, or around 8% of the annual GHG reductions needed to reduce domestic GHG emissions by 50% by 2050 (Roberts et al. 2010).

Purpose

Biochar's potential will only be realized if biochar projects prove to be financially viable. One important step towards profitability is to enable biochar projects to monetize their climate benefits. Biochar projects could do this by selling GHG offsets to regulated emitters under a cap-and-trade system. The Offset Quality Initiative (2008) discussed nine criteria that must be met for projects to qualify as offsets under such a system. This report addresses how each of these nine citerion applies to biochar projects in general and to a specific case study in Philomath, Oregon.

Project Objective

The overall goal of WESTCARB Phase II is to validate and demonstrate the region's key carbon sequestration opportunities through pilot projects, methodology development, reporting, and market validation. WESTCARB research will facilitate informed decisions by policy makers, communities, and businesses on how to invest in carbon capture and storage technology development and deployment to achieve climate change reduction objectives. The sequestration opportunity presented here is producing biochar and applying it as a soil amendment.

Project Outcomes and Conclusions

This report finds that for a project to qualify as a high quality offset supplier, it should contain the qualities described in Table 1.

Table 1: Essential carbon market investment criteria for biochar projects

Project component	Desirable quality	Carbon market rationale
Feedstock	Projects are fed by waste biomass that would otherwise be burnt or left to decompose. Feedstocks grown specifically for the biochar project are produced on marginal or degraded land.	*Leakage*. Waste feedstocks (or feedstocks grown on marginal/degraded land) do not cause land-use change.
	Feedstocks do not potentially contain heavy metals. Feedstocks do not consist of municipal solid waste, sewage sludge, or tires.	*No net harm*. Heavy metals could potentially be concentrated through pyrolysis and contaminate soils, damaging the environment and human health.
Pyrolysis process	Pyrolysis will generate at least 25,000 metric tons of biochar over ten years. Bigger projects (100,000 metric tons of biochar or more) are the most desirable.	*Verification*. Because many verification costs are fixed regardless of the size of the project, verification costs are a smaller portion of the overall cost of large projects. Economies of scale favor large projects. Projects that produce less than 25,000 metric tons of biochar over their life will not be considered for carbon market investment unless a small-scale methodology and aggregation system is developed to reduce transaction costs.
Use of biochar	The biochar producer can account for, track and monitor where all the biochar is incorporated into soils. Vertical integration, where the producer of the char is also the user of the char, is the most desirable.	*Monitoring and Permanence*. De Gryze et al. (2010) suggest the most credible method to quantify biochar projects is to measure the quantity of biochar remaining in the soil 1, 5, 10, 20 and 50 years after it is incorporated with the soil. Vertical integration makes this monitoring economically feasible. If projects are not vertically integrated, they must at least be able to easily track and account for where all the biochar is integrated into soils.

Using these investment criteria as a guide, this report evaluates a pilot-scale biochar project in Philomath, Oregon. The project, conducted at a log yard that currently produces 6,000 metric tons of waste woody biomass per year, met all but the following two investment criteria:

1. The project is too small. The pilot project is projected to produce 8 metric tons of biochar per year, while it is estimated that biochar offset projects will need to produce at least 25,000 metric tons of biochar over their lifetime, or around 2,500 metric tons per year.
2. The project plans to sell biochar to many entities, making it difficult to account for where all the biochar will be incorporated into soils.

Given the quantity of waste biomass and land available to the log yard, however, it is feasible for the pilot project to scale into an attractive offset project. However, biochar's economic and agronomic benefits are not yet sufficiently proven to justify this scale of investment. Study of the pilot project is a first attempt to make this justification.

Recommendations

As the biochar industry matures and starts producing at scale, projects are likely to be eligible to sell their climate benefits as GHG offsets to regulated emitters under a cap-and-trade program. This makes biochar a promising project type for pilot-scale investment and carbon market protocol development. A protocol will help enable the biochar industry to scale up and focus on maximizing the potential climate benefits of biomass utilization.

CHAPTER 1:
Introduction to Biochar

1.1 Definition of biochar

Biochar is frequently defined by how it is created and used rather than by its chemical composition or properties. Biochar is created through heating organic material in a low-or-no oxygen environment through a process called pyrolysis (Gaunt and Driver 2010; Roberts et al. 2010; Woolf et al. 2010; Lehmann and Joseph 2009). Pyrolysis causes biomass to thermo-chemically transform, leaving behind the concentrated carbon skeleton of the original biomass. During this transformation, pyrolysis releases gases and oils, which can be combusted to create energy. Feedstock, temperature, and time of exposure to pyrolysis determine the proportions of gas, oil and char produced and the characteristics of these outputs (Lehmann 2007; Lehmann and Joseph 2009; Roberts et al. 2010; Gaunt and Driver 2010; Woolf et al. 2010; McLaughlin et al. 2009; Lehmann, Gaunt and Rondon 2006).

The char portion created by pyrolysis is called biochar when it used as an agricultural amendment or strategy for environmental management (Driver and Gaunt 2010). When added to soils, biochar can help retain moisture and improve nutrient availability and therefore enhance soil productivity (Lehmann and Joseph 2009; Driver and Gaunt 2010). This increased fertility could be especially important as a tool to adapt to climate change, which will likely increase nutrient and moisture stress in many agricultural systems.

The biochar industry is still emerging, but has been the focus of significant interest by researchers, entrepreneurs, and government agencies over the past several years. Recent reviews by Terra Global Capital, Cornell University, and the University of California, Davis, provide summaries of biochar as a renewable energy resource and as a mechanism for carbon sequestration (Gryze et al. 2010). In addition, the biochar field is of interest to researchers (Lehmann 2010; Roberts et al. 2009; Zimmerman 2009), those interested in biochar as a carbon market mechanism (Driver and Gaunt 2010), and in national policy circles (Bracmort 2009).

1.2 Greenhouse gas emission reductions from biochar

In addition to improving soils, biochar may also provide a material contribution to the efforts to reduce concentrations of greenhouse gases in the atmosphere. Biochar, in its production and use, sequesters carbon while generating renewable energy and reducing greenhouse gas emissions from soils and the decomposition of waste.

Reductions from a biochar project vary based on how feedstocks would have been used in the absence of the project, the characteristics and quantity of biochar and energy created, and the type of soil into which the biochar is incorporated. The “% of Reductions” column in Table 1 generalizes what percentage of a biochar project’s overall emission reductions come from each category. Carbon sequestration, renewable energy, and waste diversion represent the largest reductions. This report will therefore focus on these categories.

Table 2: Biochar emission reductions

GHG Reduction	Description	GHG	% of Reductions[1]
Carbon sequestration	Photosynthesis sequesters carbon in biomass as it grows. When this biomass decomposes, it releases the carbon back into the atmosphere. If the biomass is instead converted through pyrolysis into biochar, the carbon originally sequestered in the biomass will be stored for a much longer time—for hundreds or thousands of years depending on the characteristics of the biochar and the environment into which it is incorporated (Lehmann 2007). This is because biochar is significantly more resistant to decomposition than the biomass used to produce it. Pyrolyzing biomass therefore enhances carbon sequestration.	CO_2	50-65%
Renewable energy	The energy which can be produced from the gases and oils generated by pyrolysis can replace the combustion of fossil fuels. Pyrolysis could produce electricity (which would offset fossil-fueled power plants) or heat (which could replace thermal demand at or near the pyrolysis plant previously supplied with fossil fuels).	CO_2	20-40%
Waste diversion	Many feedstocks, including rice residues, green waste sent to landfills and manure, are left to decompose without oxygen in rice paddies, landfills, and lagoons (Woolf et al. 2010). This anaerobic decomposition emits methane (CH_4). Collecting and pyrolyzing feedstocks that would otherwise anaerobically decompose avoids CH_4 emissions.	CH_4	0-20%
Reduction in soil emissions	Applying biochar to soils may reduce soil emissions of nitrous oxide (N_2O) and increase the ability of soils to uptake CH_4. These reductions are highly variable and the precise mechanism through which they occur is not yet fully understood (Van Zwieten et al. 2010).	N_2O, CH_4	0-5%
Reduction in fertilizer manufacturing	Applying biochar to fields may reduce the need to apply other conventional fertilizers. Many conventional fertilizers are energy intensive to manufacture. Reducing the demand for fertilizers reduces its manufacture, thereby reducing CO_2 emissions. When nitrogen fertilizers are applied to field, a small percentage of the nitrogen is emitted as N_2O. Reducing nitrogen fertilizer applications also reduces N_2O emissions.	CO_2, N_2O	Not quantified

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[1] Based on ranges reported in Woolf et al. (2010) and Roberts et al. (2010).

1.3 Climate mitigation potential

The potential for biochar to reduce emissions is determined by the quantity of biomass that is available for pyrolysis. Critics fears that, if feedstocks are not sustainably sourced, large-scale implementation of biochar (or other biofuels projects) could cause deforestation, habitat and biodiversity loss, soil erosion, loss of soil function, and soil contamination (Ernsting and Smolker 2009). One must define which feedstocks can be pyrolyzed without damaging the environment or human health to determine the sustainable mitigation potential of biochar. Woolf et al. (2010) states that, to be sustainable, feedstocks must meet the following criteria:

1. Not cause land-use change or deforestation.
2. Be produced on marginal or degraded land (if they are purposefully grown).
3. Be extracted at a rate that does not create soil erosion or loss of soil function (if they are taken from agricultural or forestry residues).
4. Not be sourced from industrial waste.

Assuming all feedstocks that meet these criteria are pyrolyzed, Woolf et al. (2010) estimated that the maximum GHG mitigation potential of biochar is an annual reduction of 1.8 gigatons of CO_2e. This is equivalent to 12% of current global GHG emissions. Large-scale implementation of biochar could produce a similar scale of reductions as wind, solar, efficiency, or nuclear—sectors that are the current focus of efforts to mitigate climate change.

The estimate from Woolf et al. (2010) is the theoretical upper limit of biochar's sustainable potential, not its likely potential. At a national scale, biochar can still provide a material contribution to efforts to reduce emissions. Assuming 40% of currently unused crop and forest residues were pyrolyzed in the United States, Roberts et al. (2010) estimate that biochar could annually reduce 230 million metric tons of CO_2e, or 8% of the annual reductions needed to reduce domestic emissions by 50% by 2050.

These promising mitigation potentials are based on drastic increases in biomass collection and use. Emission reductions of this scale are dependent not only upon the creation of many pyrolysis plants, but also on the collection and transportation infrastructure that is needed to get the biomass to these plants. The pyrolysis plants can also be brought to the biomass in the field; there are several companies fabricating field-scale mobile pyrolysis units.

Once biomass is in a usable place, it can produce many products with climate benefits, of which biochar is just one. Biochar, in many cases, may provide the greatest climate benefit. Woolf et al. (2010) found that creating biochar, rather than combusting the same sustainably procured biomass to extract the maximum amount of energy, on average reduced 22% to 27% more GHG emissions. The type of energy replaced is a critical factor. Full combustion of the biomass may yield a greater climate benefit than biochar when displacing energy generated with coal. The emissions benefit of creating biochar rather than full combustion for energy will likely increase as the carbon intensity of the global energy mix lowers through the implementation of cleaner technologies. This may make biochar an essential mitigation technology for achieving additional GHG reductions. Biochar has the potential to play a significant role in the effort to mitigate climate change and warrants additional study, research, financing, piloting and implementation.

1.4 Context for this report

To realize this mitigation potential, biochar projects must prove to be financially viable. A price on carbon emissions—which this report assumes will be achieved through a cap-and-trade system—is one policy that would increase the profitability of biochar projects. A cap-and-trade system would increase the cost of fossil fuel-generated energy, making the renewable energy from pyrolysis relatively cheaper. A cap-and-trade system could also generate a large pool of capital from regulated emitters that, through an offset system, could be invested into biochar projects to incentivize them to realize the carbon sequestration and waste diversion benefits discussed in section 1.3.

A cap-and-trade system would require regulated emitters to reduce GHG emissions. Offsets allow those regulated emitters to pay unregulated sectors to achieve these reductions. Offsets give regulated emitters the flexibility to find the lowest cost emission reductions available, regardless of what sector of the economy they come from. Biochar is a good illustration of the benefit of this flexibility. As the climate benefits of biochar are proven, no new policy needs to be designed to incentivize these benefits. Instead, if the reductions are low cost and can meet the quality criteria required for offset projects, regulated emitters can pay biochar project developers for offsets under the existing cap-and-trade system.

What does it mean for biochar projects to meet the quality criteria required of offset projects? Chapter 2 of this report will answer this question by applying the criteria outlined by the Offset Quality Initiative (2008) to biochar projects. De Gryze et al. (2010) discuss these issues in a paper commissioned by the Climate Action Reserve. This report will add the perspective of a carbon market investor to that analysis, outlining the specific criteria of biochar projects that will make them attractive for investment from carbon markets. Chapter 3 details a case study of the Thompson Timber/Starker Forests biochar project (TSY-Peak project) in Philomath, Oregon. Chapter 3 describes the project's hardware, inputs and outputs, economics, and GHG emissions impact. Chapter 4 compares the criteria outlined in Chapter 2 to the TSY-Peak project, discussing how the project would need to scale up in order to allow it to be eligible for offset crediting.

CHAPTER 2:
Offset Quality Criteria Applied to Biochar Projects

The Offset Quality Initiative, a consortium of national nonprofit organizations working to advance the environmental integrity of the carbon market, published a paper outlining the key criteria offset projects must meet (Offset Quality Initiative 2008). The paper concluded that, in order for projects to generate emission reductions credible enough to substitute for on-site reductions of an entity capped under climate policy, offsets meet the following criteria:

1. Be additional
2. Be based on a realistic baseline
3. Be quantified and monitored
4. Be independently verified
5. Be unambiguously owned
6. Address leakage
7. Address permanence
8. Do no net harm[2]

This chapter evaluates biochar projects in light of these criteria, recommends which types of biochar projects can most readily generate credible offsets and summarizes the types of projects that meet carbon market investor criteria.

2.1 Be additional

2.1.1 Definition of additionality

Offsets are intended to credit only new emission reductions that are "in addition" to reductions that would have occurred without the incentive provided by a carbon market. Determining the counterfactual case of whether or not a project would have been implemented in the absence of a carbon market is unavoidably subjective. Carbon markets have developed two methods of assessing additionality:

1. *Project specific analysis* – Project developers develop an additionality case that outlines a specific barrier, normally financial but also possibly technical or institutional, which impedes project development and is overcome by carbon finance.
2. *Performance standard* – Protocol developers (such as the Climate Action Reserve, Clean Development Mechanism, or a future government regulatory

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[2] The Offset Quality Initiative (2008) criteria that offsets "be real" is not included in this chapter's analysis. Instead, all the requirements discussed in the chapter are an attempt to ensure that the offsets claimed by biochar projects are "real."

body like the US Environmental Protection Agency or Department of Agriculture) develop uniformly applicable criteria that determine which types of projects are or are not additional. For biochar projects these criteria could be based on feedstock type, location, or regulatory environment.

2.1.2 Developing a performance standard for biochar

A performance standard is the most appropriate method to evaluate the additionality of biochar projects. Requiring each project to articulate a project-specific additionality case is unnecessarily arduous considering that biochar projects are still at a pilot stage of development. Instead, all biochar projects in the United States should be considered additional so long as each project can prove that its development is not required by law. The Climate Action Reserve, a respected protocol developer, has a similar performance standard for anaerobic dairy digesters, which is a technology with significantly higher market penetration. Because anaerobic digestion is implemented on less than 2% of eligible U.S. dairy farms, the protocol considers any digester to be "above and beyond common practice" and therefore additional (Climate Action Reserve 2009).

Providing certainty that all appropriate biochar projects will be eligible to monetize offsets guarantees an additional revenue stream to all biochar projects and could help to catalyze commercial-scale deployment of the technology. A performance standard that guarantees the additionality of biochar projects is appropriate, and will continue to be appropriate, as long as biochar's deployment remains limited relative to its potential. As the technology matures, this performance standard can be reevaluated to ensure carbon finance is supporting additional projects.

2.2 Be based on a realistic baseline

To quantify the offsets a project is eligible to sell, the emissions of the offset project are compared with a baseline. The baseline represents the forecasted emissions that would have occurred if the offset project were not implemented. Although the baseline case always has higher emissions than the project case, project activities can increase emissions relative to what would have happened in the baseline and these increases must be counted.

This may happen in the following two cases for biochar projects, depending on how the biomass feedstock would have been managed in the baseline case:

1. The biomass used as feedstock for the pyrolysis unit in the project case would have been fully combusted to generate energy in the absence of a project. Full combustion would generate more renewable energy than pyrolysis alone. Comprehensive accounting must calculate any additional emissions that result, because of the biochar project, from the fossil fuels that replace what would have been energy generated by biomass.

2. The biomass used as feedstock to the pyrolysis unit in the project case is left to decompose in the forest, field, or compost pile in the baseline scenario. Decomposition would incorporate a portion of the feedstock's carbon into soil organic matter. Baseline calculations should therefore be based on a model of the decomposition of the feedstock that accounts for the carbon that would have been sequestered into soil organic matter.

It is essential to incorporate baseline management of feedstocks in a biochar offset protocol. High quality biochar projects must be able to track how, in the absence of a project, their feedstocks would have been managed. This is likely to favor projects with simplified supply chains and waste streams; projects that receive many different feedstocks from many different places may struggle to establish a credible baseline.

2.3 Be quantified and monitored

All offset projects are quantified and monitored according to a protocol written specifically for the project type. There is currently no protocol that captures all the climate benefits associated with biochar projects. However, there are protocols in various stages of development for many of the different categories of reductions. Table 3 outlines the current state of protocol development. Carbon sequestration, the largest and most innovative reduction generated by biochar projects, does not have a mature protocol. This must be created before biochar projects participate in the carbon market.

Table 3: Overview of pertinent carbon market protocols for biochar projects

GHG Reduction	Mature protocol?	Pertinent Protocols	Discussion
Carbon sequestration	No	Carbon Gold's *proposed* protocol to the Voluntary Carbon Standard	This proposed protocol has been criticized by the International Biochar Initiative[3] and De Gryze et al. 2010 as insufficient to accurately quantify biochar's carbon sequestration benefit. A new protocol to quantify the carbon sequestration of biochar is needed.
Renewable energy	Yes	Clean Development Mechanism	The Clean Development Mechanism uses a variety of respected protocols to quantify the carbon benefit of renewable energy. These could be adapted to biochar projects.
Waste diversion	Yes	Clean Development Mechanism	The Clean Development Mechanism's AMS- III.L. "Avoidance of methane production from biomass decay through controlled pyrolysis" is a protocol specifically for pyrolysis projects. It is limited to projects that reduce less than 60,000 metric tons of CO_2e per year.
Reduction in soil emissions	No	None	The precise mechanisms through which biochar reduces N_2O emissions and increases CH_4 uptake are not fully understood. These reductions vary according to rainfall, temperature, land-use change, and plant growth behavior (Van Zwieten et al. 2010). There is currently insufficient understanding of this reduction to quantify its greenhouse gas benefit and monetize it as an offset.
Reduction in fertilizer manufacturing	No	None	Developing a protocol to quantify this benefit could be relatively straightforward so long as the quantity of fertilizer saved is clear and easy to document.

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[3] The International Biochar Initiative's comments are available on-line at http://v-c-s.org/docs/CG-DR.pdf.

2.4 Be independently verified

Biochar projects, like all other high quality offsets, must undergo verification. After a project developer monitors a project according to its protocol, an independent third party verifies its accuracy.

Verification is often the largest transaction cost of offset projects. Verification of anaerobic digester projects, for example, usually costs $10,000 annually, or $100,000 over the life of a project. Verification costs for forestry projects, which require forest sampling and growth and yield modeling, are approximately $15,000 to $30,000 per site visit, with up to 30 site visits for one project. Many of these costs are fixed regardless of the size of the project or the number of credits it produces. Verification costs can exceed the value of the resulting offsets for very small projects, thereby excluding them from the carbon market.

The economies of scale associated with verification imply that there will be a threshold of offsets that a biochar project must produce in order to justify these transaction costs. As a minimum, projects must reduce at least 50,000 metric tons of CO_2e over their lifetime. The market as a whole, however, favors projects that produce at least 200,000 metric tons of CO_2e reductions over their lifetime.

To understand what these size thresholds mean for biochar projects, one must estimate the number of offsets that the average metric ton of biochar will generate. As discussed, the number of offsets each project generates will vary according to how the feedstock would have been managed if the project was not implemented, the characteristics of the biochars that are produced by the project, and the ultimate destination of the biochar. The literature has some approximate values for the emission reductions associated with the average ton of biochar. Granatstein et al. (2009) estimate that biochar offsets 2.93 metric tons of CO_2e per metric ton of biochar when applied to the soils. Roberts et al. (2010) estimate 2.88 metric tons of CO_2e are offset for each ton of biochar applied to the soils. These values, however, do not incorporate baseline sequestration of the feedstock or decomposition of portions of the carbon in the biochar over 100 years. Based on these values and the principle of conservativeness, carbon market investors could estimate that each metric ton of biochar produced by a project could potentially generate 2 metric tons of CO_2e reductions.

Given these general assumptions, projects that will produce 100,000 metric tons of biochar over 10 years are the most likely to attract investment. Projects that generate less than 25,000 metric tons of biochar over 10 years are unlikely to attract offset investors.

Many efforts are underway to attempt to reduce verification costs for smaller projects. Some examples include creating separate protocols for small projects that allow small projects to aggregate credits and reduce participation costs. That said, large projects that generate at least 25,000 metric tons of biochar over their lifetime are likely to attract the first investment from carbon markets because they can be accurately quantified and verified in a cost-effective manner.

2.5 Be unambiguously owned

Table 4: Ownership of GHG emission benefit table for projects in the United States

GHG Reduction	Description	Location of Reduction	Qualify for Crediting?
Waste diversion	The feedstock would have produced CH_4 if left to decompose anaerobically instead of being used by the biochar project.	Upstream. Experienced by owner of the feedstock, whose decomposing feedstock would otherwise generate CH_4.	Yes.
Carbon sequestration	Conversion of biomass to biochar keeps carbon sequestered by preventing the biomass from decomposing and releasing CO_2.	Upstream. Experienced by owner of the feedstock, whose decomposing feedstock would otherwise generate CO_2.	Yes.
Reduction in soil emissions	Applying biochar to soils may reduce soil emissions of N_2O and CH_4.	Downstream. Experienced by the farmer utilizing the biochar.	Yes.
Reduction in fertilizer manufacturing	Applying biochar to fields may reduce the need to apply other conventional fertilizers, which are energy intensive to manufacture. Reducing the demand for fertilizer reduces fertilizer manufacturing, thereby reducing CO_2 emissions.	Not Part of Supply Chain. Experienced by many different manufacturers of conventional fertilizers.	No, unless it is determined that fertilizer manufacturers are not covered under a cap-and-trade system.
Electricity displacement	Electricity produced by biochar projects could offset electricity produced by other fossil-fueled power plants that no longer have to supply the same quantity of electricity to the grid.	Not Part of Supply Chain. Experienced by many different power plants supplying electricity to the grid.	No.
Fossil fuel displacement	The heat produced by biochar projects may fulfill thermal demand at the pyrolysis plant that was previously supplied with fossil fuels.	The pyrolysis plant.	No, unless it is determined that the displaced fuel is uncapped by a state or federal cap-and-trade program.

In order to sell an offset credit, a project developer must develop clear and uncontested title to the emission reductions that result from the biochar project. Projects reduce emissions at multiple points along the supply chain, and there is potential for multiple entities to claim the same reductions if the supply chain isn't vertically integrated. To avoid this outcome, any project developer selling an offset credit must have attained unambiguous and documented proof of ownership from any other entity with a potential claim to the emission reductions. This project developer could be the owner of the feedstock, the pyrolysis plant or the user of the biochar.

Table 4 outlines six different emission reductions that result from biochar projects, discusses where the actual reduction occurs (upstream or downstream from the biochar manufacturer), and determines whether the reduction can be credited as an offset.

2.5.1 Emissions benefits that meet ownership requirements: waste diversion, carbon sequestration, and soil emission reductions

Of the three entities that have potential claims to the emission reductions—the owner of the biomass feedstock, the owner of the pyrolysis plant, and the farmer who applies the biochar—it makes the most sense for the pyrolysis plant owner to claim the reduction. If this is the case, the plant owner must obtain contracts with the other parties to demonstrate clear and uncontested right to the reduction. These contracts would need to be produced at the time the offset is sold. Similarly, if either the feedstock owner or the landowner applying the biochar wants to sell the reduction, they would need to obtain clear and uncontested rights to the reductions from the other parties and produce those contracts when they sell the offsets.

In many biochar projects, the feedstock owner, pyrolysis plant, and user of the biochar are the same entity. These vertically integrated projects do not face any ownership ambiguity and are therefore the easiest to implement. They are likely to be the easiest projects to monitor and verify as well for the reasons in Section 2.7.1.

2.5.2 Emissions benefits that do not meet ownership requirements: reduction in electricity displacement, fertilizer manufacturing, and fossil fuel displacement

Three of the reductions achieved by a biochar project could have ownership claims placed on them by entities that are likely to face GHG reduction requirements from a cap-and-trade program or similar policy. These entities would be in the electricity, fertilizer production, and fossil fuel distribution sectors. If these sectors are capped, portions of the reductions achieved through the biochar project's existence will make it easier for these sectors to comply with their cap. As such, these portions of reductions will be ineligible to generate offsets because they will be claimed under the cap.

Until it is determined whether a U.S. cap-and-trade scheme covers fertilizer production and fossil fuel distribution, offsets that represent these benefits should not be sold. However, the electric sector has already developed a complementary mechanism to monetize the benefit of renewable energy generation called Renewable Energy Certificates (RECs). Biochar projects should take advantage of that mechanism by selling RECs for the electricity they produce.

2.5.3 Conclusions

- A project developer can claim clear, uncontested, and unambiguous ownership over the emission reductions that result from waste diversion, carbon sequestration, and soil emission reductions.
- These reductions occur upstream and downstream of the pyrolysis plant. If the plant is the entity claiming and selling these reductions, it must obtain contractual title to the reductions to ensure the feedstock owner and the user of the biochar do not double count reductions.
- A project developer cannot claim unambiguous title to the reductions that result from electricity displacement, reduction in fertilizer manufacturing, and fossil fuel displacement. The means through which electricity producers, fertilizer manufacturers, and fossil fuel distributors will claim ownership over these or any reductions depends upon the type of GHG regulation that emerges at the state and federal level. Until this regulation is clear, biochar project developers should not claim these reductions.

2.6 Address leakage

Leakage occurs when the implementation of an offset project causes emissions to rise outside of that specific project's accounting boundary. Projects must avoid or account for leakage to accurately represent an emission reduction. This section recommends avoiding leakage by prohibiting the crediting of biochar projects that use feedstocks that cause land-use change.

2.6.1 Leakage from land-use change

If the feedstock used by a biochar project has alternate beneficial uses, the project could cause land-use change. Some examples of feedstocks with other beneficial uses include:

- Merchantable wood – The feedstock provider or another market participant may increase harvest outside of the project's boundary to make up for the merchantable wood that is now used by the biochar project. Those reduced carbon stocks must be accounted for.
- Corn, soybeans or other food products – New land could be deforested in order to grow food that is no longer sold to the market because it is used for a biochar project.

The economic modeling needed to accurately account for the direct and indirect land-use impacts of projects that utilize biomass feedstocks with other beneficial uses is still in its infancy. When different models analyze the same project, they produce disparate results. Roberts et al. (2010) compared the land-use impacts of a biochar project feed by switchgrass (a bioenergy crop) using two different models. One model estimated land-use change leakage to be more than twice as large as the other (0.89 metric tons of CO_2e versus 0.41 metric tons of CO_2e for each ton of swtichgrass used by the project). Accurate accounting for land-use change requires more study before it can be integrated into a protocol for biochar projects.

Feedstocks that, in the absence of a project, will simply be burnt without generating energy or left to decompose do not cause land-use change. Due to high collection and transportation costs, lots of biomass is simply considered waste that is either burnt or left to decompose. These feedstocks do not need to account for leakage and have a correspondingly greater emission benefit. Until accounting protocols for land-use change mature, biochar project that use feedstocks without any alternate beneficial use will be the most attractive for carbon market investment.

In agreement with these recommendations, De Gryze et al. (2010) recommend focusing protocol development on the following feedstocks:

1. Corn stover (waste leaves and stalks of the corn plant) that is left to decompose in the field in the absence of a biochar project.
2. Switchgrass that is grown on marginal/degraded land.[4]
3. Yard waste that is landfilled or composted in the absence of a biochar project.
4. Wood waste that is left to decompose in the absence of a biochar project.

2.6.2 Feedstock opportunities in the Pacific Northwest

Given these limitations, the Pacific Northwest still contains enough waste feedstocks to open opportunities for biochar projects. The Oregon Department of Energy estimates that 0.7 million short tons of woody biomass waste are unused and available in Oregon annually (Oregon Department of Energy 2007). Beyond current waste streams, a 2006 study commissioned by the Oregon Forest Resources Institute demonstrated there are approximately 4.25 million acres (15% of Oregon's forest lands) in need of thinning to reduce wildfire risk and to restore forest health (Lord et al. 2006). An estimated 1.0 million bone dry short tons per year could be produced from thinning treatments on these Oregon forest lands, not including merchantable sawtimber (Lord et al. 2006). Biochar project development in the Pacific Northwest could likely be well supplied by wood waste that does not induce land-use change.

Straw has also been studied as a potential feedstock for biomass energy utilization in the Pacific Northwest (Banowetz et al. 2008). An estimated 5.7 million short tons are available annually across the region (Oregon, Washington, and Idaho) and an estimated 0.69 million short tons in Oregon.

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[4] This switchgrass is not a waste product, but De Gryze limits it to switchgrass grown on marginal/degraded land because using this land does not displace food or timber production and therefore does not cause land-use change.

2.6.3 Conclusions

- The largest potential source of leakage for biochar projects is land-use change.
- Feedstocks that affect the market for timber, wood products, or food are the most likely to create direct and indirect land-use change.
- Methodologies to account for this land-use change are immature and therefore cannot be trusted for offset accounting.
- Carbon markets should, at this time, only credit biochar projects that utilize feedstocks that are unlikely to cause land-use change.
- These feedstocks include agricultural residues, yard waste, and wood waste that, in the absence of a biochar project, are burned or left to decompose.

2.7 Address permanence

All carbon sequestration, including the carbon that is sequestered in biochar, can be reversed. In biochar projects, reversals could happen unintentionally– if the biochar decomposes, erodes or is burnt. Reversals could also occur intentionally– if the land where the biochar is incorporated is developed or tilled.[5] Sequestration cannot be monitored if the soil containing the biochar is removed and conservativeness dictates that it should be accounted for as a reversal.

Project developers must demonstrate that the carbon in the biochar which is sold as offsets is present 100 years after the biochar is produced. This is the industry standard for permanence in forestry projects under the Climate Action Reserve. Unlike forestry and other types biological of sequestration, which accumulate carbon through photosynthesis over time, biochar projects begin with the maximum quantity of carbon sequestration. This carbon is then lost to varying degrees over time through decomposition, erosion, burning, development, soil removal, or intensive tilling.

2.7.1 Accounting for the decomposition of biochar

Decomposition of the carbon sequestered in biochar is likely to be the largest and most consistent loss of carbon over a project's crediting period. The rate at which biochar decomposes varies significantly and depends primarily on the feedstock, the method of pyrolysis (temperature and length of time) used to make the biochar, and the environment where the biochar char is incorporated. This makes it difficult to create standard decomposition rates for each type of biochar because there are so many permutations of production and use.

Since the characterization and therefore rates of decomposition vary, De Gryze et al. (2010) recommend field measurements of the quantity of biochar that remains after original application. On-site measurements can be used to calibrate a "two-component kinetic model" of decomposition. As more data is gathered, the model can predict with increasing certainty the quantity of biochar that will remain in the soil after 100 years. The paper suggests sampling 1, 5,

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[5] Compared with other strategies to sequester carbon, like forestry or soil carbon projects, biochar's risk of reversal is low because it sequesters carbon in a more stable form that is resistant to reversal.

10, 20, and 50 years after biochar is applied to soils. Offsets are delivered to the project developer as greater certainty develops, through monitoring and modeling. A full description of this methodology, which is beyond the scope of this paper, can be found in the “Monitoring of Biochar Carbon in Soils” section of De Gryze et al. (2010).

The requirement for long periods of on-site measurement of biochar represents a significant limitation to owners of pyrolysis plants that want to sell biochar on the retail market to nurseries, gardeners, farmers, and other small-scale buyers. To sell offsets, pyrolysis plants must be able to account for and track where all of the biochar produced is incorporated into soils. This biochar must then be monitored and verified over a 50-year period. This requirement will make vertically integrated projects (that use all biochar they produce) the most attractive projects for carbon investment. Other projects that produce biochar and sell it to a limited number of buyers will also likely be eligible, so long as they can account for where the biochar they have sold is now incorporated into soils.

Retail biochar producers, whose biochar is incorporated into many different soils, will not be eligible to generate offsets because tracking and monitoring all soils where it would be applied would be prohibitively costly and complicated. The monitoring methodology suggested by De Gryze et al. (2010) is one suggested approach, and the implications of it are carried throughout this report. Because this methodology prohibits so many types of biochar projects from participating in the carbon market, alternative approaches may need to be investigated.

2.7.2 Other unintentional reversals: fire and erosion

Although less likely, unintentional reversal could result from a fire, which releases sequestered carbon to the atmosphere, or a major erosion event, which removes the biochar from the site and therefore makes it impossible to monitor and verify.

To mitigate these unintentional reversal risks, forestry projects are required to set aside offsets in a buffer pool, which is drawn upon in the event of an unintentional reversal. The risk of reversal for biochar projects is likely smaller than in forestry. Instead of requiring a buffer pool, the risk of fire and erosion should simply be mitigated to prevent high-risk projects from qualifying for carbon finance. Therefore this report recommends a biochar protocol require wildfire control measures and restrict projects on steep slopes. If the risk of fire or erosion were found to be greater than anticipated, a buffer pool to compensate for unintentional reversals would need to be developed.

2.7.3 Intentional reversals: development, soil removal, intensive tillage

If soils incorporated with biochar are removed, intensively tilled, or developed, the biochar in these soils can no longer be monitored or verified. Any issued offsets would therefore be reversed. In forestry offset projects, project developers compensate for intentional reversals by purchasing offsets for at least each of the offsets that were issued and sold by a project. The Climate Action Reserve contractually obligates forestry project developers to do so through its

Project Implementation Agreement. A similar contract with the landowner who incorporates biochar into their soils will need to be developed.

Attaining commitment from the entity that will incorporate biochar into their soils to not develop the land, remove soil, or intensively till their land over the next 100 years will likely significantly limit the number of entities interested in selling offsets from biochar projects. This commitment, however, is essential to ensuring the permanence of biochar projects.

2.8 Do no net harm

Biochar projects could potentially cause the following adverse effects on human health or the environment:

1. If feedstocks contain heavy metals, pyrolysis could concentrate these heavy metals into the biochar. Heavy metal-laced char applied to agricultural fields could then contaminate food, habitat, and watersheds.
2. Chars can develop polycyclic aromatic hydrocarbons (PAHs), some of which have been identified to be carcinogenic, mutagenic, and teratogenic.
3. If biochar is ground finely and applied to the top of the soil, it can become airborne by winds. Airborne char is air pollution and could create a fire hazard.

Only projects that take actions to mitigate these possible adverse effects should qualify for offset crediting. A protocol should require the following mitigation measures:

1. Biochar projects that pyrolyze municipal solid waste, sewage sludge, or tires do not qualify in order to mitigate the potential for concentrating heavy metals. Projects should also be required to periodically test the chars they produce to ensure they do not contain heavy metals.
2. All projects must frequently test their chars for PAHs.
3. Projects that surface apply finely ground biochar must wet the char before application (or implement other measures to minimize air pollution) to mitigate airborne particles.

The three potential adverse affects listed above are not comprehensive. Other unforeseen environmental and human health consequences could arise. It is essential to the credibility of both the biochar industry and the carbon market that comprehensive and regularly updated sustainability protocols are implemented to ensure biochar projects cause no net harm.

2.9 Summary of carbon market investment criteria for biochar project

To summarize, the characteristics of a biochar project that will enable it to most easily meet the criteria outlined by the Offset Quality Initiative are discussed in Table 5. Carbon market investors will evaluate potential investment opportunities in the biochar sector against the qualities outlined in this table.

Table 5: A summary of carbon market investment criteria for biochar projects

Project component	Desirable quality	Carbon market rationale
Feedstock	Projects are fed by waste biomass that would otherwise be burnt or left to decompose. Feedstocks grown specifically for the biochar project are produced on marginal or degraded land.	*Leakage*. Waste feedstocks (or feedstocks grown on marginal/degraded land) do not cause land-use change, for which carbon accounting is immature.
	Feedstocks do not potentially contain heavy metals. Feedstocks do not consist of municipal solid waste, sewage sludge, or tires.	*No net harm*. Heavy metals could potentially be concentrated through pyrolysis and contaminate soils, damaging the environment and human health.
	Projects can track how their feedstock was managed before the implementation of the biochar project and forecast how it likely would have been managed in the absence of project implementation.	*Baseline*. Baseline accounting must account for any energy generated by a feedstock before the project was implemented and any portion of the feedstock that was incorporated into the soil organic matter.
	The seller of the offsets can obtain clear contractual title to the emission reductions that result from waste diversion and carbon sequestration from the original owner of the feedstock.	*Ownership*. This ensures the project developer will not double count the reductions of the project.
Regulatory environment	Projects are not required to be implemented by law.	*Additionality*.
Pyrolysis process	Pyrolysis will generate at least 25,000 metric tons of biochar over ten years. Bigger projects (100,000 metric tons of biochar or more) are the most desirable.	*Verification*. Because many verification costs are fixed regardless of the size of the project, verification costs are a smaller portion of the overall cost of large projects. Economies of scale favor large projects. Projects that produce less than 25,000 metric tons of biochar over their life will not be considered for carbon market investment unless a small-scale methodology and

		aggregation system is developed to reduce transaction costs.
Use of biochar	Projects incorporate biochar into soils. Stable soils that are unlikely to erode during extreme weather events are most desirable.	*Permanence*. Biochar faces less of a risk fire or erosion, and therefore unintentional reversal, when it is incorporated into soils.
	Entity using the biochar is willing to contractually obligate him/herself to not develop, intensively till, or remove the soil in which biochar will be incorporated for the next 100 years.	*Permanence*. Carbon must remain sequestered for 100 years. This cannot be guaranteed if development, intensive tillage, or soil removal occurs.
	The biochar producer can account for, track, and monitor where all the biochar is incorporated into soils. Vertical integration, where the producer of the char is its user of the char, is the most desirable.	*Monitoring and Permanence*. De Gryze et al. (2010) suggest the most credible method to quantify biochar projects is to measure the quantity of biochar remaining in the soil 1, 5, 10, 20, and 50 years after it is incorporated with the soil. Vertical integration makes this monitoring economically feasible. If projects are not vertically integrated, they must at least be able to easily track and account for where all the char produced is integrated into the soils.

CHAPTER 3:
Case Study of the TSY-Peak Biochar Pilot Project

In order to address issues of waste utilization from industrial processes, reduce energy costs, create viable co-products, and reduce CO_2 emissions, the Thompson Timber log yard in Philomath, Oregon has incorporated a pilot-scale slow pyrolysis biochar system into its existing forestry mill operation. Although the company is still testing and refining its system, it agreed to share input and output data and available but limited financial data for this case study in order to advance the developing biochar industry and to explore means of generating company revenue from biochar and offset sales.

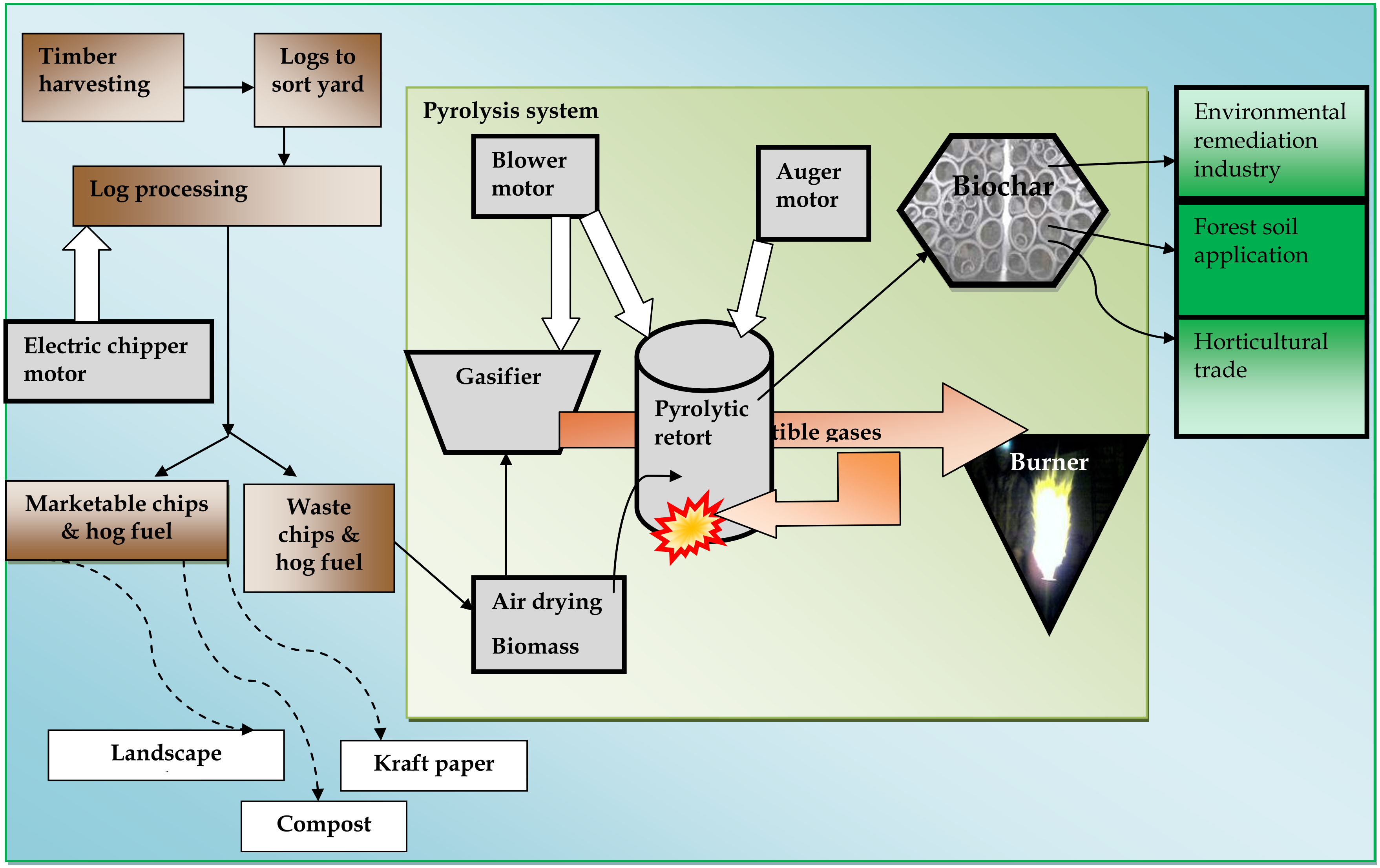
This chapter will use the pilot-scale system at Thompson Timber log yard as a case study. It provides an overview of the project's hardware, feedstock, inputs and outputs, economics, and greenhouse gas emissions. With this description as a foundation, the next chapter concludes by applying the Offset Quality Initiative criteria described in Chapter 2 to the pilot project.

3.1 Description of project hardware

Construction of the biochar system, referred to as TSY-Peak, began in January 2010. The project reached its initial test phase in June 2010 and is still undergoing refinement and development. Currently, the TSY-Peak biochar system is a slow pyrolysis biochar unit with the capability to create biochar under various temperatures, ranging from 350^{o}C to 600^{o}C. The system produces biochar and combustible gases; it is designed to minimize the production of bio-oil.

The system has three main components: a gasifier, a pyrolytic retort, and external motors (including start-up, cooling, blower, auger, and shaker motors). Figure 1 is a diagram of the TSY-Peak system and the project boundary.

Figure 1. Project diagram. Solid line arrows indicate flows of material (logs, chips, biochar). Black arrows indicate flows of energy (diesel fuel, electricity for the system motors, or combustible gases). Dashed lines indicate current product uses for the wood waste. (Adapted from Roberts et al. 2010)



A Fluidyne Pacific Class down-draft gasifier provides thermal drive for the entire system. The gasifier utilizes a small portion of the oversized wood chips that are screened out during the chipper plants' sorting process. These chips are air dried to 15% moisture. Wood chips are thermally reduced in a high temperature, low oxygen environment, to yield a relatively low heat value combustible gas known as producer gas. At approximately 164 BTU per standard cubic foot, producer gas by volume has around one-seventh the heat energy of natural gas. However using this pathway the thermal requirements of the pyrolytic retort can be achieved with low value biomass. The gas is ignited and then used to heat the pyrolytic retort.

Figure 2. Fluidyne Gasifier (left background, metallic surface) and pyrolytic retort (right front, black paint) in the log-sorting yard of Thompson Timber/Starker Forest, Philomath OR.

Photo Credit: John Miedema

The second hardware component in the system is called a pyrolytic retort (PR). The PR consists of two steel tubes, one nested inside the other, approximately 8 feet in length and 13 feet in height. The inside of the outer tube is lined with fire bricks to a height of 3 feet. Inside is a second smaller tube where hog fuel is loaded. The inner tube also has an auger that mixes the hog fuel to ensure that it pyrolyzes at an even temperature during biochar production (Figure 2).

The PR was constructed with scrap metal and parts from the forest mill site with other materials being added as needed (tubing, valve boxes, and temperature gauges). The PR can be loaded with up to 400 pounds of biomass feedstock, but approximately 200 pounds are used per run.

The third components are small electric production motors used to run the system. The gasifier uses a start up motor, two cooling motors and a shaker motor. The PR uses a blower motor and a hydraulic unit to power a mixing auger. Each eight hour work day the motor systems use approximately 2.468 kilowatt hours (kWh) of electricity.

3.2 Description of the feedstock

Thompson Timber Company produces approximately 2 million metric tons of clean woodchips and 5,000 metric tons of hog fuel (wood waste bark from log sorting and grading as well as other non-merchantable material) per year during normal operations. The chipped material is a mixture of Pacific Northwest forest species: approximately 75% Douglas fir (*Pseudotsuga menziesii*), 15% red alder (*Alnus rubra*) and 10% big leaf maple (*Acer macrophyllum*). Logs are transported by truck from approximately 50 miles. Once the logs are brought into the Thompson Timber yard, they are sorted and scaled. Merchantable sawlogs are separated and sold to local timber mills and for export, whereas un-merchantable sawlogs are fed into the log-chipper.

Bark and wood cambium that falls to the ground during the sorting and scaling process creates a waste stream of no value. The remaining bark that is removed as the unmerchantable logs are loaded onto the chipper is set aside as hog fuel. The de-barked log is then run through a chipper that produces a chip product approximately 2 inches by 2 inches in size. As the logs are processed two products are created: hog fuel and wood chips. The hog fuel is set aside and the chips are run over a series of screens for size and quality selection. Wood chips that meet size and quality criteria are collected and sold to the domestic kraft paper market (for construction of products like paper plates). The chips that fail to meet the quality standard are collected to run the gasifier for the TSY-Peak system.

The hogfuel (bark and low quality chips) is not otherwise used for energy production currently, either on site by the company or after it is sold to buyers. It is sold for local landscaping applications and used by a local compost company. Thompson Timber Company runs its chipper using an electric motor using energy from the local power company.

In addition to the 5,000 metric tons/year of hog fuel that is sold by Thompson Timber Company, there is approximately 6,000 metric tons of waste available for biochar production. Only a very small portion of this waste stream is being used for the pilot system (Figure 3).

Figure 3. Wood waste used in the TSY-Peak biochar system. Left is the hog fuel used to power the gasifier. Right is the waste biomass currently left to rot in the log yard, which feeds the pyrolytic retort.
Photo Credit: Matt Delaney (left) and Peter Weisberg (right)

3.3 Biochar system operations

3.3.1 Inputs

The TSY-Peak biochar system is a batch processor that averages about two runs per day. It takes about an hour to prepare the system before each run, approximately two hours to make biochar, and another hour for the system to be switched off and cooled down enough to remove the char from the bottom of the PR. On average, 120 pounds of chips are used in the gasifier and 200 pounds of hog fuel are used in the PR for a total of 320 pounds of biomass feedstock. Improved insulation of the PR could dramatically reduce the amount of chips required for the gasifier.

Under current estimates, the log yard will run the pyrolysis plant three days a week for 45 weeks out of the year. Annually, the plant will use 16.2 metric tons of hog fuel to power the gasifier and 27 metric tons of waste biomass to feed the PR.

To start the biochar system, oversized chips are taken off the top sizing screen at the chipper plant. A small portion of these oversized chips fall through a four-inch gate into a 1.4 yard tipping bin and are transported via forklift from the chipper plant to the pilot system (which is about 200 yards away). The chips are spread onto the ground and air-dried (Figure 4).

Figure 4. Air-dried hog fuel used in the TSY-Peak biochar system
Photo Credit: Matt Delaney

Oversized wood chips that are dried to 15% moisture content are loaded into the top of the gasifier. A small bed of charcoal is placed at the bottom of the gasifier manifold. The gasifier is started by turning on the blowing motor which forces air over the charcoal bed. The draft mechanism draws a sub-stoichiometric amount of ambient air across the hearth of charcoal which is then lighted by a propane torch. This results in a high temperature oxidation zone with a lower temperature (about 850^{o} C) anoxic reduction zone just below. Combustible producer gas, the outcome of this gasification process, is fed through a high temperature flexible hose (approximately 2 inches in diameter) to a burner inserted in the base of the PR. The resulting ~ 1200^{o} C flame and combustion gases circulate around the outside of the inner PR tube.

Over a short period of time, the PR reaches a sufficient temperature to start producing biochar. The auger motor turns the PR material to maintain even temperatures. Pyrolysis oils and gases produced within the PR are re-circulated from the top of the tube back into the combustion chamber at the base of the retort, where they are burned to maintain the desired operating temperature. If temperatures begin to exceed desired parameters these gases are flared in by auxiliary burner, which is illustrated by the flame in Figure 2.

3.3.2 Outputs

Approximately 120 pounds of gasifier wood chips and 200 pounds of wood waste are used per run, with an output of approximately 52 pounds of biochar. On a bone-dry basis, this is a 19% yield. Considering just the pyrolytic retort (again on a bone-dry basis) an average of 31% yield of biochar from the wood waste is achieved. Other systems average 30% yields with ranges of 28-33% depending on the feedstock (Roberts et al. 2010). The resulting biochar is approximately 0.5 to 1.5 inches in size (Figure 5). The TSY-Peak project currently anticipates loading 27 metric tons of feedstock into the PR each year it operates at its current scale; at this rate, the plant should produce 8.25 metric tons of biochar per year.

The operators of the TSY-Peak project plan to sell the biochar to research universities, to apply the char to portions of their own forests 15 to 50 miles away, and to sell the biochar for other horticultural applications.

Figure 5. Biochar product produced by the TSY-Peak system.
Photo Credit: Matt Delaney

Waste heat generated by the PR is currently not utilized on-site, but the company is investigating small-scale electrical production. The hot exhaust gases are also not currently utilized (other than to heat the PR) but Thompson Timber has begun the construction of an enclosed chamber to dry and preheat the fuel inputs using these gases.

3.4 Economics

Capital costs for the TSY-Peak project are very low. Other than the gasifier, which was purchased as a unit, the motors and PR were modified from equipment that was available on the Thompson Timber log yard. This kept capital costs extremely low, at an estimated $59,000. Below are the line-item costs:

- Fluidyne Pacific Class down-draft gasifier: $15,000.
- Pyrolytic retort: $13,000.
- Motors: $0 (modified from unused motors at the log yard).
- Labor: $31,000.

Annual operations and maintenance costs are estimated to be $33,324. Major costs are saved through utilizing waste feedstock.

- Maintenance: $3,000. Estimated at 3-5% of the capital costs (De Gryze et al. 2010).
- Labor: $30,000.
- Opportunity cost of feedstock: $324. An estimated 16.2 metric tons of wood chips are used per year to feed the gasifier. The log yard could alternatively sell these chips for an estimated $20/ton. The feedstock fed into the PR has no opportunity cost, because without the project it would be left to rot in the log yard.

Annual revenue is currently limited to the biochar produced by the pilot system. The system is currently projected to produce 8 metric tons of biochar a year. While the value for biochar is uncertain, biochar for researchers and nurseries has sold for $200/ton (Miles 2009) to $500/ton.

- Annual biochar sales: $1,600 - $4,000

3.5 Greenhouse gas emissions

3.5.1 Sources of greenhouse gas emissions

Source	Data/assumptions	Emissions
Electricity used at the pyrolysis plant	The plant consumes 2.468 kWh to produce 13 pounds of biochar. The average kilowatt hour consumed by the project emits 0.902 pounds of CO_2e (EPA 2007).	0.17 mt CO_2e/metric ton of biochar

Emissions from harvesting and transporting the feedstock to the pyrolysis plant are not included in this accounting because waste biomass and hog fuel are created with or without the pyrolysis process. The biochar project therefore does not increase harvesting or transportation emissions. If they did, these GHG emissions are relatively small—around 0.34 mt CO_2e/metric ton of biochar produced by the plant, based on the assumptions of Manomet (2010).

Emissions associated with transporting the biochar from the Thompson Timber log yard to the forest where it is applied are also not included in this accounting. Trucks from the log yard must go back to the forests to collect additional logs. While these trucks currently return empty, under the project scenario they will return with biochar. It is therefore assumed that the biochar projects do not add any transportation emissions to return biochar to the soils.

Emissions from combustion of the pyrolysis oils, pyrolysis gases and the producer gas are not included in the accounting above. All of the combustible gases, the producer gas from the gasifier, and the pyrolysis oils and gases evolving from the top of the pyrolytic retort are captured and fed to the combustion chamber surrounding the base of the unit. An auxiliary burner flares excess combustible gas. All combustible gases developed in the TSY-Peak system see a flame front prior to exiting the system to the atmosphere, so no methane in the pyrolysis gases and producer gases is released to the atmosphere.

3.5.2 Sources of emission reductions

Source		**Emission Reductions**
Carbon sequestered in the biochar	Assume 1 metric ton of biochar is 0.80 metric tons of carbon and that only 80% of this carbon will remain 100 years after it is created (Roberts et al. 2010). These assumptions are justified below.	2.35 mt CO_2e sequestered /metric ton of biochar. **Subtracting emissions from the electricity used to create the biochar, each metric ton of biochar reduces roughly 2.18 mt CO_2e.**

Testing the amount of carbon in the biochar produced by the TSY-Peak biochar system is underway currently and the results are not available at the time of publication, but studies of biochar indicate increasing carbon content by pyrolysis temperature, ranging from 55% to 93% (McLaughlin et al 2009; Okimori 2003). Researchers at Oregon State University conducted an analysis of ponderosa pine wood chips and found a similar pattern, with biochar carbon content ranging from 50% to 92% with pyrolysis temperatures ranging from 100 ^{o}C to 700 ^{o}C (Keiluweit et al. 2010). The operating temperatures of the TSY-Peak biochar system is approximately 500^{o}C, so a carbon content of 80% or, approximately of 2.93 mt CO_2 is kept out of the atmosphere, per ton of biochar.

Based on Roberts et al. (2010), it is assumed that 80% of the carbon in the biochar remains sequestered over 100 years. Project-specific monitoring of the biochar over time will be needed in order to accurately measure and then model this decomposition as discussed in Section 2.7.1.

The TSY-Peak project has no renewable energy or waste diversion benefits. The project is not yet generating any energy from the syngas or waste heat. The waste biomass and hog fuel are left to decompose aerobically in the absence of the biochar project, so there are no methane reductions associated with managing this feedstock with pyrolysis.

CHAPTER 4:
Conclusion

Building from the description of the project in the previous chapter, the conclusion of this report will analyze the TSY-Peak project under the carbon market investment criteria of Chapter 2 and then summarize the lessons learned from this case study.

4.1 Analysis of TSY-Peak's potential for carbon market investment

Table 6 compares the desirable qualities for offset investment outlined in Chapter 2 to the qualities of the TSY-Peak project described in Chapter 3. The criteria not met by the TSY-Peak project are discussed after the table.

Table 6: Comparison of the TSY-Peak project with carbon market investment criteria

Project component	Desirable quality	Criterion met by TSY-Peak?
Feedstock	Projects are fed by waste biomass that would otherwise be burnt or left to decompose. Feedstocks grown specifically for the biochar project are produced on marginal or degraded land.	Yes. The Thompson Timber log yard annually generates 6,000 metric tons of waste biomass and hog fuel that is currently left to decompose in the log yard or as a yard amendment. Before the project, the hog fuel was not used as an energy source. Utilizing this feedstock for biochar will not cause direct or indirect land-use change.
	Feedstocks do not potentially contain heavy-metals. Feedstocks do not consist of municipal solid waste, sewage sludge or tires.	Yes. The hog fuel and wood waste used by the project does not contain heavy metals.
	Projects can track how their feedstock was managed before the implementation of the biochar project and project how it likely would have been managed in the absence of project implementation.	Yes. All feedstock comes from the Thompson Timber log yard, which can easily document how it has been managing its wood waste and hog fuel.
	The seller of the offsets can obtain clear contractual title to the emission reductions that result from waste diversion and carbon sequestration from the original	Yes. The pyrolysis plant and feedstock owners are the same entity, so there is no potential for double counting.

	owner of the feedstock.	
Regulatory environment	Projects are not required to be implemented by law.	Yes. The project has been implemented voluntarily.
Pyrolysis process	Pyrolysis will generate at least 25,000 metric tons of biochar over ten years. Bigger projects (100,000 metric tons of biochar or more) are the most desirable.	No. The pilot program is currently projected to generate 8 metric tons of biochar per year, or 80 metric tons over 10 years. (See discussion below on the potential to scale the project.)
Use of biochar	Projects incorporate biochar into soils. Stable soils that are unlikely to erode during extreme weather events are most desirable.	Yes. Thompson Timber's nearby upland forests have slopes between 3% and 60%. Sufficient forest space should be available to only incorporate biochar in areas that do not face the possibility of major landslides.
	Entity using the biochar is willing to contractually obligate him/herself to not develop, intensively till, or remove soil from the soil in which biochar will be incorporated for the next 100 years.	Likely yes. Starker Forests, which supplies the material for the Thompson Timber log yard, are highly productive forests that have been used as timberland for nearly 100 years.
	The biochar producer can account for, track, and monitor where all the biochar is incorporated into soils. Vertical integration, where the the producer of the char is also the user of the char, is the most desirable.	No. The pilot program plans to sell biochar to a variety of researchers, nurseries, and farms. (See discussion below.)

The TSY-Peak project passes all the investment criteria outlined except two:

1. The pilot project is too small. It is projected to produce 8 metric tons of biochar per year, while it is estimated that biochar offset projects will need to produce at least 25,000 metric tons of biochar over their lifetime, or around 2,500 metric tons per year.
2. The project plans to sell biochar to many entities, making it difficult to account for where all the biochar is incorporated into soils.

The quantity of waste biomass available at the Thompson Timber log yard opens the potential for a larger project which could qualify for offset funding. The log yard current produces 6,000 metric tons of waste biomass per year. A much larger pyrolysis plant that converts 30% of the biomass input into biochar could produce 1,800 metric tons of biochar per year with this waste alone. By bringing in additional waste, a larger TSY-Peak project could operate at a scale that is attractive for carbon investment.

This larger project would also need to simplify the number of entities to whom it sells biochar in order to qualify for carbon finance. This, too, is a possibility. There are approximately 60,000 acres of forests owned by Starker Forests, on which biochar could potentially be applied. The amount of biochar applied per acre varies but one common suggestion is 10 metric tons of biochar per acre (De Gryze et al. 2010; Blackwell et al. 2010). In this scenario, the forest lands associated with the log yard alone could demand 600,000 metric tons of biochar.

4.2 Conclusion

Given the availability of significantly more feedstock and land, it is feasible for the TSY-Peak project to scale into an attractive offset project. This would require commitment to pyrolyzing all available material at the log yard and applying at least 25,000 metric tons of biochar to available forest land. Biochar's economic and agronomic benefits are not yet sufficiently proven to justify this scale of investment. The TSY-Peak project is an attempt to begin proving these benefits.

Revenue from offset sales alone is not enough to drive this investment. If each metric ton of biochar results in approximately 2 metric tons of CO_2e reductions, at an assumed offset price of \$6/metric tons of CO_2e, offset sales are only \$12/metric ton of biochar produced. A cap-and-trade system could raise prices to \$15 to \$40/metric tons of CO_2e, or \$30 to \$80/metric ton of biochar produced. The TSY-Peak project sold biochar for research or agricultural applications at \$200 to \$500 per metric ton. A long-term buyer willing to purchase a large quantity of biochar at these prices is the fundamental driver for the economics of these early stage biochar projects that face an uncertain market for their product. That said, carbon offset sales can add another significant revenue to biochar projects.

Given the potential of biochar to sequester carbon, generate renewable energy, increase soil productivity, and provide jobs in natural resource-based rural economies, policy makers, investors, engineers, agronomists and carbon market participants should focus on developing the sector. Pilot projects that prove these benefits are the essential next step for the industry. During this early stage of project implementation, a carbon market protocol to qualify the right subset of biochar projects and quantify their carbon sequestration and waste diversion benefits must be developed. This protocol could add an additional revenue stream to biochar projects, accelerating their implementation by increasing economic profitability, and aligning the economic incentives needed for these projects to maximize their climate benefits.

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The Climate of Opportunity

REDDING, CA; February 24, 2012 - Our weather is something that impacts each of us on a daily basis - If you’re a farmer the amount of rain affects your crops -. If you enjoy winter recreation you are affected by the amount of snow in the mountains. The impacts associated with greenhouse gases and the potential impact on weather is well understood and documented. *The Climate of Opportunity*, a locally produced documentary, engages the viewer in a discussion about local efforts by individuals, policy makers, businesses and foresters that have an impact on greenhouse gas emissions.

“Our natural resources, our economy, our local food supply, our health, and our weather are all interconnected”, explains program producer and host Minnie Sagar “That connection reminds us that we have the ability to ensure the long term success of our species simply by being good stewards of our Earth.”

Exclusive interviews with Jared Blumenfeld – EPA Region 9 Administrator and Kurt Malchow – Climate Change Adaptation Coordinator, California Natural Resources Agency help explain how climate change and green house gasses affect our local weather patterns. Their knowledge is crucial to helping understand how human behavior, from energy use to transportation, has an impact on our weather.

The program visits with local individuals that, each in their own way, are doing their part in reducing their carbon footprint and greenhouse gases. Dane Wigington lives off the grid in Northern California and has chosen to use solar, wind and hydroelectric power. Heinz Hamann lives in a residential neighborhood and utilizes solar power and composting.

The program concludes with a discussion about terrestrial carbon sequestration or how trees store carbon. A land owner’s involvement in something as simple as tree planting can have a large impact. In Shasta County, 12 sites were chosen and a total of 476 acres of trees were planted by the West Coast Regional Carbon Sequestration Partnership, led by the California Energy Commission. The overall goal was to research how effective afforestation projects could be in reducing state level Green House Gases or GHG emissions.

Katie Goslee, Winrock international suggest that involvement in such projects offers "… an opportunity to show other land owners what type of projects are possible on their lands and to determine what type of projects are possible in various areas.”

Weather patterns affect our daily lives. Changing weather and climate can have an impact on such diverse issues as lifestyle, health and our local economy. *The Climate of Opportunity* offers explanations and choices opening a broader discussion.

About West Coast Regional Carbon Sequestration Partnership (WESTCARB)

WESTCARB is a collaborative research project bringing together dedicated scientists and engineers from more than 90 public agencies, private companies, and nonprofits to identify and validate the best regional opportunities for keeping CO_2 out of the atmosphere, thereby reducing humankind's impact on the climate.

About Winrock International

Winrock International is a nonprofit organization that works with people in the United States and around the world to empower the disadvantaged, increase economic opportunity, and sustain natural resources.

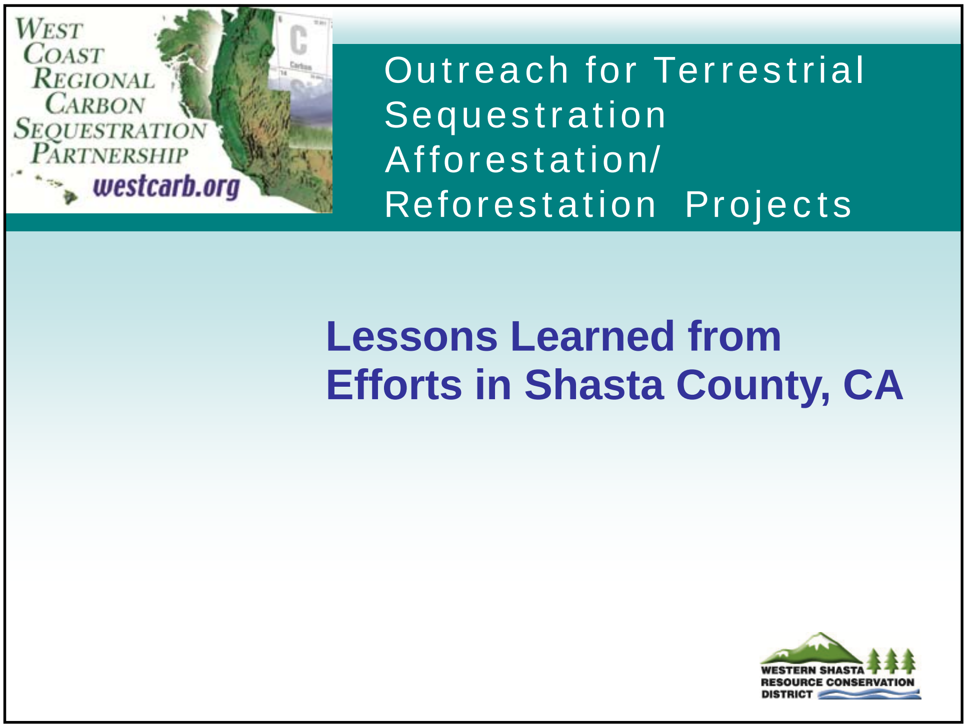
About Western Shasta Resource Conservation District (WSRCD)

The **WSRCD** is a special district of the State of California and is funded entirely by grants and contracts. The mission of the WSRCD is to collaborate with willing landowners, government agencies and other organizations to facilitate the conservation and restoration of Western Shasta County's natural resources.

About KIXE

KIXE is Northern California's preeminent public broadcaster which serves California ten northeastern most counties. It features programs from the PBS programming service as well as relevant and topical local programs.

A Climate or Opportunity is a presentation of KIXE and was funded by WESTCARB. Additional support was provided by WSRCD and Winrock International. The program was produced by Adams Video Productions and Meenakshi Media.



West Coast Regional Carbon Sequestration Partnership
westcarb.org

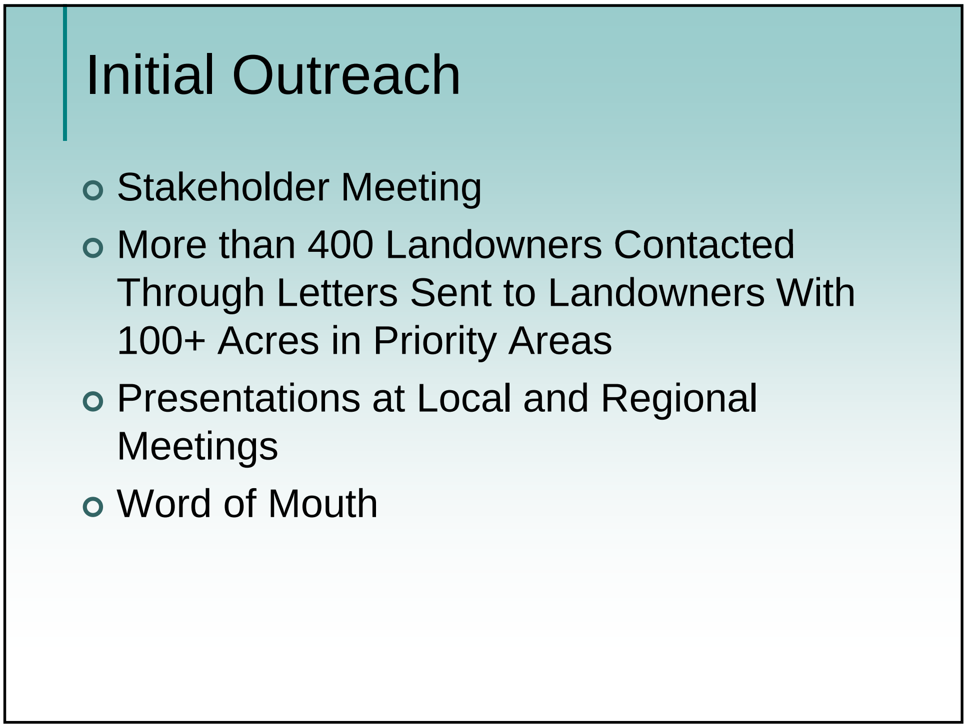
Outreach for Terrestrial Sequestration Afforestation/ Reforestation Projects

Lessons Learned from Efforts in Shasta County, CA

Western Shasta Resource Conservation District

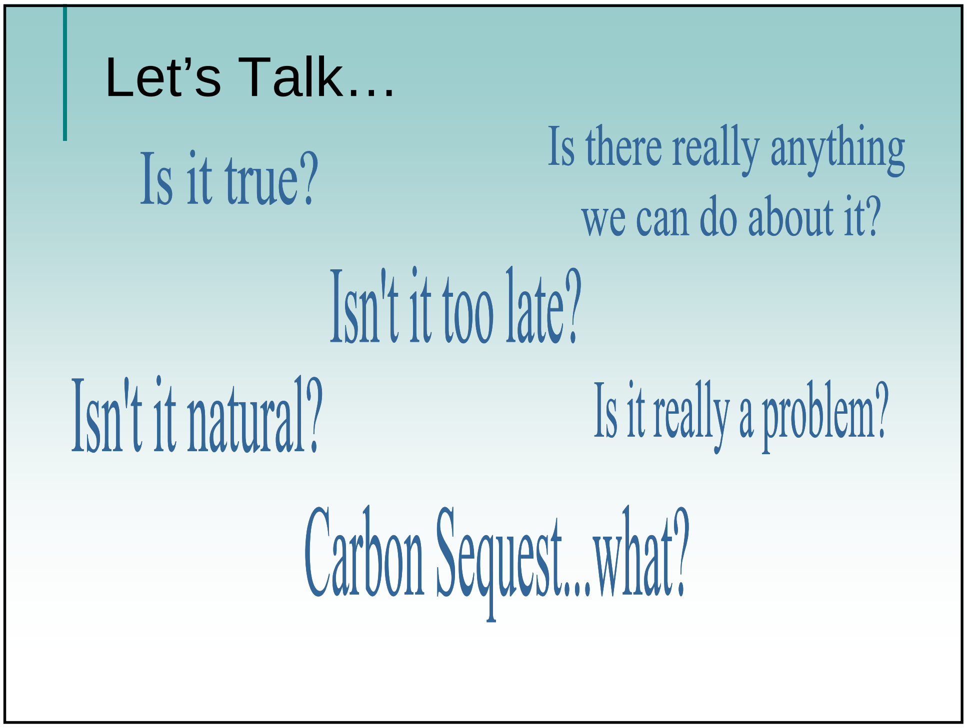
Multiple Audiences

- Landowners
- Land Managers
- General Public
- Local Government
- Agencies
- Local and Regional Organizations
- Environmental Advocates
- Education Community



Initial Outreach

- Stakeholder Meeting
- More than 400 Landowners Contacted Through Letters Sent to Landowners With 100+ Acres in Priority Areas
- Presentations at Local and Regional Meetings
- Word of Mouth



Let’s Talk…

Is it true?

Is there really anything we can do about it?

Isn't it too late?

Isn't it natural?

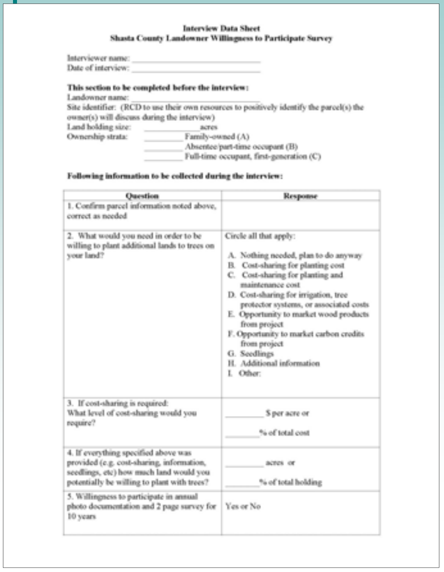
Is it really a problem?

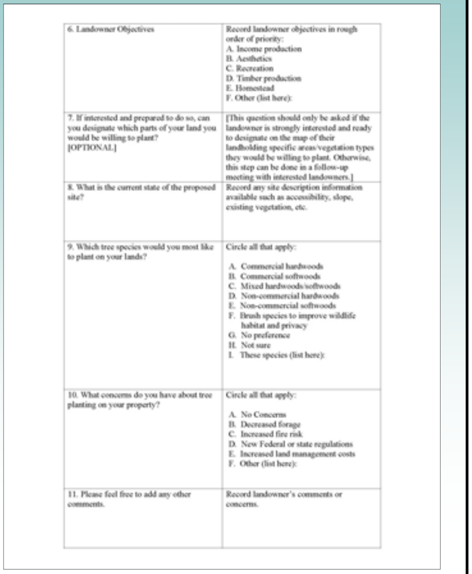
Carbon Sequest...what?

OK, Maybe I’m Interested… Survey Me!

+ 50 Landowners Interested & Interviewed
  - Willingness
  - Cost-sharing
  - Site Conditions
  - Acres
  - Species Preferences

Formal Surveys





Interview Data Sheet
Shasta County Landowner Willingness to Participate Survey

Interviewer name: ______________________
Date of interview: ______________________

This section to be completed before the interview:
Landowner name: ______________________
Site identifier: (RCD to use their own resources to positively identify the parcel(s) the owner(s) will discuss during the interview)
Land holding size: __________acres
Ownership strata: ________ Family-owned (A)
________ Absentee/part-time occupant (B)
________ Full-time occupant, first-generation (C)

Following information to be collected during the interview:

Question	Response
1. Confirm parcel information noted above, correct as needed	
2. What would you need in order to be willing to plant additional lands to trees on your land?	Circle all that apply: A. Nothing needed, plan to do anyway B. Cost-sharing for planting cost C. Cost-sharing for planting and maintenance cost D. Cost-sharing for irrigation, tree protector systems, or associated costs E. Opportunity to market wood products from project F. Opportunity to market carbon credits from project G. Seedlings H. Additional information I. Other:
3. If cost-sharing is required: What level of cost-sharing would you require?	________ $ per acre or ________% of total cost
4. If everything specified above was provided (e.g. cost-sharing, information, seedlings, etc) how much land would you potentially be willing to plant with trees?	________ acres or ________% of total holding
5. Willingness to participate in annual photo documentation and 2 page survey for 10 years	Yes or No
6. Landowner Objectives	Record landowner objectives in rough order of priority: A. Income production B. Aesthetics C. Recreation D. Timber production E. Homestead F. Other (list here):
7. If interested and prepared to do so, can you designate which parts of your land you would be willing to plant? [OPTIONAL]	[This question should only be asked if the landowner is strongly interested and ready to designate on the map of their landholding specific areas/vegetation types they would be willing to plant. Otherwise, this step can be done in a follow-up meeting with interested landowners.]
8. What is the current state of the proposed site?	Record any site description information available such as accessibility, slope, existing vegetation, etc.
9. Which tree species would you most like to plant on your lands?	Circle all that apply: A. Commercial hardwoods B. Commercial softwoods C. Mixed hardwoods/softwoods D. Non-commercial hardwoods E. Non-commercial softwoods F. Brush species to improve wildlife habitat and privacy G. No preference H. Not sure I. These species (list here):
10. What concerns do you have about tree planting on your property?	Circle all that apply: A. No Concerns B. Decreased forage C. Increased fire risk D. New Federal or state regulations E. Increased land management costs F. Other (list here):
11. Please feel free to add any other comments.	Record landowner's comments or concerns.

Landowner Outreach

- +50 interest surveys resulting in majority desk review for consideration
- 20 site visits resulting in 17 plans
- Contract negotiations including amendments adding additional acreage, revising herbicide prescription and extending agreements
- Measuring, site prep, planting, and monitoring activities
- Scheduling field trips and interviews
- Project updates individually and via landowner meetings

Involved Discussion: Site Visits, Telephone, Email

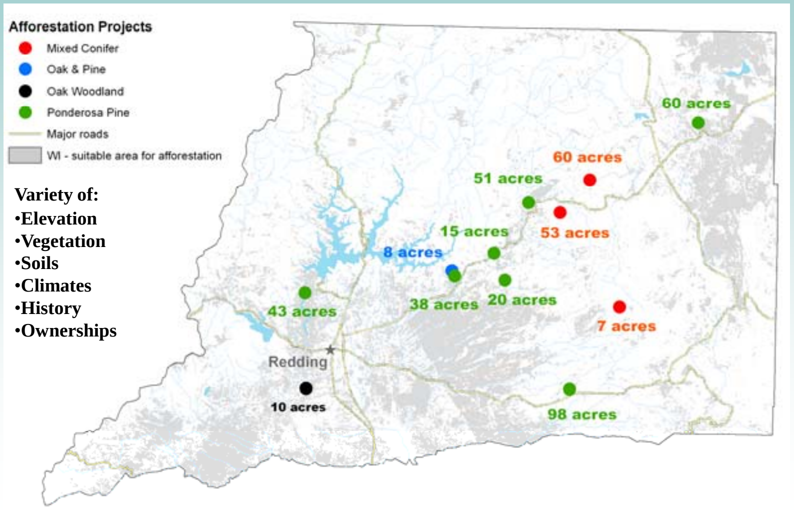
How much will it cost?

What's it going to look like?

What will it look like 5, 10, 50+ years from now?

What's a carbon credit?

Variety of Sites = Variety of Landowners



Variety of:

- **Elevation**
- **Vegetation**
- **Soils**
- **Climates**
- **History**
- **Ownerships**

Landowner Education

- Climate Change
- Forestry 101
  - Site Conditions
  - Species
  - Site Prep
  - Herbicides
  - Maintenance

Continuing Communication

Community Outreach

- Local/Regional Meetings
- County Fairs and Festivals
- WSRCD Website
- Newsletter Articles
- Newspaper Articles
- Prairie Public PBS Documentary
- Natural Resource Conservation Service Success Story

Local and Regional Government and Organizations

- County Board of Supervisors
- City Council
- Electric Utilities
- Fire Safe Councils
- Local Forest Education Council
- Watershed Groups
- Local and Regional Land Management and Conservation Organizations

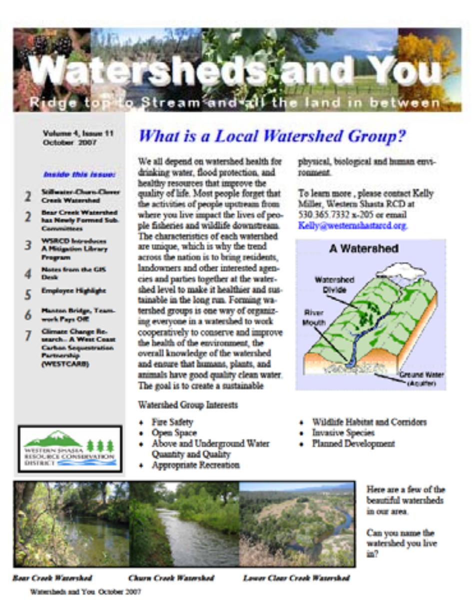
Each Landowner/Group is Unique

- Values
- Understanding of Natural Systems
- Concerns
- Goals

Challenges

- “Us against them” mentality
- Language barriers
- Passed down beliefs
- Landowners - Individual ownership / family trust
- Time investment

Traditional Outreach



Watersheds and You

Ridge top to Stream and all the land in between

Volume 4, Issue 11
October 2007

Inside this issue:

What is a Local Watershed Group?

We all depend on watershed health for drinking water, flood protection, and healthy resources that improve the quality of life. Most people forget that the activities of people upstream from where you live impact the lives of people fisheries and wildlife downstream. The characteristics of each watershed are unique, which is why the trend across the nation is to bring residents, landowners and other interested agencies and parties together at the watershed level to make it healthier and sustainable in the long run. Forming watershed groups is one way of organizing everyone in a watershed to work cooperatively to conserve and improve the health of the environment, the overall knowledge of the watershed and ensure that humans, plants, and animals have good quality clean water. The goal is to create a sustainable physical, biological and human environment.

To learn more , please contact Kelly Miller, Western Shasta RCD at 530.365.7332 x-205 or email Kelly@westernshastarcd.org.

A Watershed

Watershed Group Interests

- Fire Safety
- Open Space
- Above and Underground Water Quantity and Quality
- Appropriate Recreation
- Wildlife Habitat and Corridors
- Invasive Species
- Planned Development

WESTERN SHASTA RESOURCE CONSERVATION DISTRICT

Bear Creek Watershed *Churn Creek Watershed* *Lower Clear Creek Watershed*

Here are a few of the beautiful watersheds in our area.

Can you name the watershed you live in?

Watersheds and You October 2007

Non-Traditional Outreach “The Times They Are A Changing”~ Bob Dylan

- Website
- Festivals – Video Contests
- You Tube
- Facebook
- Webzines
- Blogs

Climate Stewardship

solutions for future generations

- Climate Change Information
- California's Global Warming Solutions Act
- Latest Climate Change News
- You Tube Climate Change Videos
- What You Can Do
- Kids

Welcome

Folks from around the world are learning about climate change, and are discovering ways to reduce their impact on the climate as well as ways to adapt to a changing climate. Information and links provided on this website are intended to provide background on the climate issue, California's response to it, the latest news and opinions from around the world, and how the WSRCD is involved.

We especially hope you take the time to visit our "Carbon Sequestration" page to find out about some great research taking place in Shasta County. This research involves sequestration of the "terrestrial" type (growing trees for capturing and storing carbon dioxide).

One of the attractions of terrestrial sequestration is its lower initial cost (relative to other CO2 storage options) coupled with the potential for significant environmental, economic, and aesthetic co-benefits. These may include:

- Improving forest health
- Creating new wildlife habitat
- Preventing soil erosion and stream sedimentation
- Boosting local and regional economies
- Reclaiming poorly managed soils
- Increasing the recreational value of lands

Thanks for stopping by, and feel free to contact WSRCD Climate Stewardship Coordinator Leslie Bryan at leslie@westernshastarcd.org, or 365-7332 ext 215 for more information.

Carbon Sequest...what?

Carbon Sequestration

Presentations and Publications

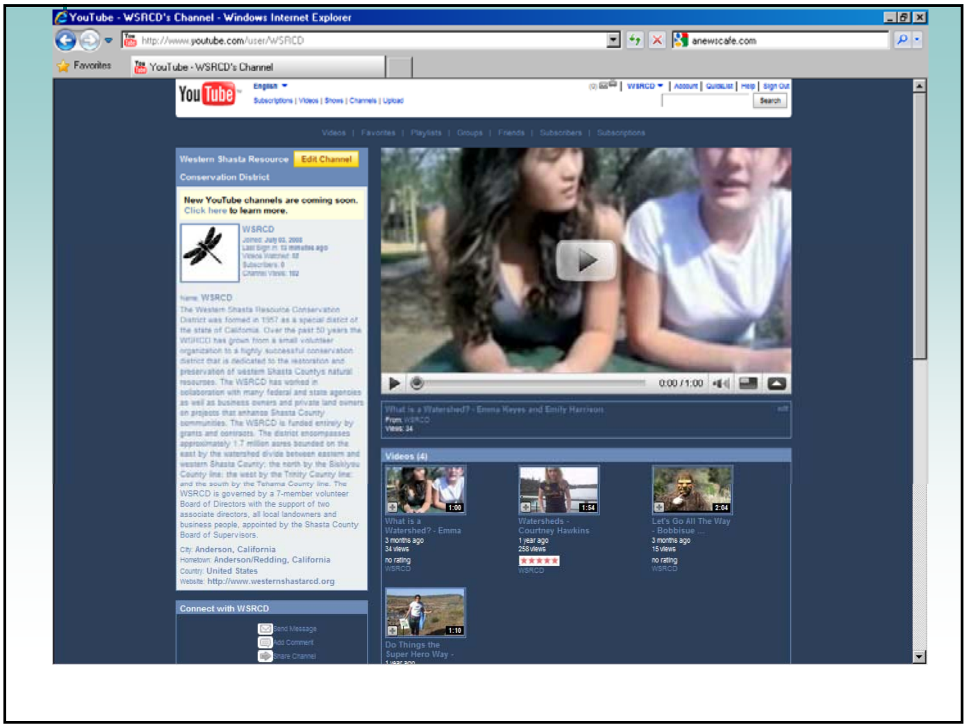
Flex your POWER

1-866-431-FLEX

www.fypower.org

2009 Whole Earth and Watershed Festival
Event Schedule

8:00am	Site opens for Exhibitors and Vendors
9:45am	Exhibitors and Vendors are ready for the public
10:00am	Main Stage: Whole Earth and Watershed Festival Opening Ceremony
10:15am	Main Stage: Frank Meek, Meeks Lumber
10:30am	Community Room: Documentary Film: "The Bounty of Marin"
11:00am	Community Room: Meet your Local Farmer
11:30am	Main Stage: Jeff Lewis, Shasta College: "Sustainability"
12:00pm	Main Stage: Live Music begins
1pm	Community Room: Documentary Film: "State of Resolve: California Environmental Law"
1:30pm	Main Stage: Dr. Raymond L. John "Animal Recycling: The Role of Haven Humane"
1:45pm	Community Room: Student Video Contest Viewing
2pm	Community Room: Documentary Film: "Out of the Air-Into the Soil: Land Practices That Reduce Atmospheric Carbon Levels"
2:30pm	Main Stage: Shasta Conservation Fund Awards and Student Video Awards
3pm	2009 Whole Earth and Watershed Festival Closing



Western Shasta Resource Conservation District

New YouTube channels are coming soon. Click here to learn more.

WSRCD

Name: WSRCD

The Western Shasta Resource Conservation District was formed in 1957 as a special district of the state of California. Over the past 50 years the WSRCD has grown from a small volunteer organization to a highly successful conservation district that is dedicated to the restoration and preservation of western Shasta Countys natural resources. The WSRCD has worked in collaboration with many federal and state agencies as well as business owners and private land owners on projects that enhance Shasta County communities. The WSRCD is funded entirely by grants and contracts. The district encompasses approximately 1.7 million acres bounded on the east by the watershed divide between eastern and western Shasta County; the north by the Siskiyou County line; the west by the Trinity County line; and the south by the Tehama County line. The WSRCD is governed by a 7-member volunteer Board of Directors with the support of two associate directors, all local landowners and business people, appointed by the Shasta County Board of Supervisors.

City: Anderson, California
Hometown: Anderson/Redding, California
Country: United States
Website: http://www.westernshastarcd.org

Connect with WSRCD

Send Message
Add Comment
Share Channel

What is a Watershed? - Emma Keyes and Emily Harrison
From: WSRCD
Views: 34

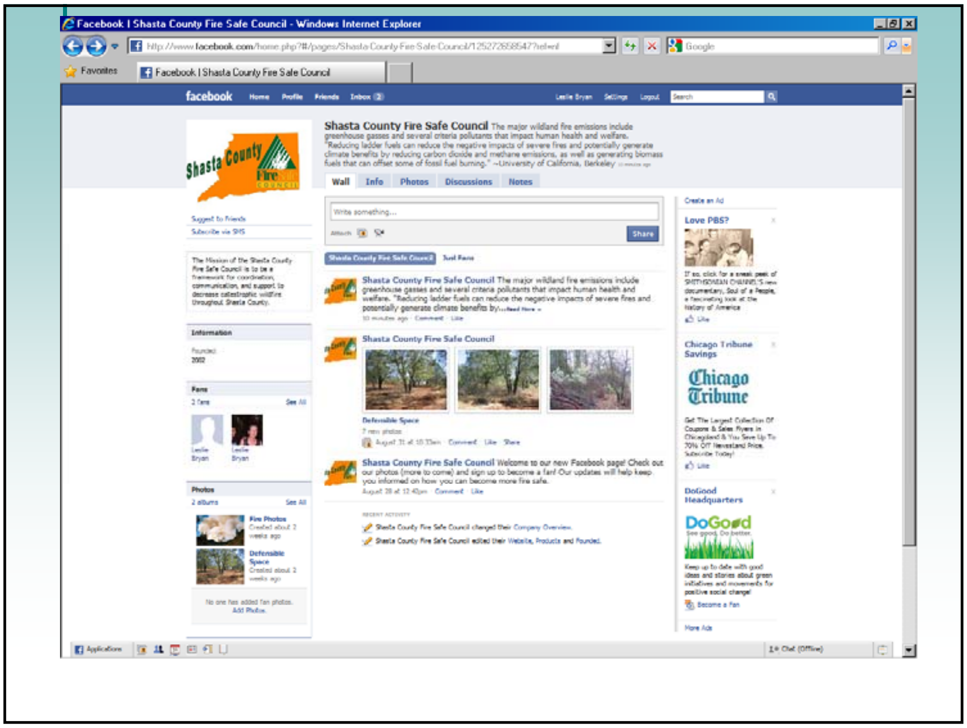
Videos (4)

What is a Watershed? - Emma
3 months ago
34 views
no rating
WSRCD

Watersheds - Courtney Hawkins
1 year ago
258 views
★★★★★
WSRCD

Let's Go All The Way - Bobbisue ...
3 months ago
15 views
no rating
WSRCD

Do Things the Super Hero Way -
1 year ago



Shasta County Fire Safe Council The major wildland fire emissions include greenhouse gasses and several criteria pollutants that impact human health and welfare. "Reducing ladder fuels can reduce the negative impacts of severe fires and potentially generate climate benefits by reducing carbon dioxide and methane emissions, as well as generating biomass fuels that can offset some of fossil fuel burning." --University of California, Berkeley

Suggest to Friends
Subscribe via SMS

The Mission of the Shasta County Fire Safe Council is to be a framework for coordination, communication, and support to decrease catastrophic wildfire throughout Shasta County.

Information

Founded:
2002

Fans

2 fans See All

Leslie Bryan
Leslie Bryan

Photos

2 albums See All

Fire Photos
Created about 2 weeks ago

Defensible Space
Created about 2 weeks ago

No one has added fan photos.
Add Photos.

Shasta County Fire Safe Council The major wildland fire emissions include greenhouse gasses and several criteria pollutants that impact human health and welfare. "Reducing ladder fuels can reduce the negative impacts of severe fires and potentially generate climate benefits by....Read More »
10 minutes ago · Comment · Like

Shasta County Fire Safe Council
Defensible Space
7 new photos
August 31 at 10:33am · Comment · Like · Share

Shasta County Fire Safe Council Welcome to our new Facebook page! Check out our photos (more to come) and sign up to become a fan! Our updates will help keep you informed on how you can become more fire safe.
August 28 at 12:40pm · Comment · Like

RECENT ACTIVITY
Shasta County Fire Safe Council changed their Company Overview.
Shasta County Fire Safe Council edited their Website, Products and Founded.

Shasta County area on leading edge of climate-change research

By Guest Speaker December 15, 2008 4 Comments Printer-Friendly ShareThis

WESTERN SHASTA RESOURCE CONSERVATION DISTRICT

By Leslie Bryan

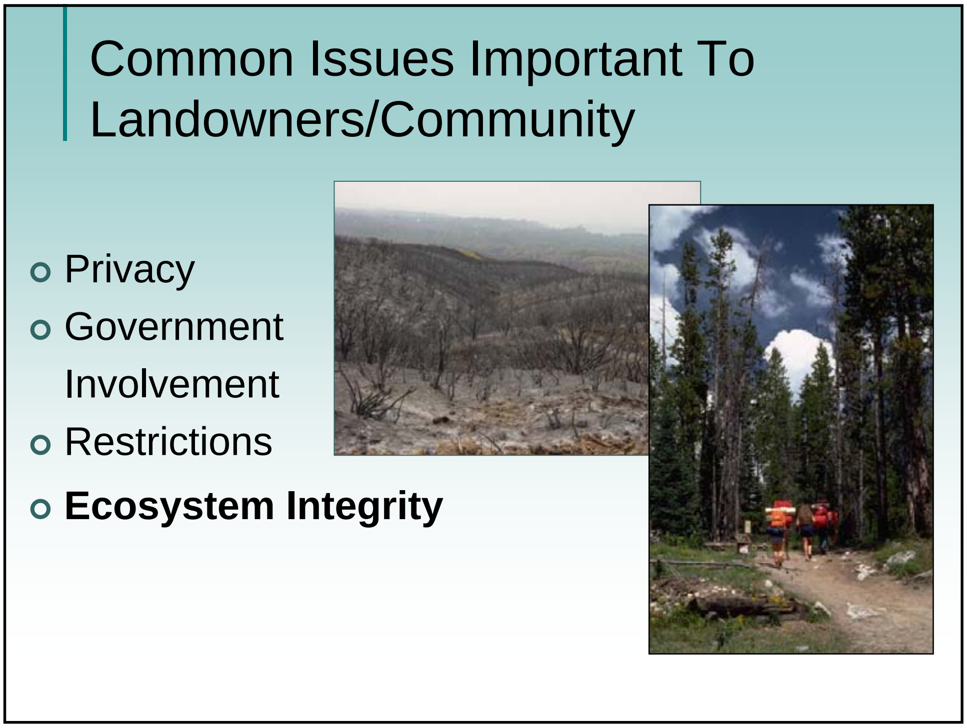
The Western Shasta Resource Conservation District is involved in a research project regarding climate change, a topic of great importance and interest. The project is pretty exciting as we here in Shasta County are on the very "cutting edge" of climate-change mitigation and how California may reach its goals set forth in AB32, the CA Global Warming Solutions Act.

As part of the West Coast Regional Carbon Sequestration Partnership (WESTCARB), the district is in partnership with the non-profit organization Winrock International to implement a research project involving carbon sequestration. Carbon sequestration, simply put, is the capture and storage of the greenhouse gas, carbon dioxide (CO2). The WESTCARB Team is made up of more than 80 organizations, public agencies, private companies and nonprofits and is working toward the goal of identifying and testing opportunities to keep CO2 out of the atmosphere, thereby reducing humankind's impact on the climate.

Shasta County has been identified as an area capable of cost-effective carbon sequestration, and the district is actively involved in validating the science behind the idea. Sequestration options being investigated for Shasta County include

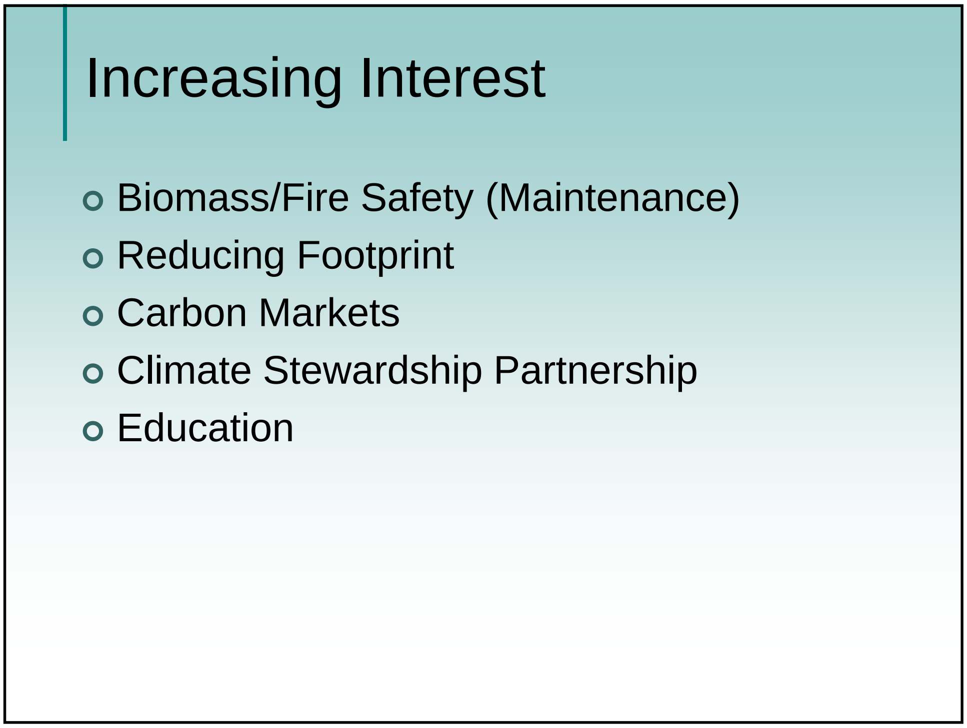
Education Community

- Community College
- ROP and Environmental Education Advisory Groups
- Local Museums
- Forest Foundation's Talk About Trees Program
- American Forest Foundation's "Project Learning Tree" Program



Common Issues Important To Landowners/Community

- Privacy
- Government Involvement
- Restrictions
- **Ecosystem Integrity**



Increasing Interest

- Biomass/Fire Safety (Maintenance)
- Reducing Footprint
- Carbon Markets
- Climate Stewardship Partnership
- Education

Message and Motto:
“Listen” and “*All Together Now*”
~ Beatles

- Tailor Message to Audience
- Develop Relationships
- Be open to mutual conversation
- Invest time for project success and ongoing far into the future for sustainability

Thank You

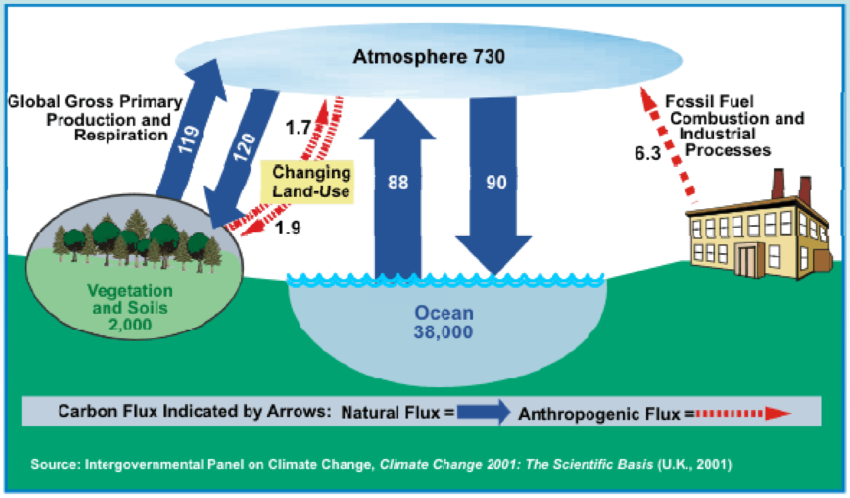
West Coast Regional Carbon Sequestration Partnership
westcarb.org

Forest Carbon

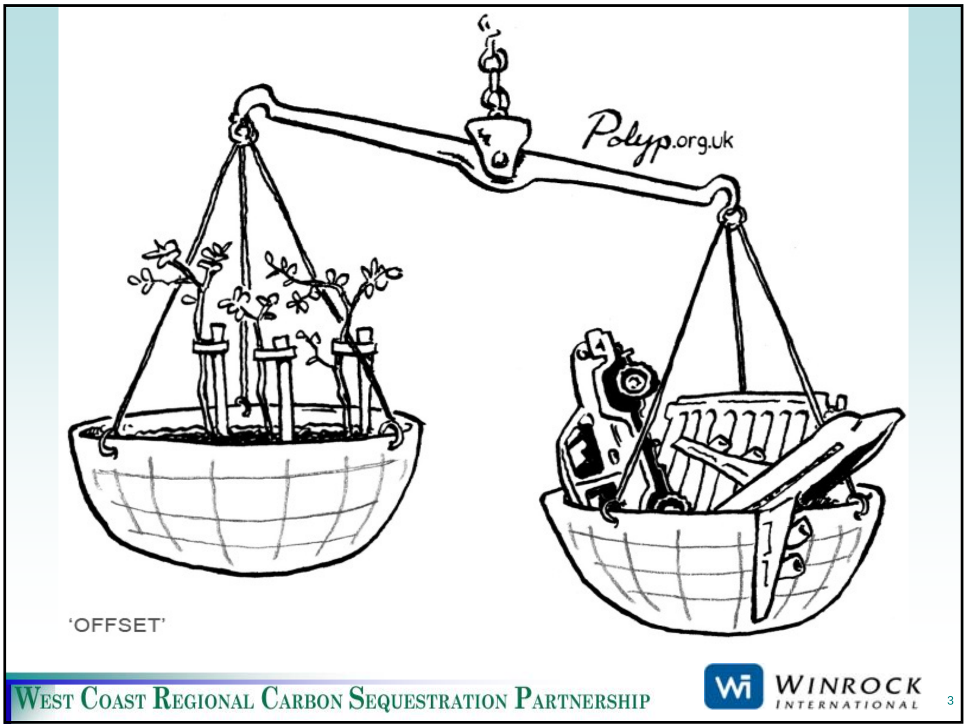
Basics of Terrestrial Offset Projects

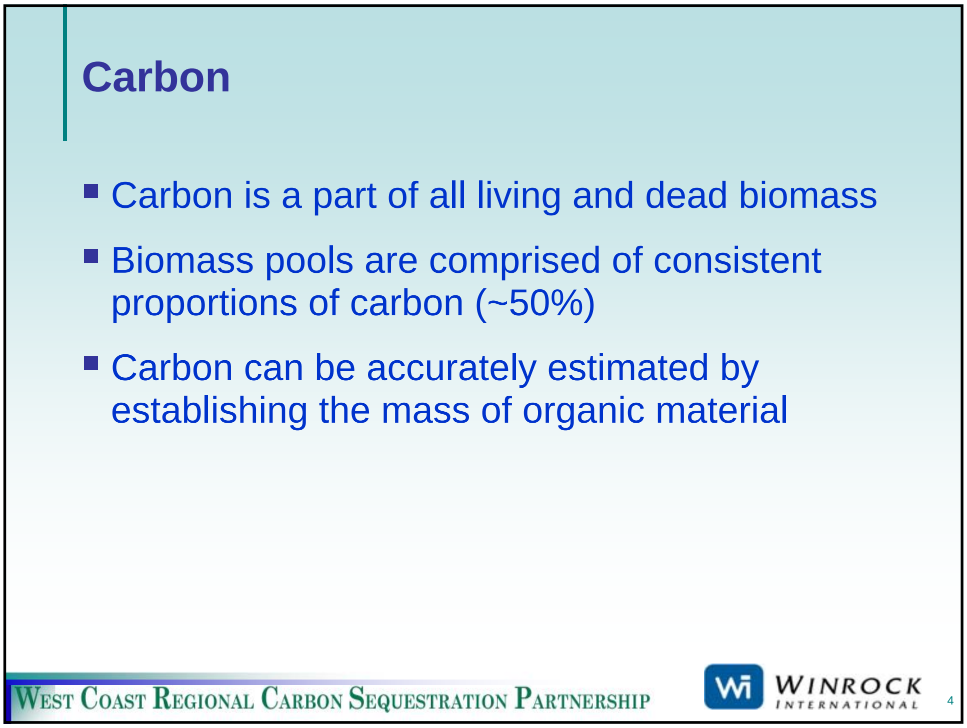
WINROCK INTERNATIONAL

Global Carbon Cycle



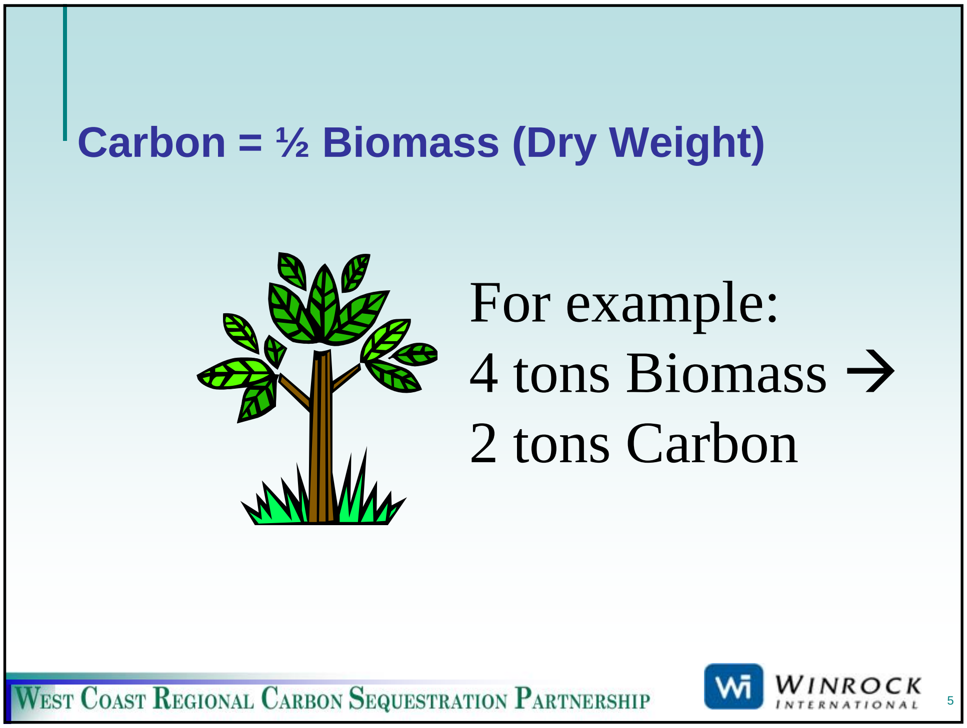
Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (U.K., 2001)





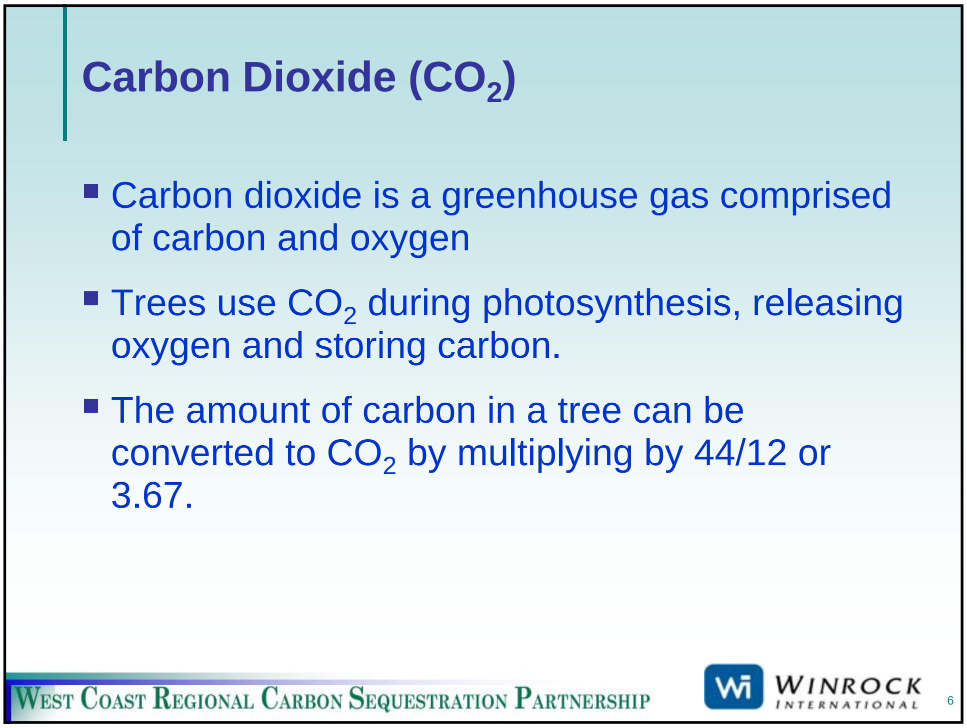
Carbon

- Carbon is a part of all living and dead biomass
- Biomass pools are comprised of consistent proportions of carbon (~50%)
- Carbon can be accurately estimated by establishing the mass of organic material



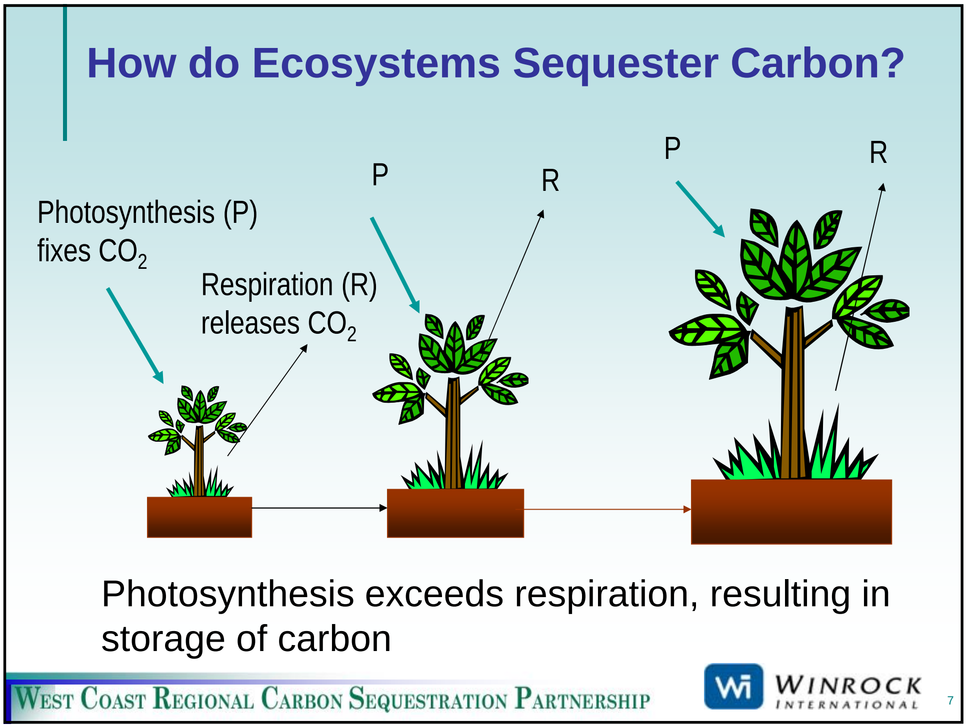
Carbon = ½ Biomass (Dry Weight)

For example:
4 tons Biomass →
2 tons Carbon



Carbon Dioxide (CO_2)

- Carbon dioxide is a greenhouse gas comprised of carbon and oxygen
- Trees use CO_2 during photosynthesis, releasing oxygen and storing carbon.
- The amount of carbon in a tree can be converted to CO_2 by multiplying by 44/12 or 3.67.



How do Ecosystems Sequester Carbon?

Photosynthesis (P) fixes CO_2

Respiration (R) releases CO_2

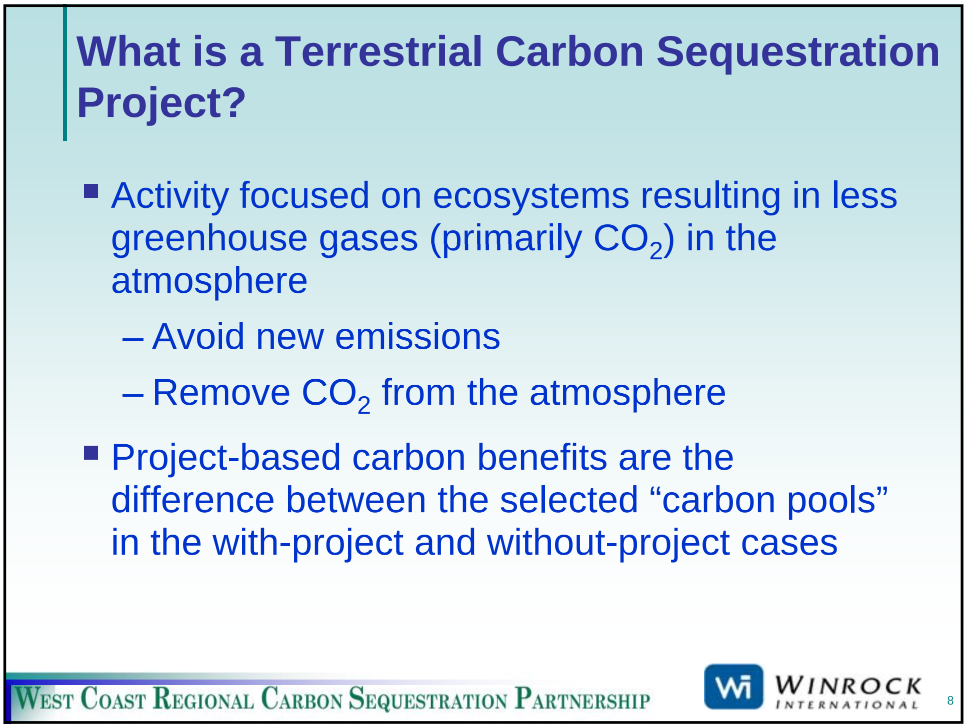
P

R

P

R

Photosynthesis exceeds respiration, resulting in storage of carbon



What is a Terrestrial Carbon Sequestration Project?

- Activity focused on ecosystems resulting in less greenhouse gases (primarily CO_2) in the atmosphere
  - Avoid new emissions
  - Remove CO_2 from the atmosphere
- Project-based carbon benefits are the difference between the selected “carbon pools” in the with-project and without-project cases

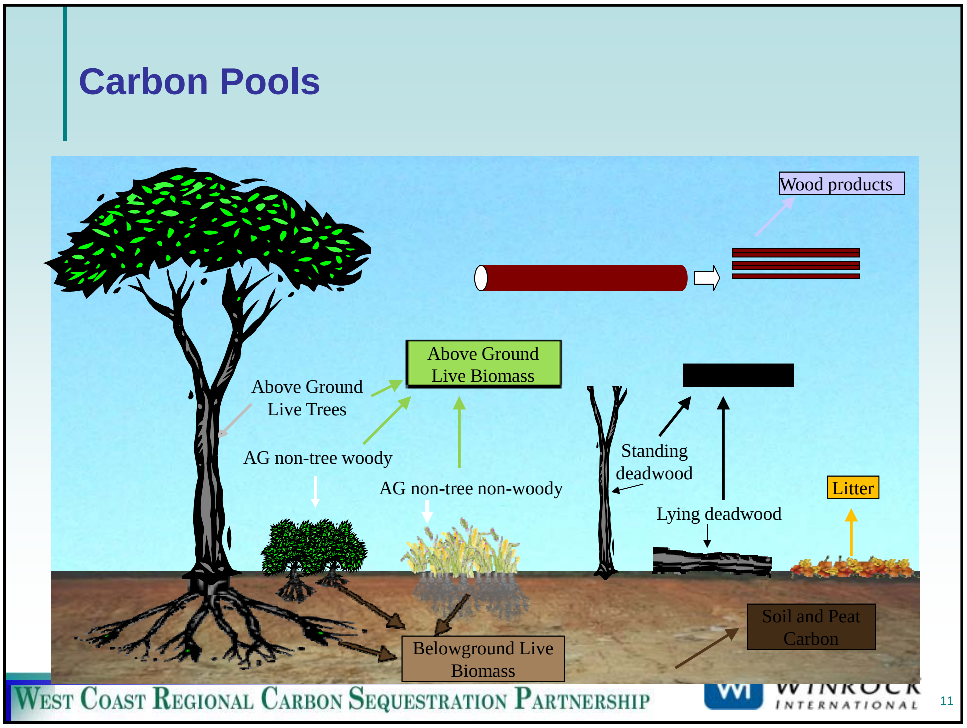
Forestry Practices that Sequester or Preserve Carbon

- Afforestation: tree planting on lands previously not in forest
- Reforestation: tree planting on previous forest lands
- Forest preservation or avoided deforestation: protection of threatened forest lands
- Forest management: modification of management practices

Where is Carbon Sequestered?

- Live biomass
  - Trees
  - Understory
  - Roots
- Dead biomass
  - Standing
  - Down
    - Coarse
    - Fine
- Wood products
- Soil

“Carbon Pools”



Carbon Pools

Wood products

Above Ground Live Biomass

Above Ground Live Trees

AG non-tree woody

AG non-tree non-woody

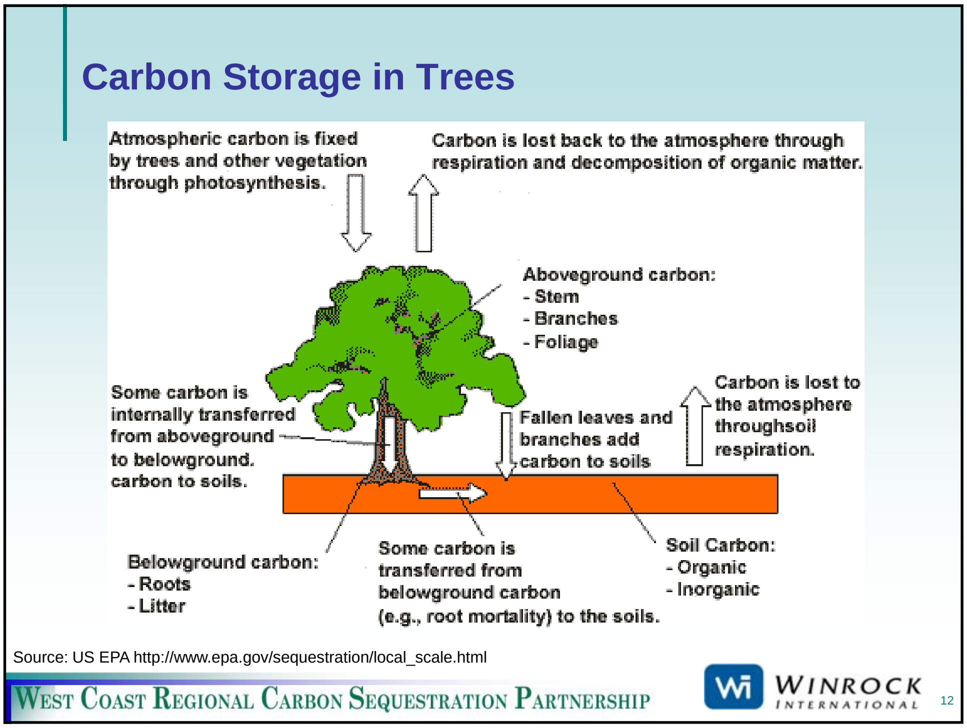
Standing deadwood

Lying deadwood

Litter

Soil and Peat Carbon

Belowground Live Biomass



Carbon Storage in Trees

Atmospheric carbon is fixed by trees and other vegetation through photosynthesis.

Carbon is lost back to the atmosphere through respiration and decomposition of organic matter.

Aboveground carbon:
- Stem
- Branches
- Foliage

Some carbon is internally transferred from aboveground to belowground. carbon to soils.

Fallen leaves and branches add carbon to soils

Carbon is lost to the atmosphere throughsoil respiration.

Belowground carbon:
- Roots
- Litter

Some carbon is transferred from belowground carbon (e.g., root mortality) to the soils.

Soil Carbon:
- Organic
- Inorganic

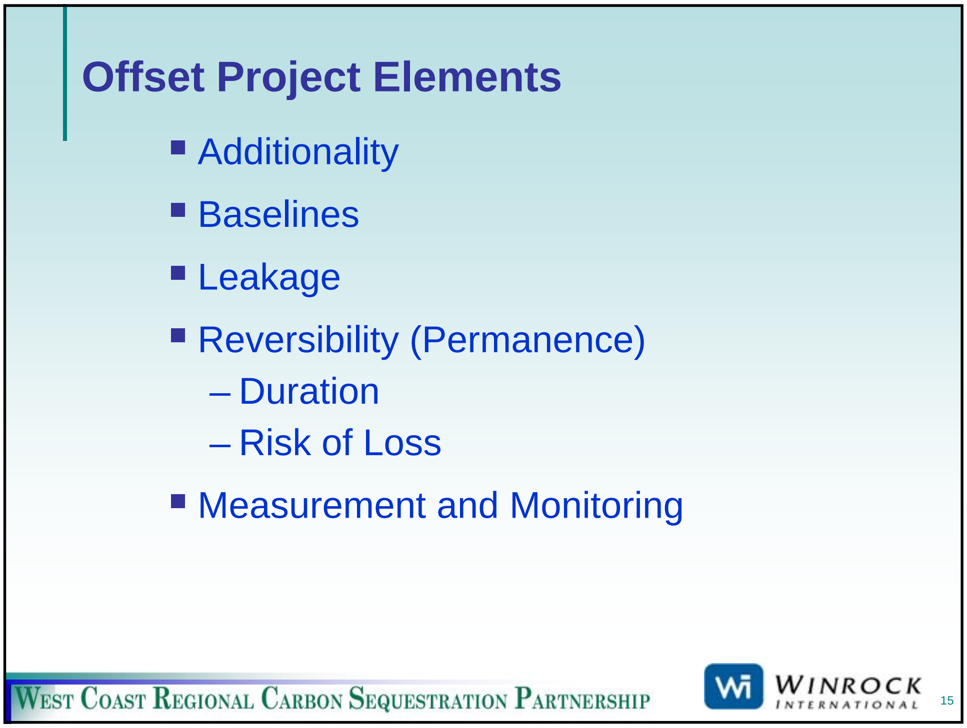
Source: US EPA http://www.epa.gov/sequestration/local_scale.html

Carbon Pools

- Selection of pools depends on:
  - Expected rate of change
  - Expected magnitude and direction of change
  - Availability of methods, accuracy and cost of methods to measure and monitor
- For A/R, REDD:
  - Always measure AG+BG biomass
  - Other pools: dependent on project

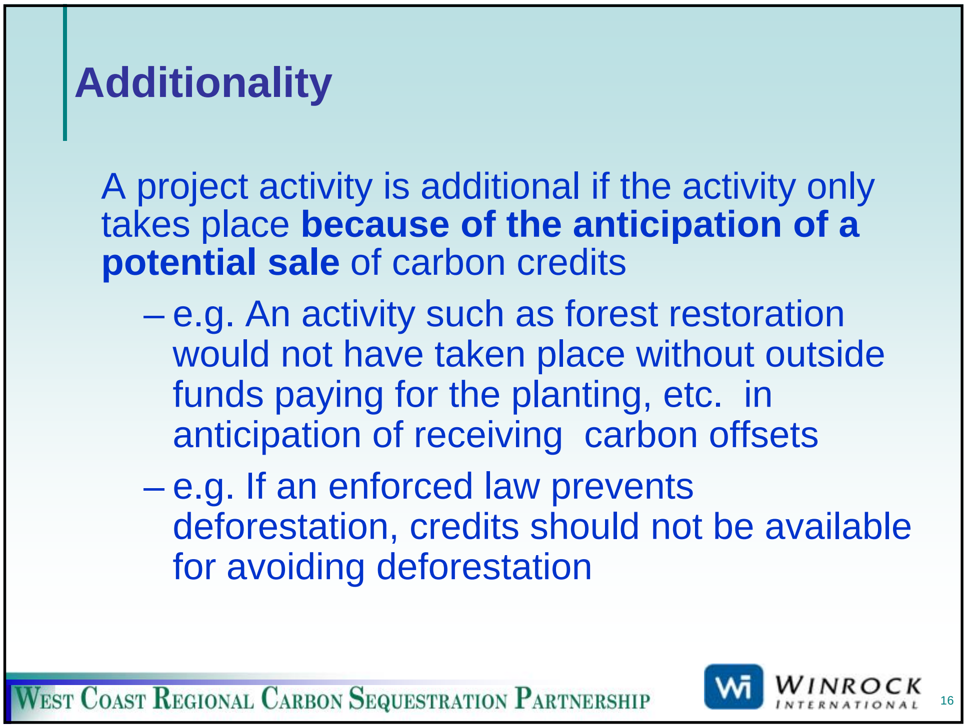
Current Land Use Dictates Sequestration Potential

- Sequestration is most attractive where low-value land is readily availably and has a high capacity for additional carbon storage (i.e. non-forest land)
- Co-benefits can be wide-ranging and add commercial value to sequestration projects as well as elevate project visibility and improve public perception
- Risks: Environmental factors can lead to lower-than-expected yields for sequestration projects



Offset Project Elements

- Additionality
- Baselines
- Leakage
- Reversibility (Permanence)
  - Duration
  - Risk of Loss
- Measurement and Monitoring



Additionality

A project activity is additional if the activity only takes place **because of the anticipation of a potential sale** of carbon credits

- e.g. An activity such as forest restoration would not have taken place without outside funds paying for the planting, etc. in anticipation of receiving carbon offsets
- e.g. If an enforced law prevents deforestation, credits should not be available for avoiding deforestation

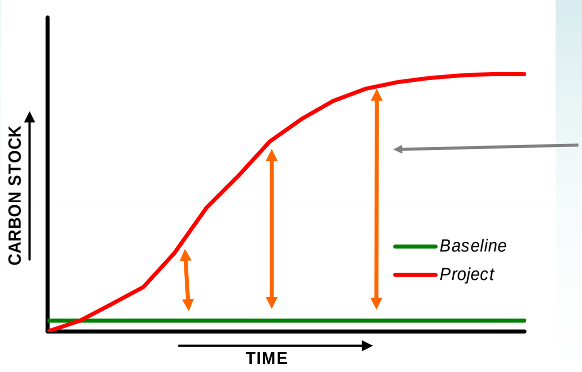
Baselines

- Setting a baseline requires projecting future activities in the absence of a project = What would have happened in the absence of the project activity
- Baseline has two components—land use/cover and corresponding carbon
- Must be prepared in a *transparent* and *conservative* manner

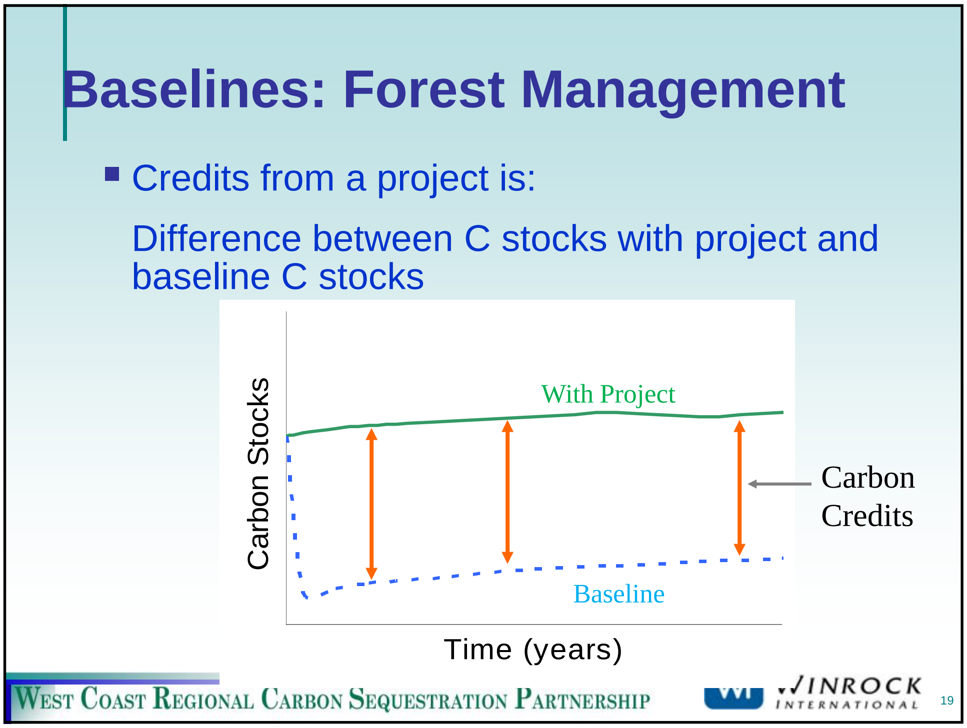
Baselines: Reforestation

- Credits from a project is:

  Difference between C stocks with project and baseline C stocks



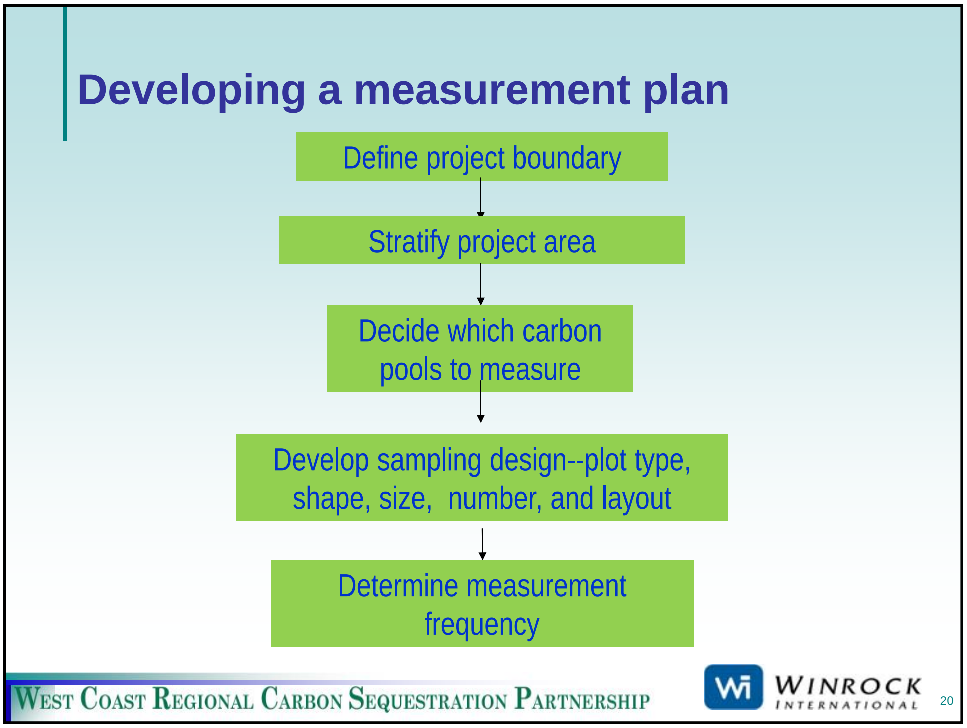
Carbon Credits



Baselines: Forest Management

- Credits from a project is:

  Difference between C stocks with project and baseline C stocks



Developing a measurement plan

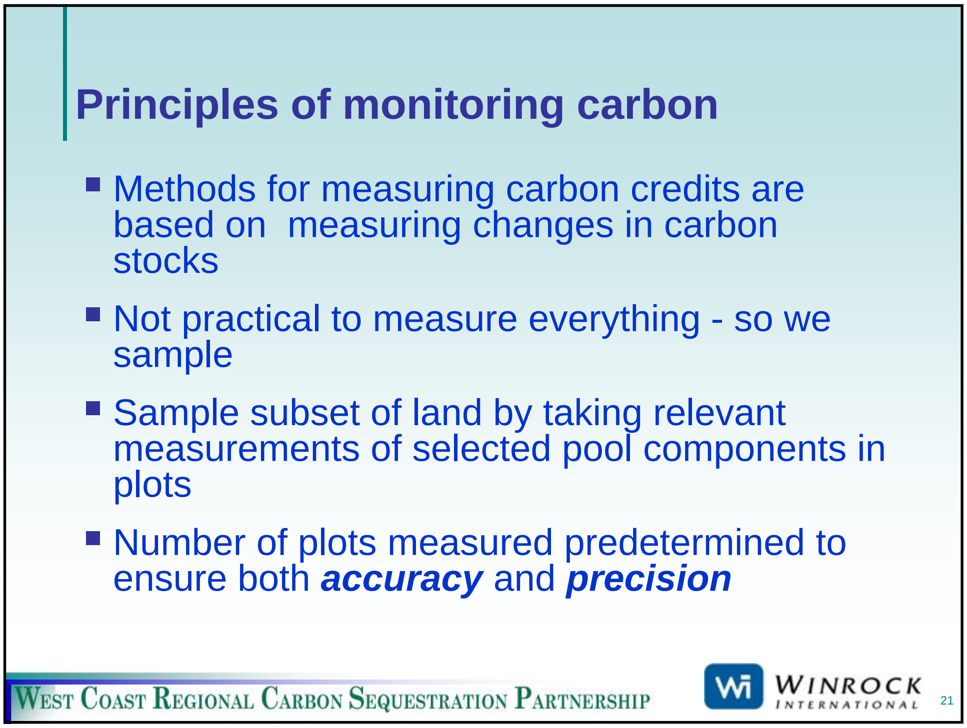
Define project boundary

Stratify project area

Decide which carbon pools to measure

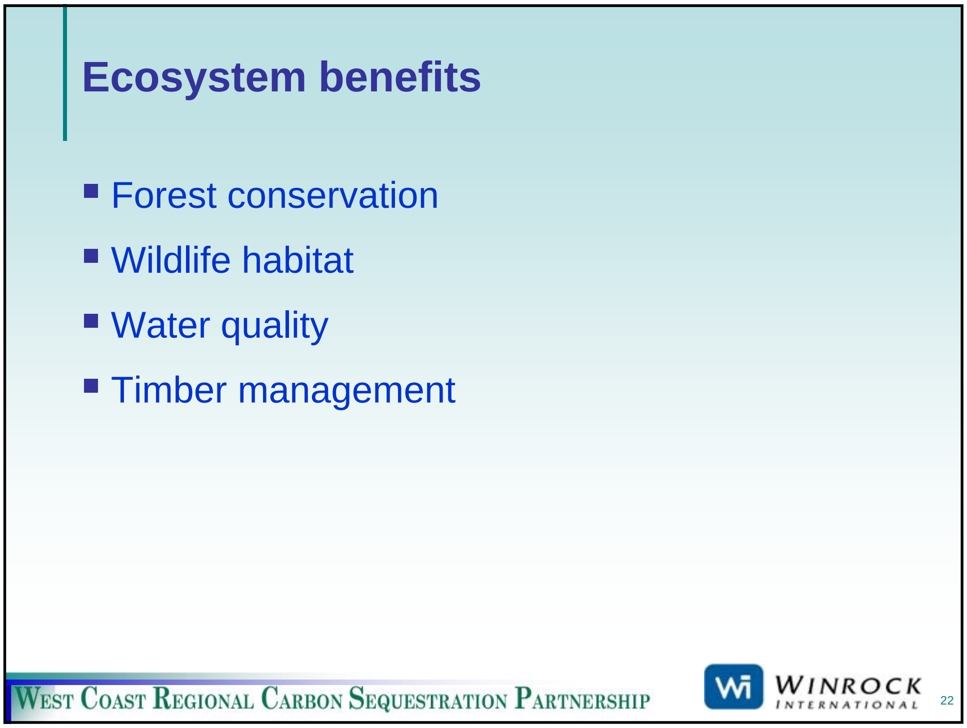
Develop sampling design--plot type, shape, size, number, and layout

Determine measurement frequency



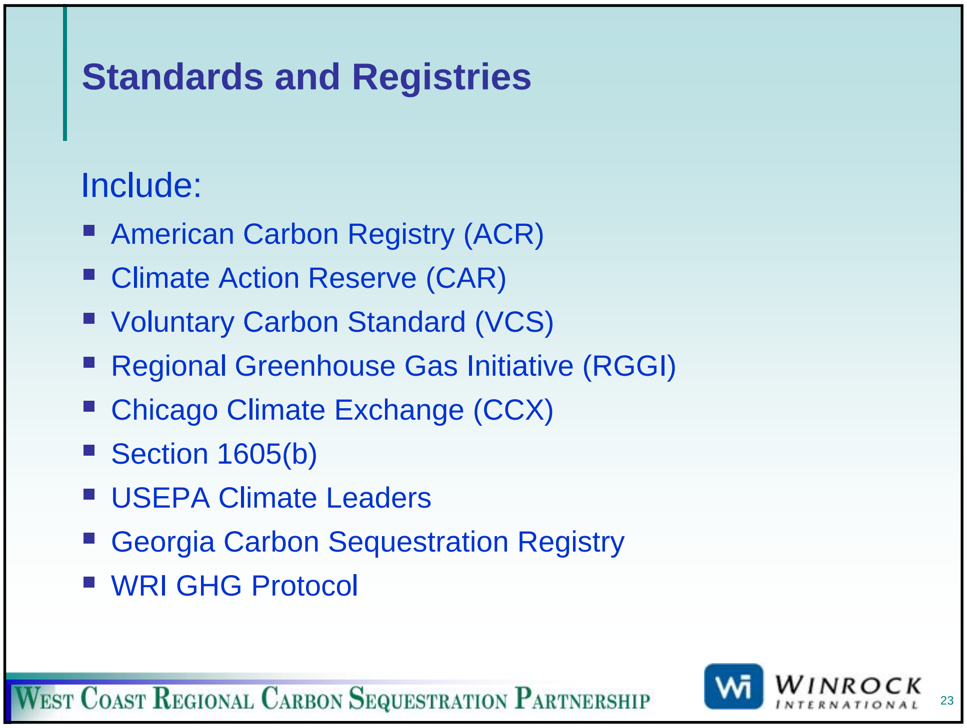
Principles of monitoring carbon

- Methods for measuring carbon credits are based on measuring changes in carbon stocks
- Not practical to measure everything - so we sample
- Sample subset of land by taking relevant measurements of selected pool components in plots
- Number of plots measured predetermined to ensure both ***accuracy*** and ***precision***



Ecosystem benefits

- Forest conservation
- Wildlife habitat
- Water quality
- Timber management



Standards and Registries

Include:

- American Carbon Registry (ACR)
- Climate Action Reserve (CAR)
- Voluntary Carbon Standard (VCS)
- Regional Greenhouse Gas Initiative (RGGI)
- Chicago Climate Exchange (CCX)
- Section 1605(b)
- USEPA Climate Leaders
- Georgia Carbon Sequestration Registry
- WRI GHG Protocol

West Coast Regional Carbon Sequestration Partnership
westcarb.org

Reforestation Pilot Projects in Shasta County

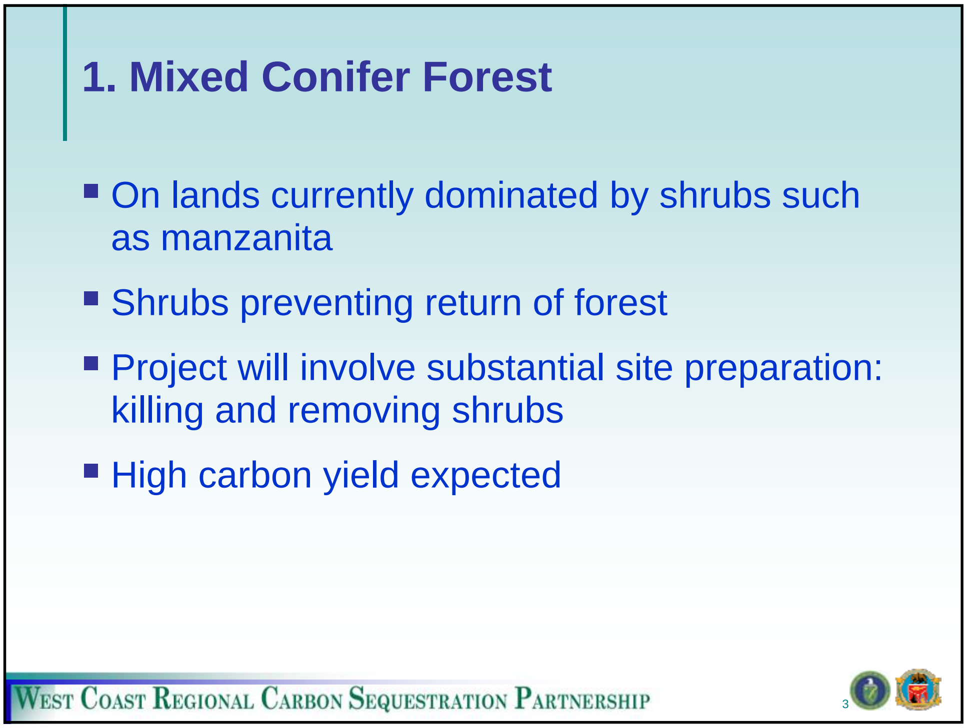
Western Shasta Resource Conservation District

W. M. Beaty & Associates, Inc.

Introduction to WESTCARB Afforestation

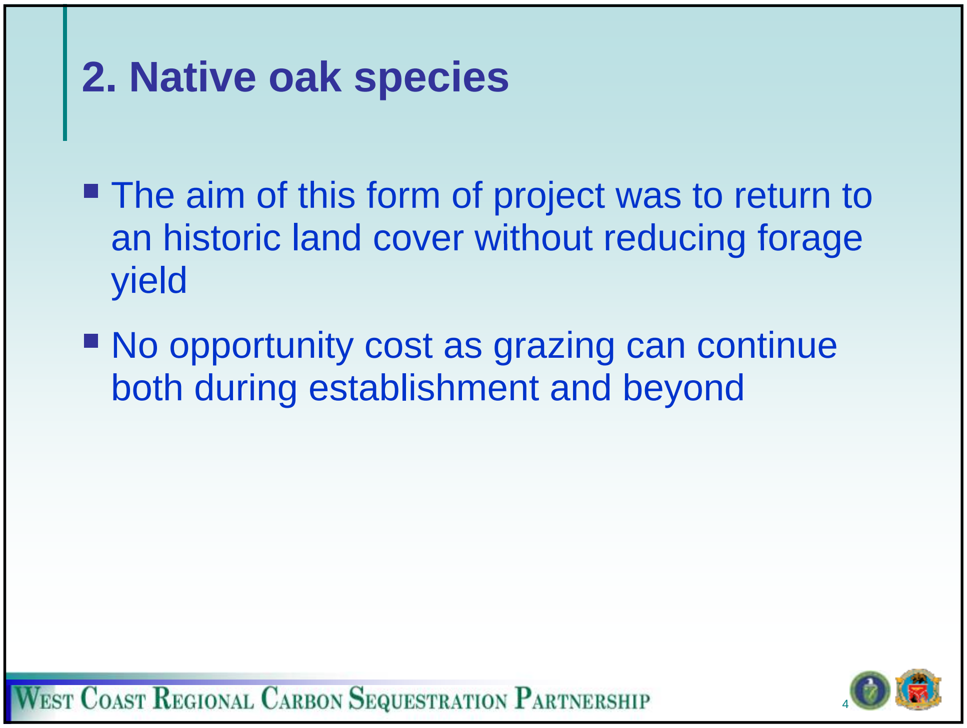
Project aims were to:

- Determine feasibility of producing carbon offsets from afforestation of private lands in Shasta County
- To enable maximization of land potential, additional income streams while not foregoing existing streams
  - Plus gives landowners the chance to impact climate change
- Encourage afforestation of rangelands
- Examine costs associated with afforestation
- Examine costs of monitoring plantings for carbon credit



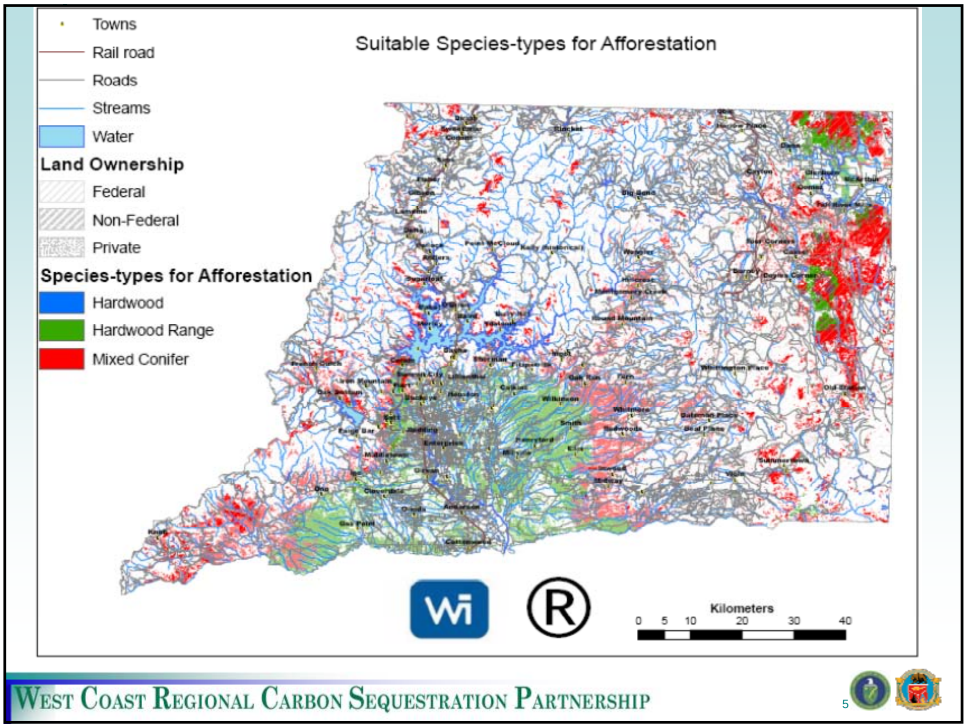
1. Mixed Conifer Forest

- On lands currently dominated by shrubs such as manzanita
- Shrubs preventing return of forest
- Project will involve substantial site preparation: killing and removing shrubs
- High carbon yield expected

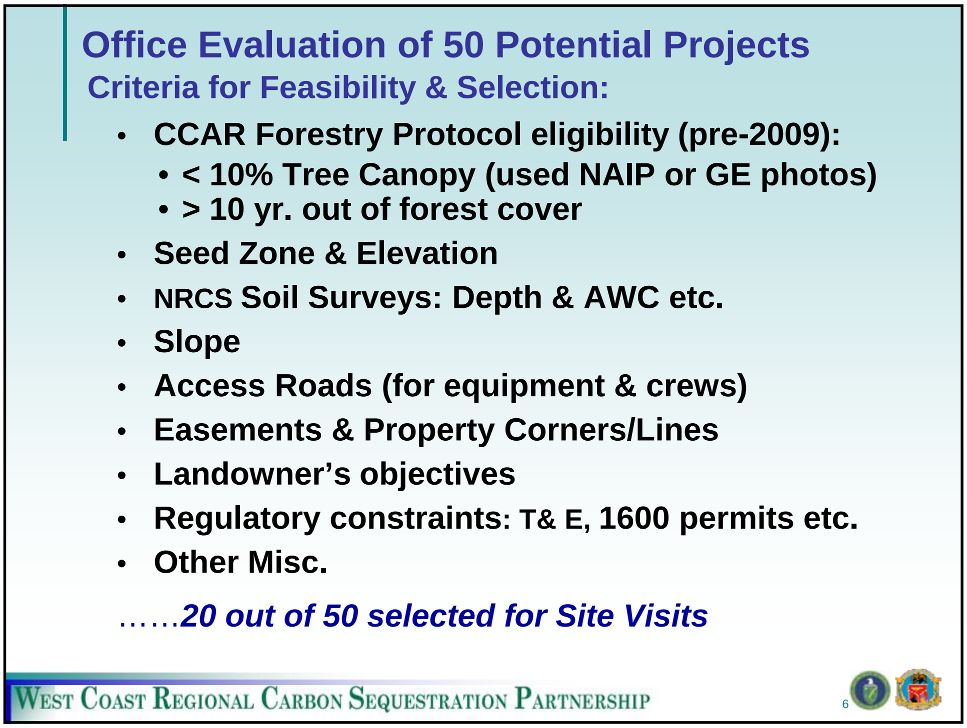


2. Native oak species

- The aim of this form of project was to return to an historic land cover without reducing forage yield
- No opportunity cost as grazing can continue both during establishment and beyond



Suitable Species-types for Afforestation

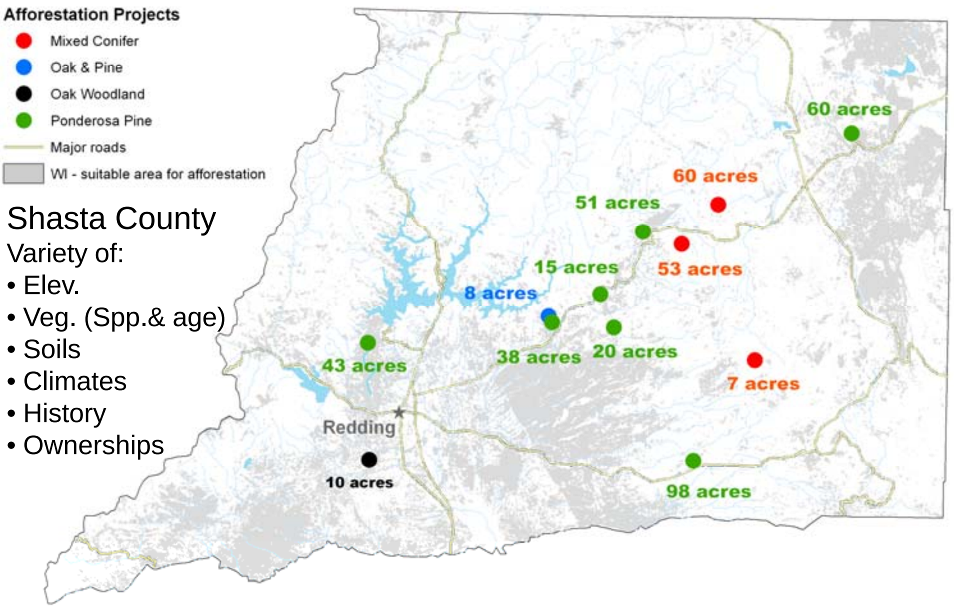


Office Evaluation of 50 Potential Projects

Criteria for Feasibility & Selection:

- **CCAR Forestry Protocol eligibility (pre-2009):**
  - **< 10% Tree Canopy (used NAIP or GE photos)**
  - **> 10 yr. out of forest cover**
- **Seed Zone & Elevation**
- **NRCS Soil Surveys: Depth & AWC etc.**
- **Slope**
- **Access Roads (for equipment & crews)**
- **Easements & Property Corners/Lines**
- **Landowner's objectives**
- **Regulatory constraints: T& E, 1600 permits etc.**
- **Other Misc.**

……***20 out of 50 selected for Site Visits***



Shasta County

Variety of:

- Elev.
- Veg. (Spp.& age)
- Soils
- Climates
- History
- Ownerships

12 projects / Landowner Agreements totaling 470 acres.

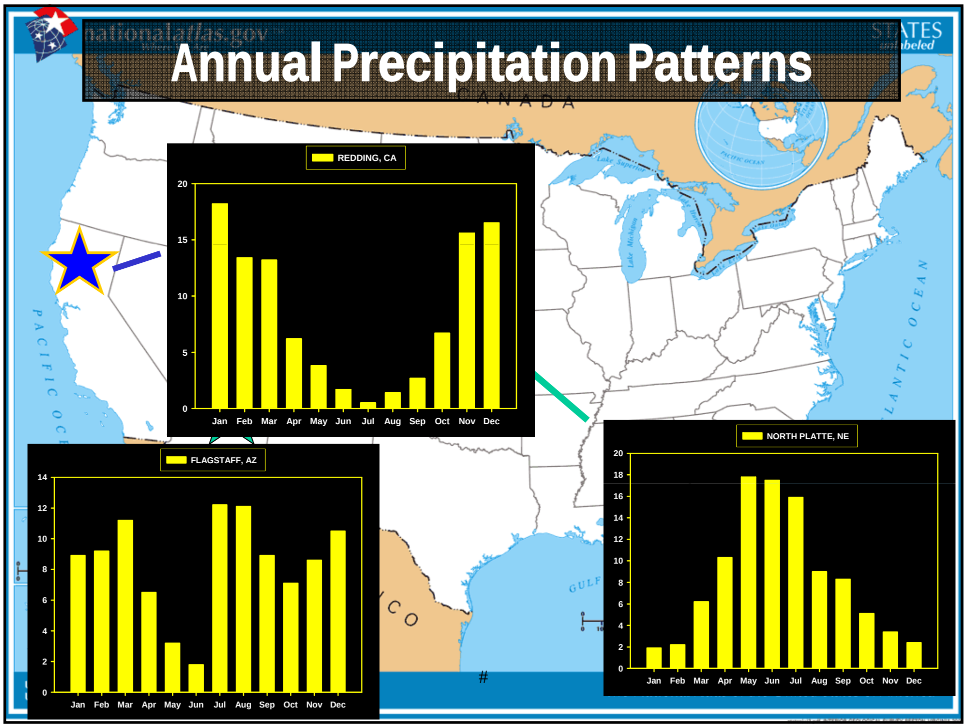
Shasta Afforestation Projects

98 ac	Ponderosa pine afforestation, *brush removal for bioenergy*
7 ac	Mixed conifer afforestation – ponderosa pine and red fir
20 ac	Ponderosa pine afforestation, easement on property
60 ac	Mixed conifer afforestation – ponderosa pine, Douglas fir, incense cedar; past fire site
50 ac	Mixed conifer afforestation – ponderosa pine, Douglas fir; past fire site (1992)
43 ac	Ponderosa pine afforestation, affected by copper smelting in 1910
51 ac	Mixed conifer afforestation, - ponderosa pine and Douglas fir, past fire site (1992)
46 ac	Ponderosa pine afforestation
20 ac	Oak/pine afforestation
14 ac	Ponderosa pine afforestation
60 ac	Ponderosa pine afforestation, recent fire (2007)
7 ac	Oak woodlands

Mediterranean Climate

- Cool/wet Winters
  - Competing vegetation/fuel
- Warm/dry Summer
  - Annual fire season
  - Soil moisture is limiting factor for conifer seedling survival
- Lightning

Annual Precipitation Patterns

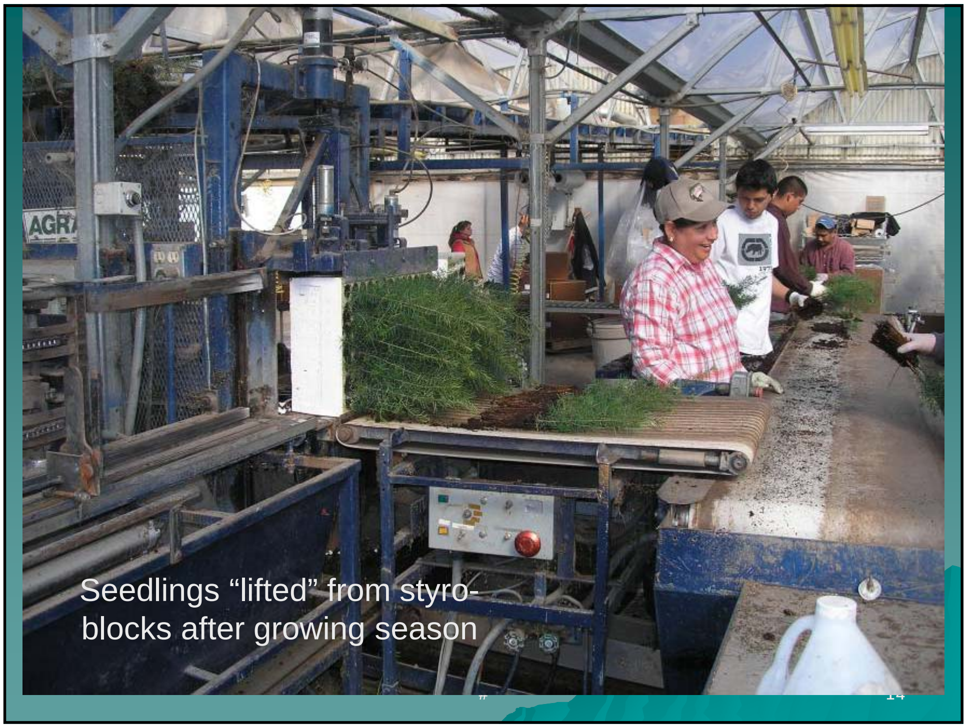


Conifer Seed from:
CAL FIRE, W.M. Beaty & SPI

Various:
- Species
- Elevations
- Seed Zones

CAL FOREST NURSERY
Sowing seeds into styro-block containers

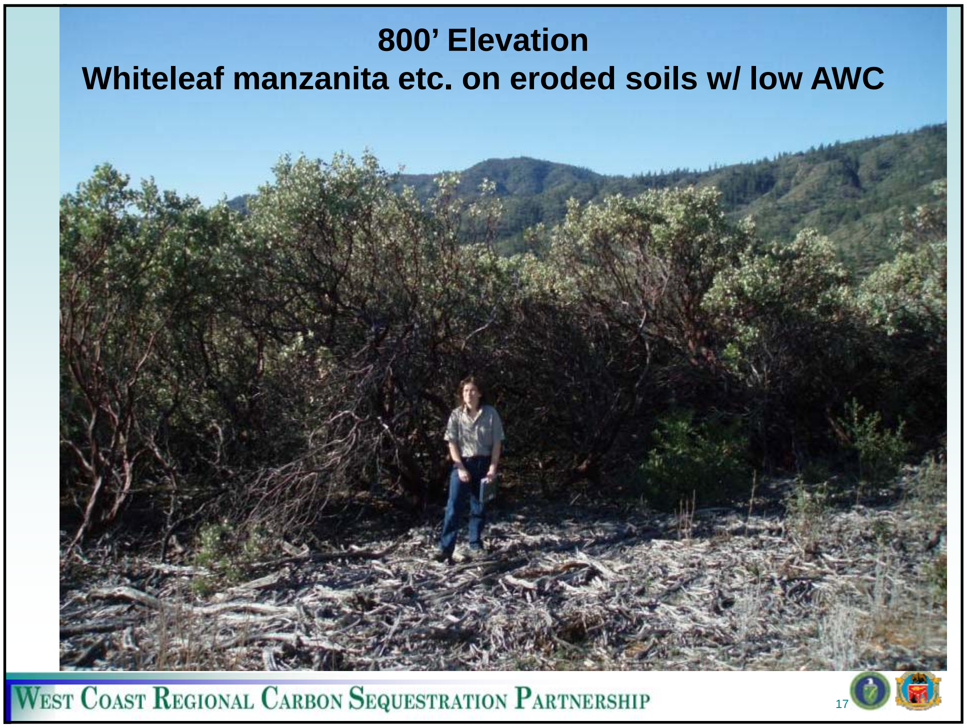
Seeds germinate into seedlings & grow for one season at the nursery



Seedlings “lifted” from styro-blocks after growing season

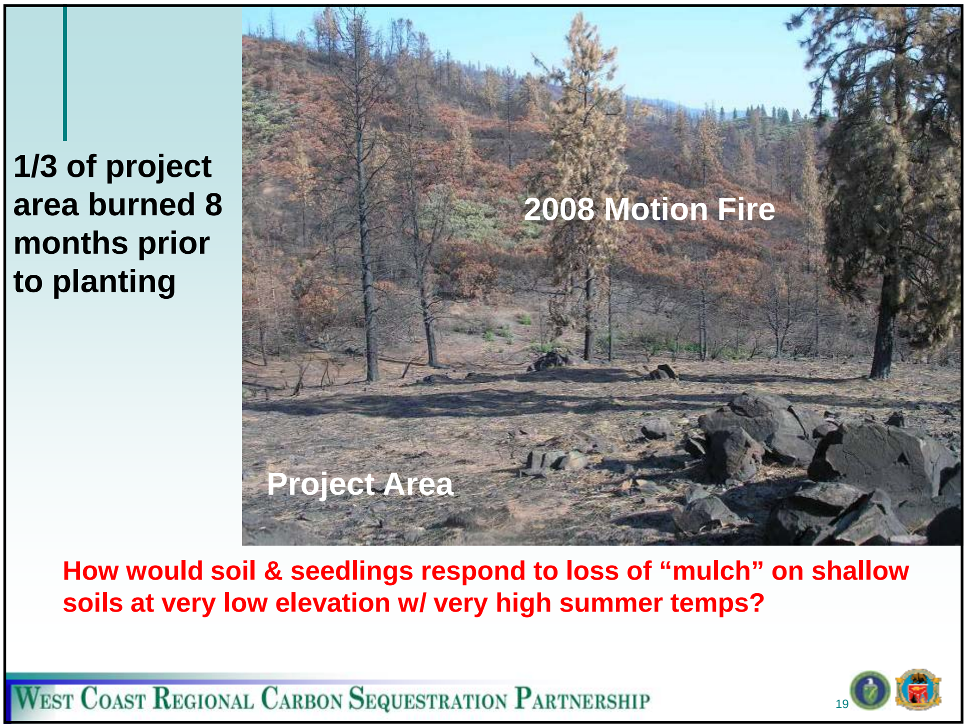
Seedlings packed into boxes by seed lot, elevation, species, project name etc.

Seedlings must be kept in cold storage from lifting/packing until they are planted in the field



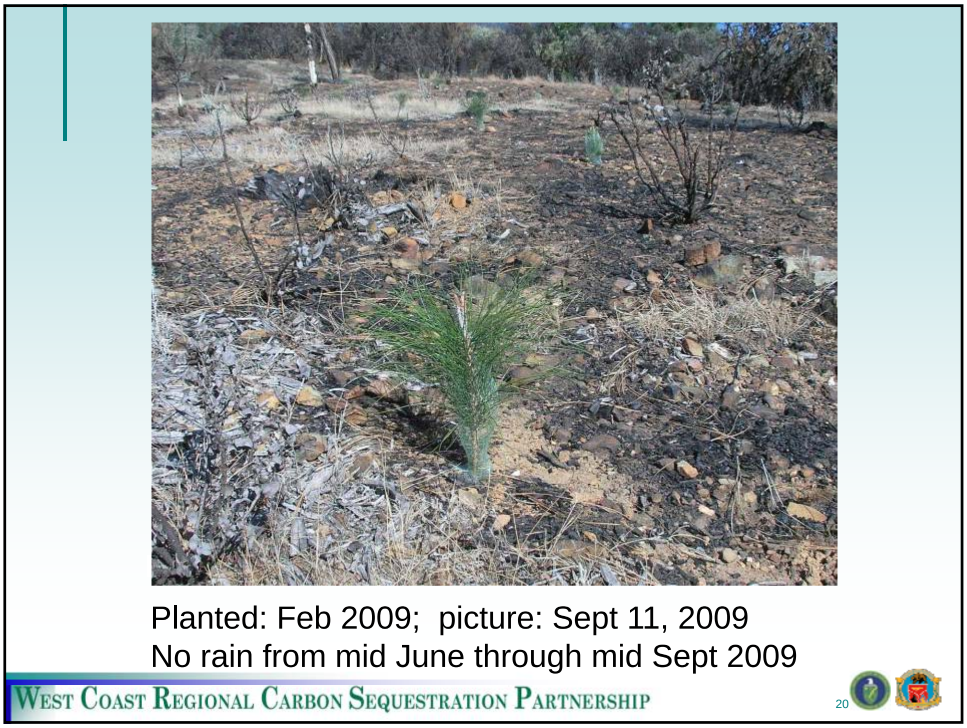
800’ Elevation
Whiteleaf manzanita etc. on eroded soils w/ low AWC

2008 Spray to prep site for planting in 2009

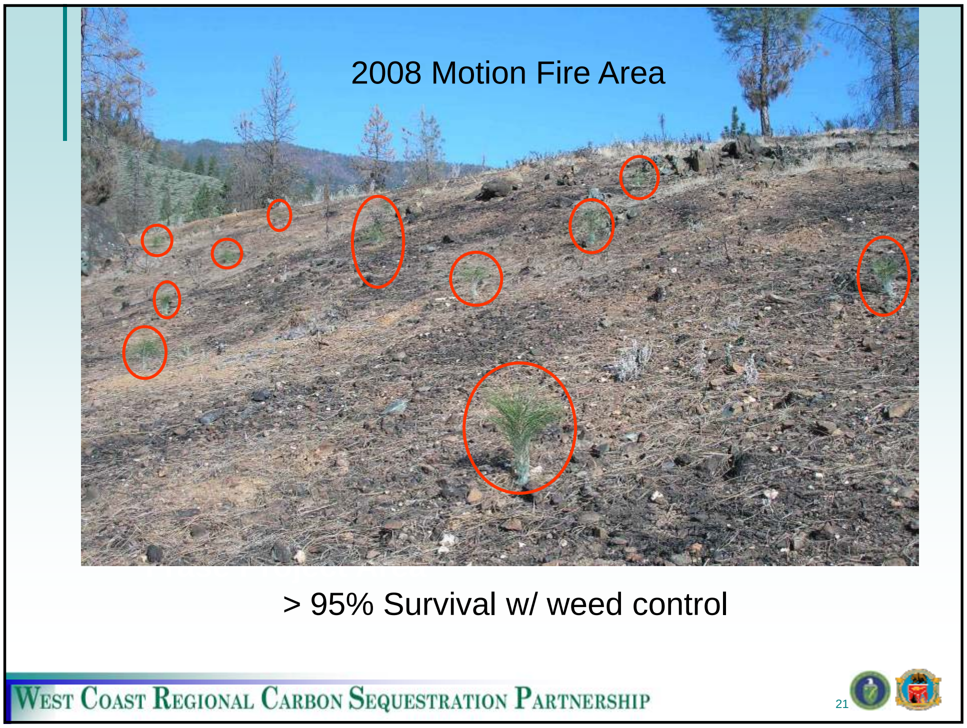


1/3 of project area burned 8 months prior to planting

How would soil & seedlings respond to loss of "mulch" on shallow soils at very low elevation w/ very high summer temps?

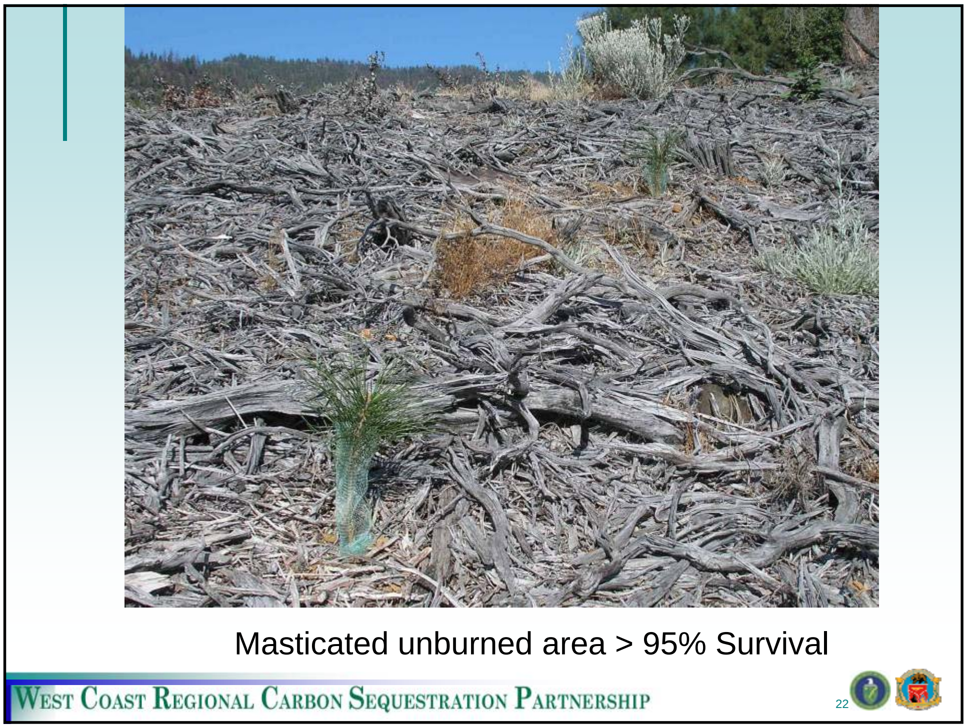


Planted: Feb 2009; picture: Sept 11, 2009
No rain from mid June through mid Sept 2009



2008 Motion Fire Area

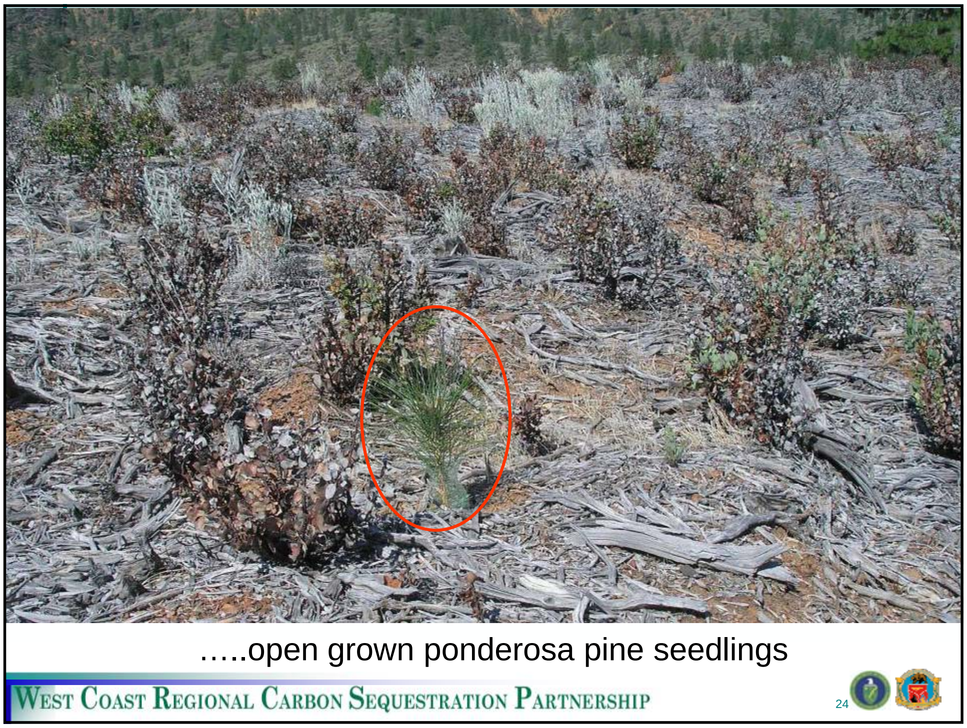
> 95% Survival w/ weed control



Masticated unburned area > 95% Survival

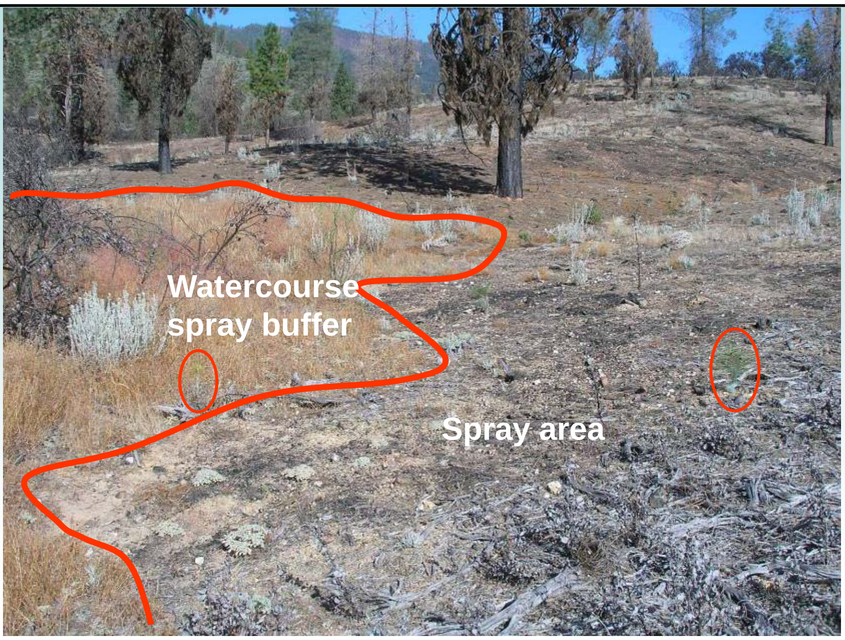
PP seedling under “sparse” canopy are less vigorous than….

West Coast Regional Carbon Sequestration Partnership



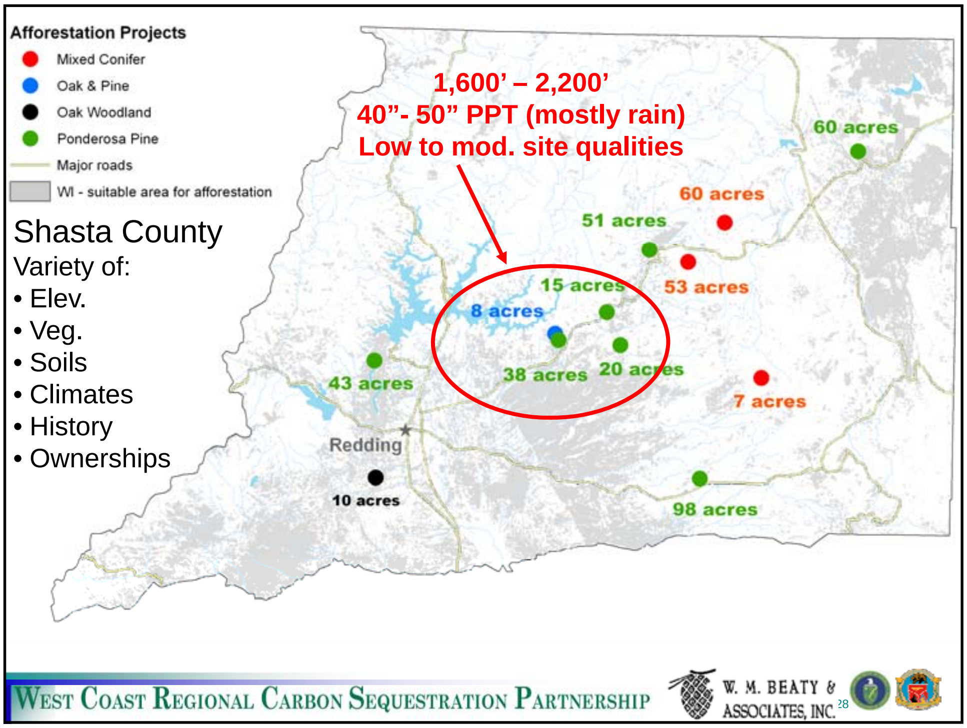
…..open grown ponderosa pine seedlings

West Coast Regional Carbon Sequestration Partnership


Watercourse spray buffer
Spray area


Watercourse spray buffer area

Almost all seedlings died within watercourse buffer - no spray areas



Afforestation Projects

- 🔴 Mixed Conifer
- 🔵 Oak & Pine
- ● Oak Woodland
- 🟢 Ponderosa Pine
- — Major roads
- ▨ WI - suitable area for afforestation

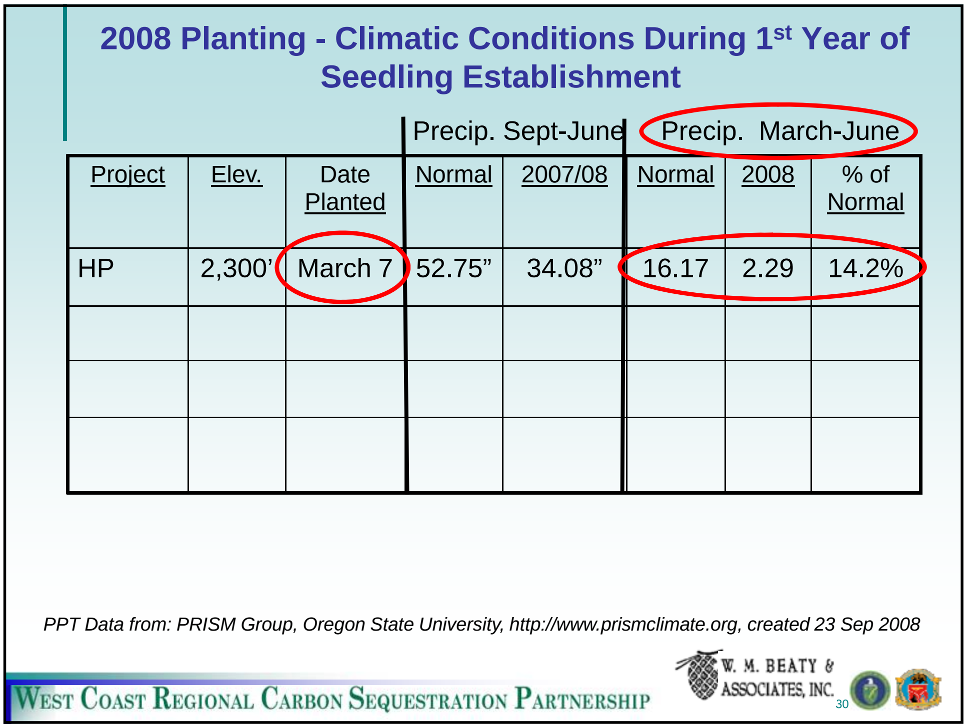
Shasta County

Variety of:

- Elev.
- Veg.
- Soils
- Climates
- History
- Ownerships

1,600' – 2,200'
40"- 50" PPT (mostly rain)
Low to mod. site qualities

Manzanita etc. @ 2,300'
Cohasset Soils: > 40" deep & mod/high AWC (10"-14")



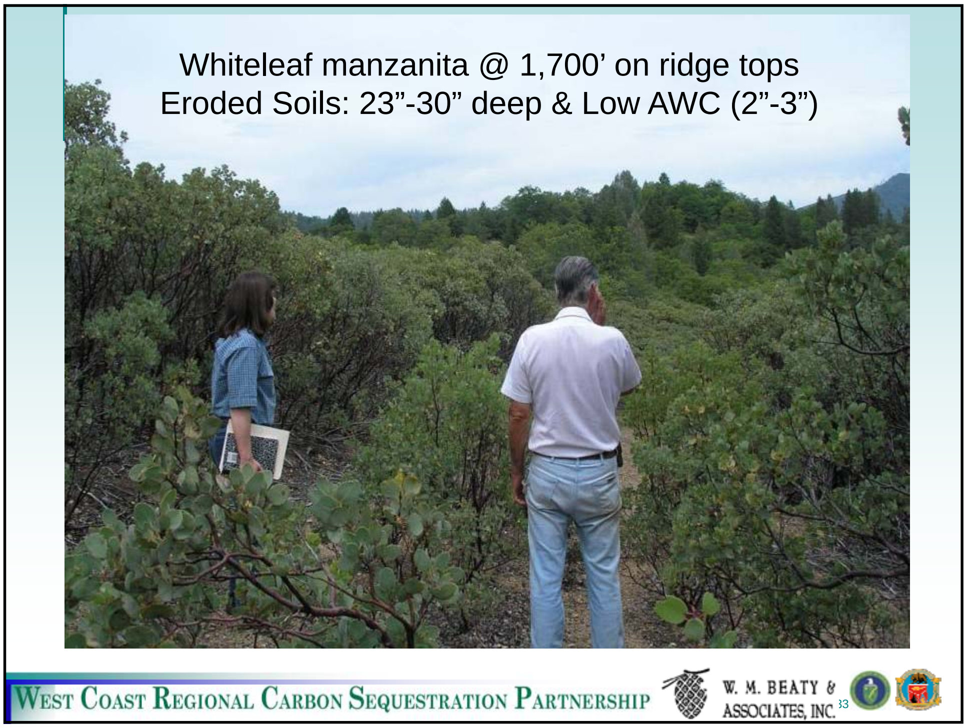
2008 Planting - Climatic Conditions During 1st Year of Seedling Establishment

			Precip. Sept-June		Precip. March-June		
Project	Elev.	Date Planted	Normal	2007/08	Normal	2008	% of Normal
HP	2,300'	March 7	52.75"	34.08"	16.17	2.29	14.2%

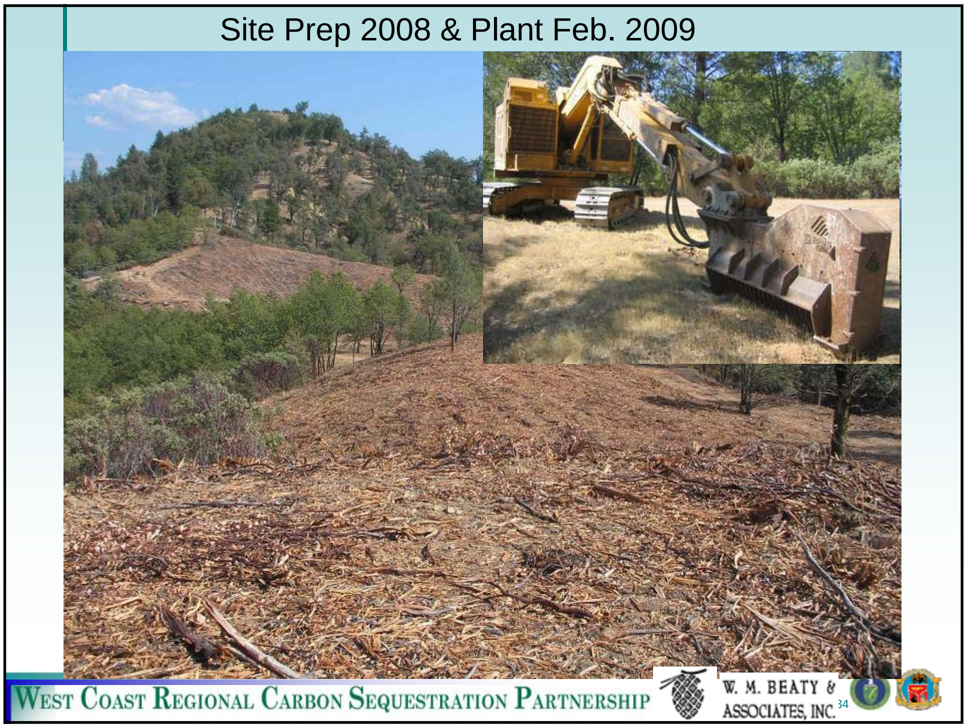
PPT Data from: PRISM Group, Oregon State University, http://www.prismclimate.org, created 23 Sep 2008

Seedlings @ end of summer 2008
> 90% survival

2 ½ years after planting



Whiteleaf manzanita @ 1,700’ on ridge tops
Eroded Soils: 23”-30” deep & Low AWC (2”-3”)

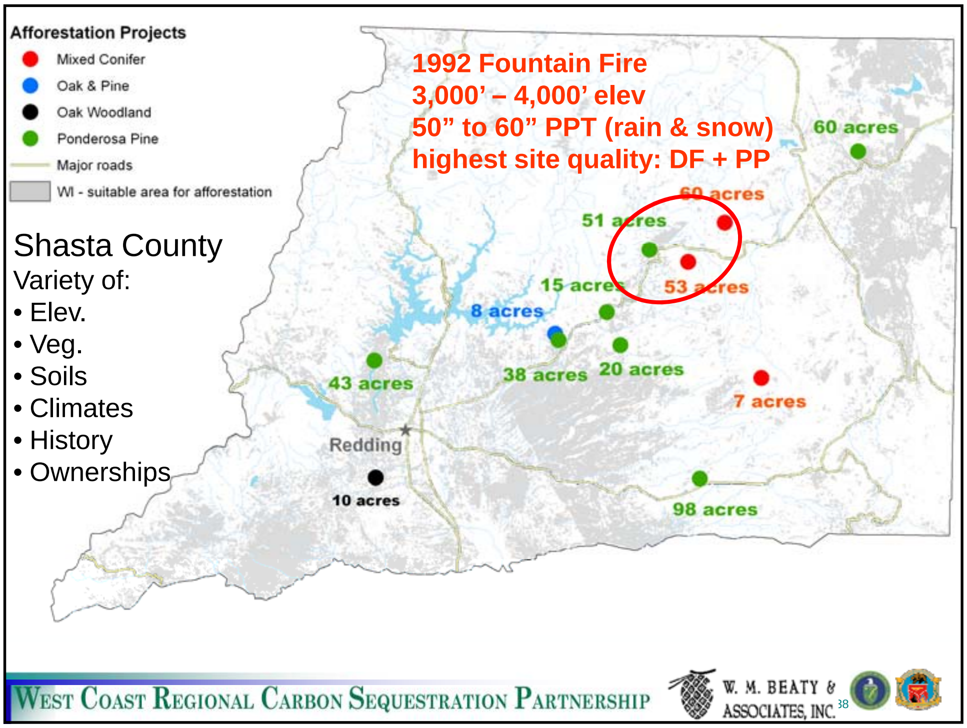


Site Prep 2008 & Plant Feb. 2009

Ponderosa Pine seedling one month after planting &
Just prior to weed control treatment

Ponderosa Pine seedling 6 months after planting

Ponderosa Pine seedlings 18 months after planting



Afforestation Projects

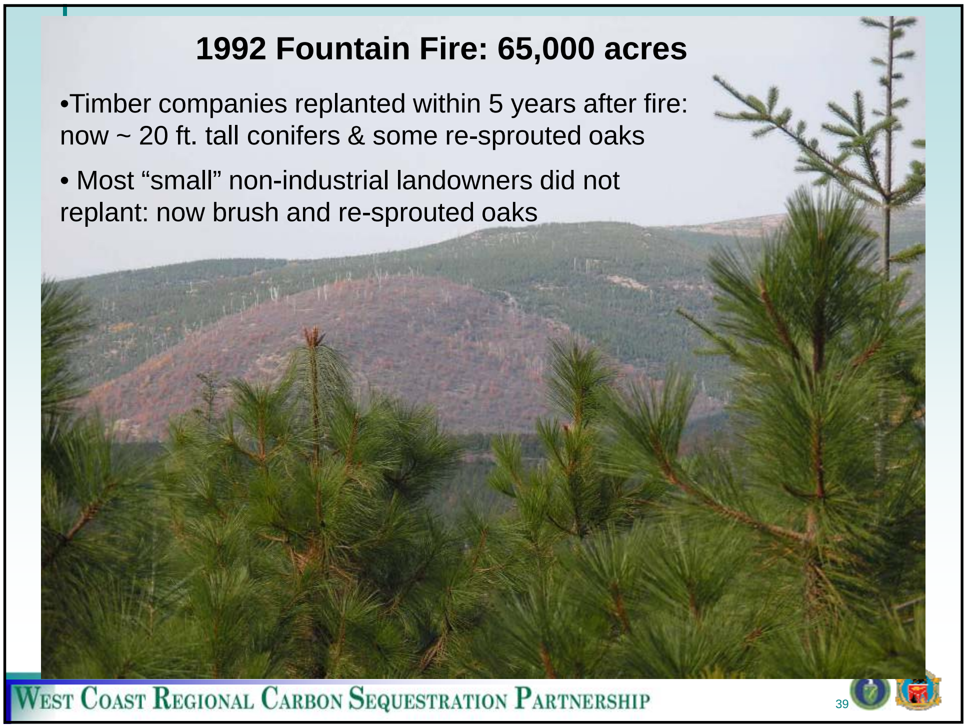
- 🔴 Mixed Conifer
- 🔵 Oak & Pine
- ⚫ Oak Woodland
- 🟢 Ponderosa Pine
- — Major roads
- ▨ WI - suitable area for afforestation

1992 Fountain Fire
3,000' – 4,000' elev
50" to 60" PPT (rain & snow)
highest site quality: DF + PP

Shasta County

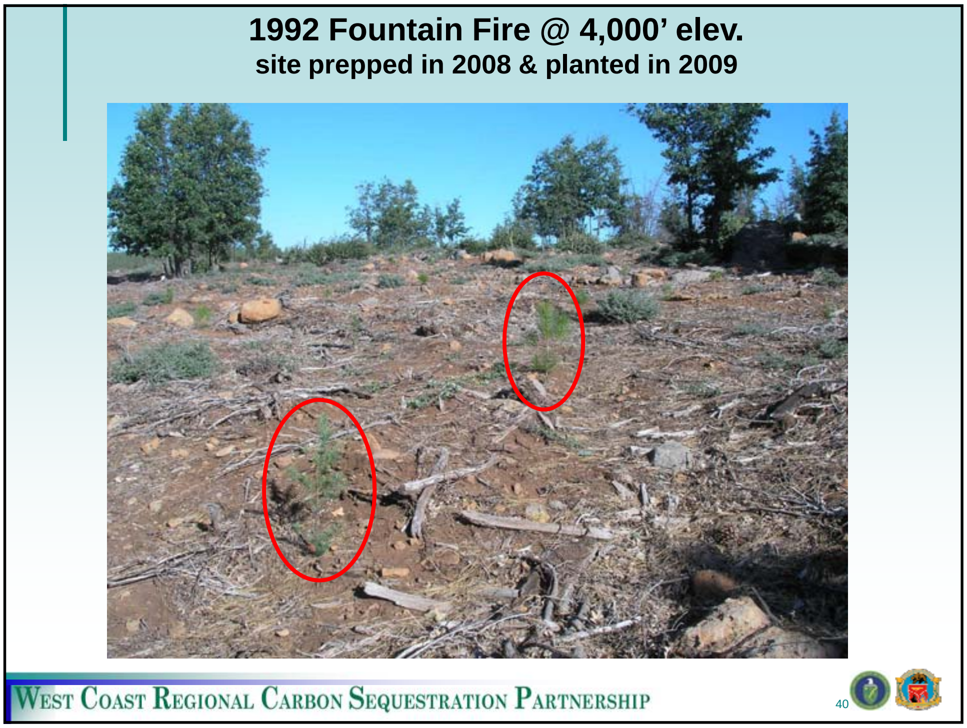
Variety of:

- Elev.
- Veg.
- Soils
- Climates
- History
- Ownerships



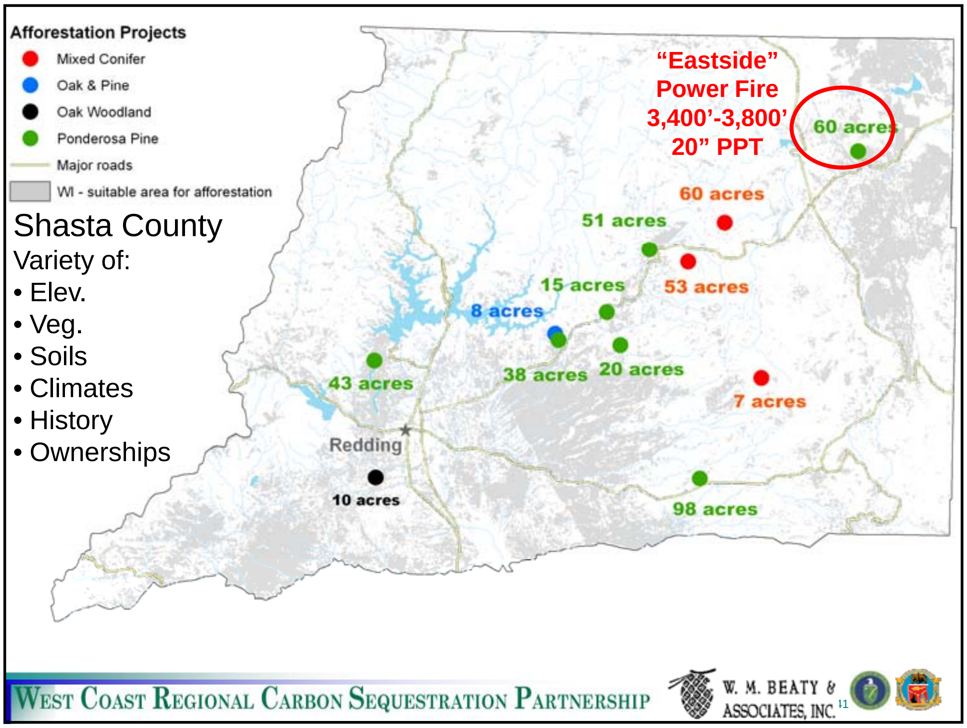
1992 Fountain Fire: 65,000 acres

- Timber companies replanted within 5 years after fire: now ~ 20 ft. tall conifers & some re-sprouted oaks
- Most “small” non-industrial landowners did not replant: now brush and re-sprouted oaks



1992 Fountain Fire @ 4,000’ elev.

site prepped in 2008 & planted in 2009



Afforestation Projects

- 🔴 Mixed Conifer
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- — Major roads
- ▨ WI - suitable area for afforestation

Shasta County

Variety of:

- Elev.
- Veg.
- Soils
- Climates
- History
- Ownerships

"Eastside" Power Fire
3,400'-3,800'
20" PPT

West Coast Regional Carbon Sequestration Partnership

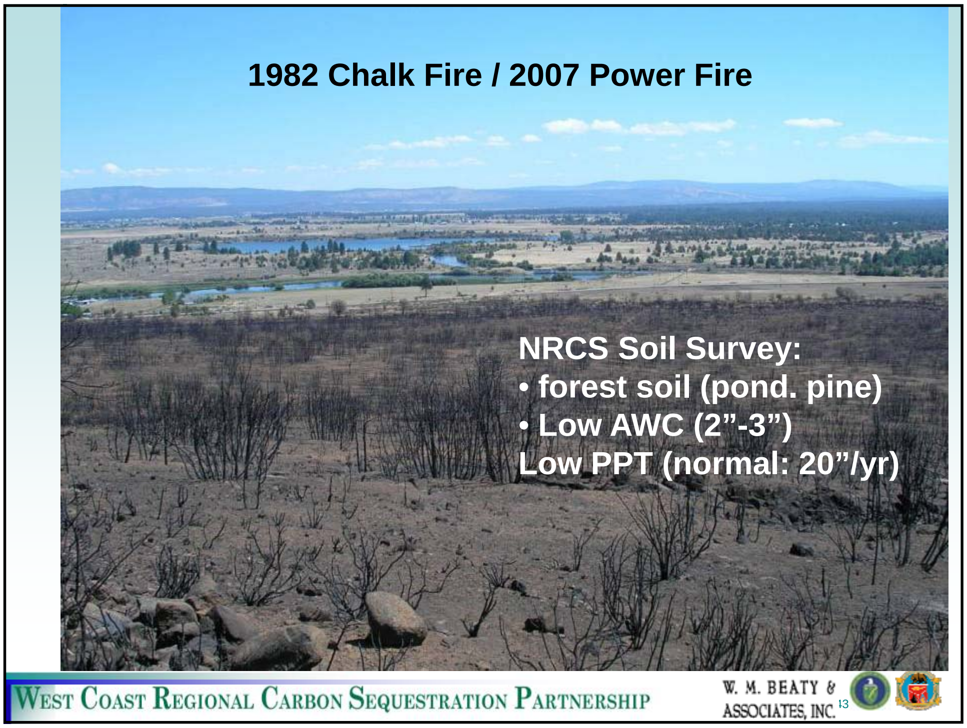
W. M. BEATY & ASSOCIATES, INC.

July 2007 *Power Wildfire*
NE Shasta County

Re-burned a portion of
1982 *Chalk Fire* area

West Coast Regional Carbon Sequestration Partnership

W. M. BEATY & ASSOCIATES, INC.

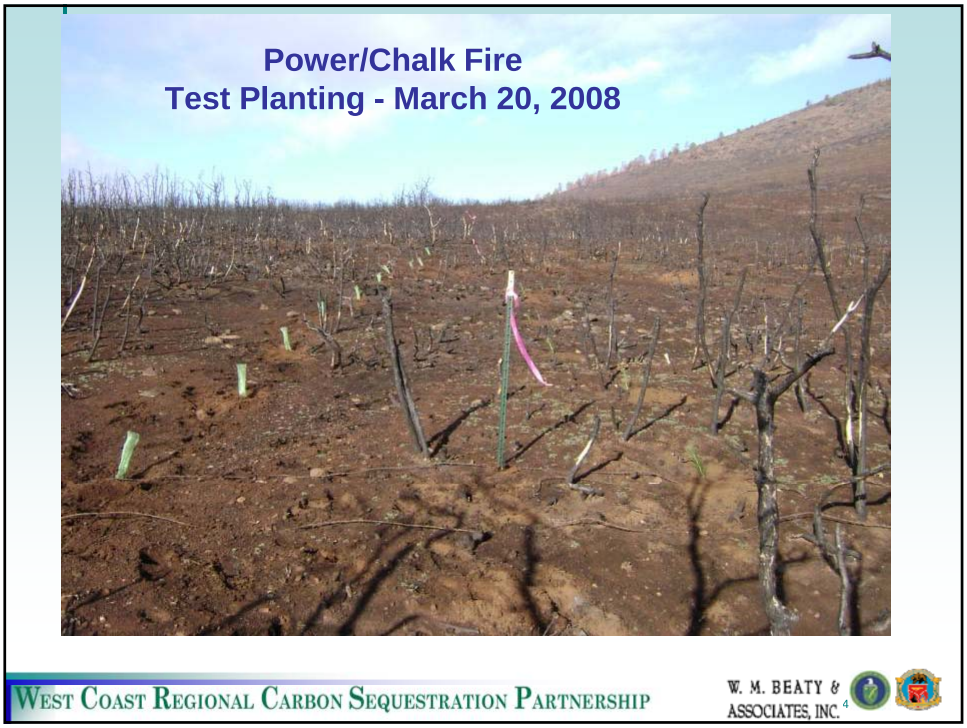


1982 Chalk Fire / 2007 Power Fire

NRCS Soil Survey:

- forest soil (pond. pine)
- Low AWC (2”-3”)

Low PPT (normal: 20”/yr)

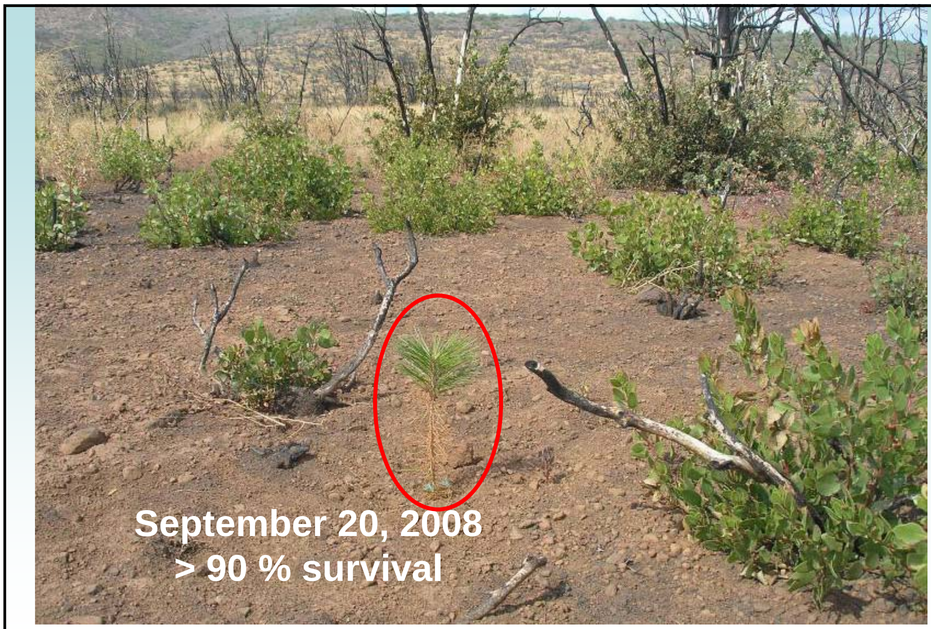


Power/Chalk Fire
Test Planting - March 20, 2008

2008 Planting - Climatic Conditions During 1st Year of Seedling Establishment

			Precip. Sept-June		**Precip. March-June**		
Project	Elev.	Date Planted	Normal	2007/08	Normal	2008	% of Normal
(Test - Power fire)	3,400’	**Mar. 20**	20.03”	13.89”	6.74”	**1.99”**	**29.5%**
	3,800’		19.85”	12.96”	6.67”	**1.59”**	**23.8%**

PPT Data from: PRISM Group, Oregon State University, http://www.prismclimate.org, created 23 Sep 2008

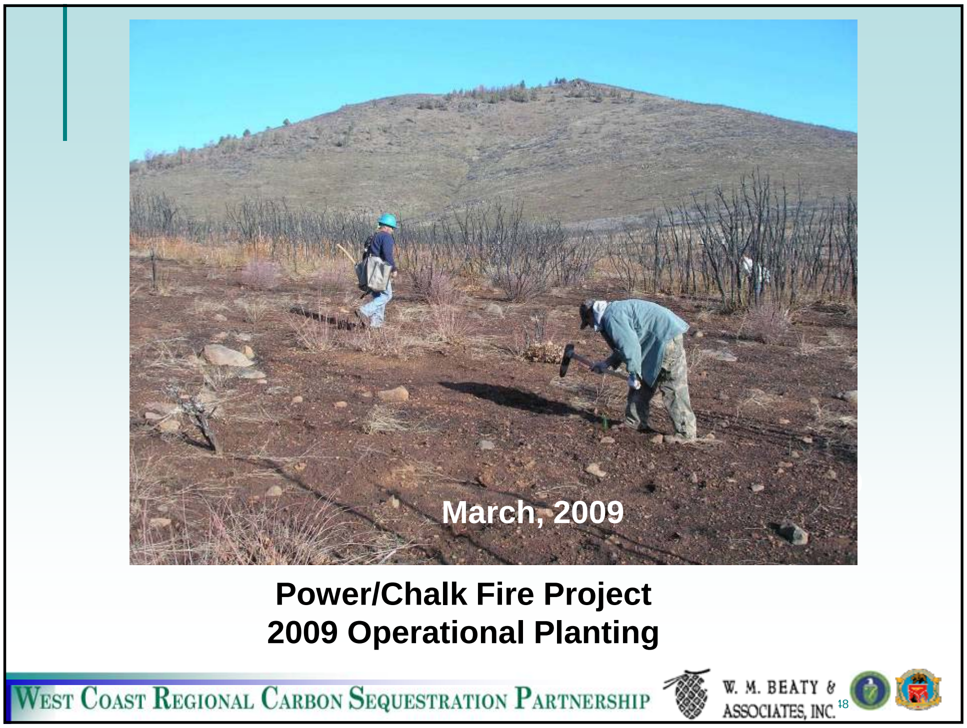


September 20, 2008
> 90 % survival

March 20, 2008 Test Planting

No mechanical site prep

Directed foliar spray on re-sprouting brush



March, 2009

Power/Chalk Fire Project
2009 Operational Planting

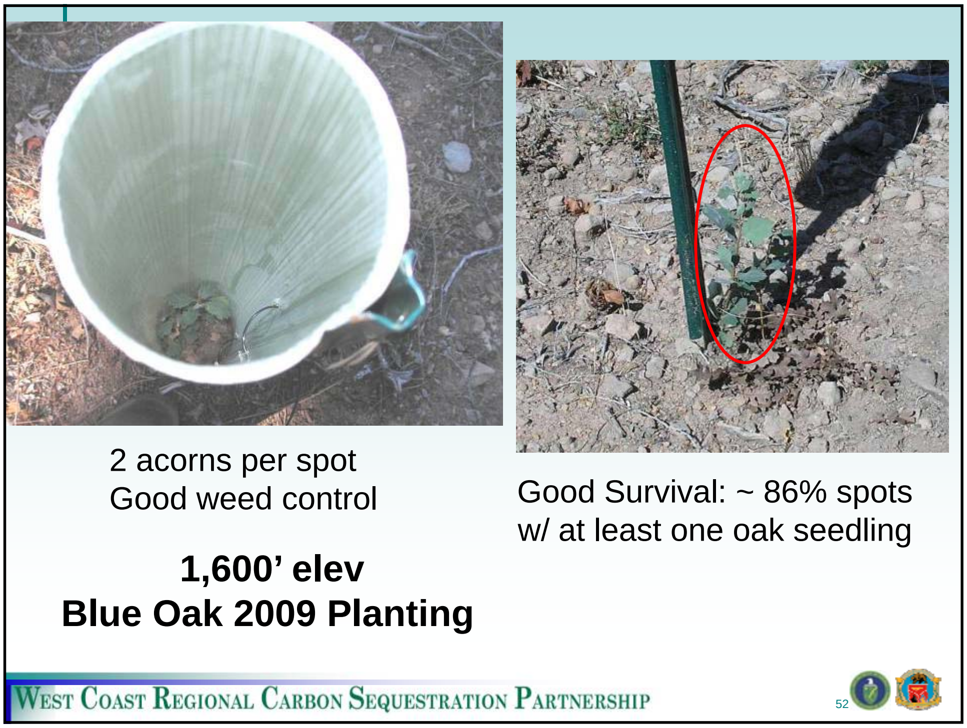
Power/Chalk Fire Project
Seedling in Sept (3 months after last rain)

BLM – Redding – 500’
Canyon Live Oak
.
Gravelly sandy loam
24” – 60” deep
Low/Mod AWC (3.6”-6.6”)

Poor weed control = poor survival (~ 5%)

Canyon Live Oak 2009 Planting (one acorn / spot)

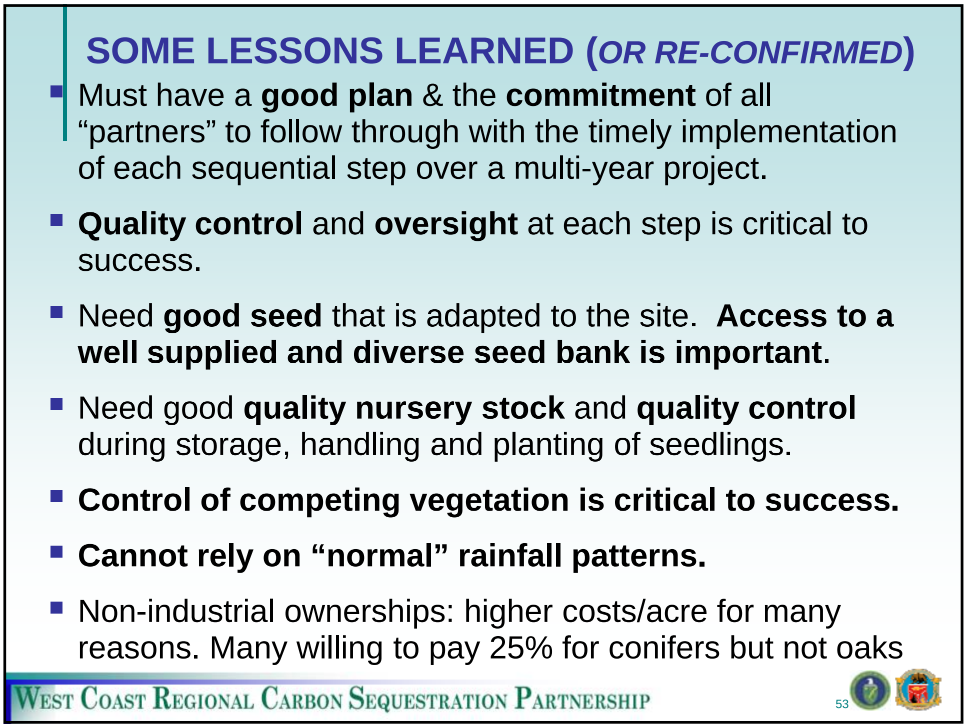
Survival ~ 5% (~ 40% no germ & ~ 55% seedling died during summer)



2 acorns per spot
Good weed control

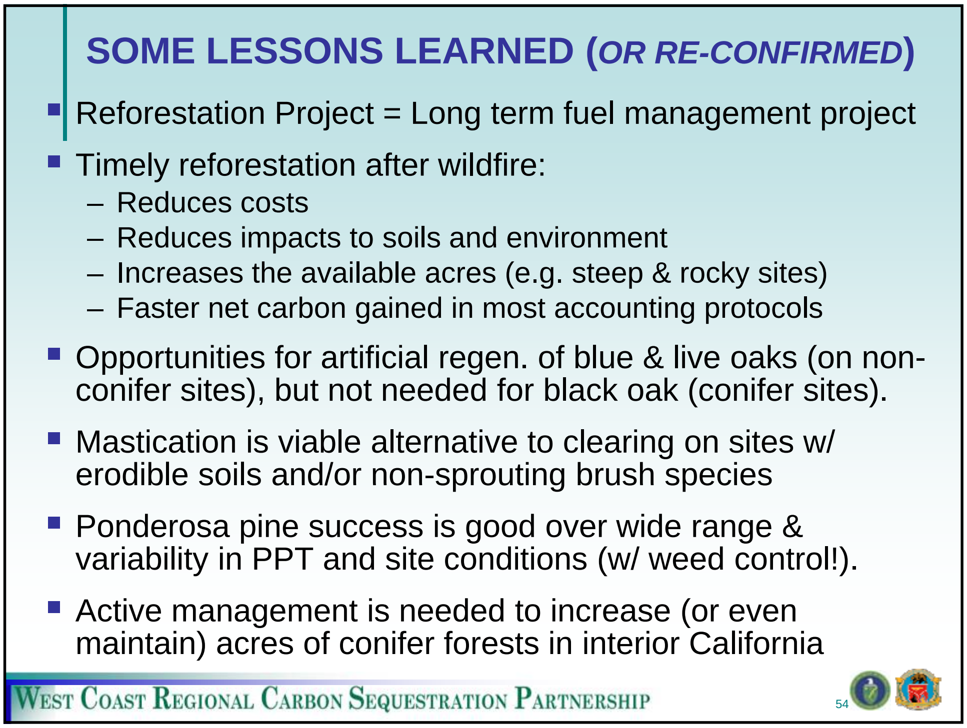
Good Survival: ~ 86% spots
w/ at least one oak seedling

1,600’ elev
Blue Oak 2009 Planting



SOME LESSONS LEARNED (*OR RE-CONFIRMED*)

- Must have a **good plan** & the **commitment** of all “partners” to follow through with the timely implementation of each sequential step over a multi-year project.
- **Quality control** and **oversight** at each step is critical to success.
- Need **good seed** that is adapted to the site. **Access to a well supplied and diverse seed bank is important**.
- Need good **quality nursery stock** and **quality control** during storage, handling and planting of seedlings.
- **Control of competing vegetation is critical to success.**
- **Cannot rely on “normal” rainfall patterns.**
- Non-industrial ownerships: higher costs/acre for many reasons. Many willing to pay 25% for conifers but not oaks



SOME LESSONS LEARNED (*OR RE-CONFIRMED*)

- Reforestation Project = Long term fuel management project
- Timely reforestation after wildfire:
  - Reduces costs
  - Reduces impacts to soils and environment
  - Increases the available acres (e.g. steep & rocky sites)
  - Faster net carbon gained in most accounting protocols
- Opportunities for artificial regen. of blue & live oaks (on non-conifer sites), but not needed for black oak (conifer sites).
- Mastication is viable alternative to clearing on sites w/ erodible soils and/or non-sprouting brush species
- Ponderosa pine success is good over wide range & variability in PPT and site conditions (w/ weed control!).
- Active management is needed to increase (or even maintain) acres of conifer forests in interior California

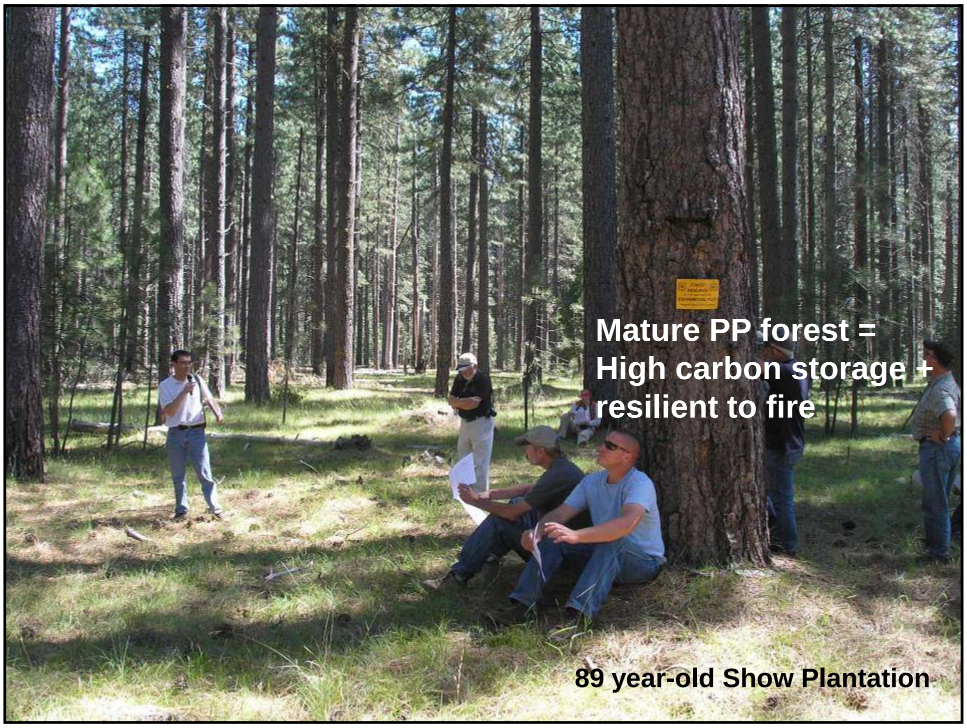
15 YEAR-OLD PLANTATION

Established after wildfire in Northeastern California

Both areas were planted after the same wildfire but:

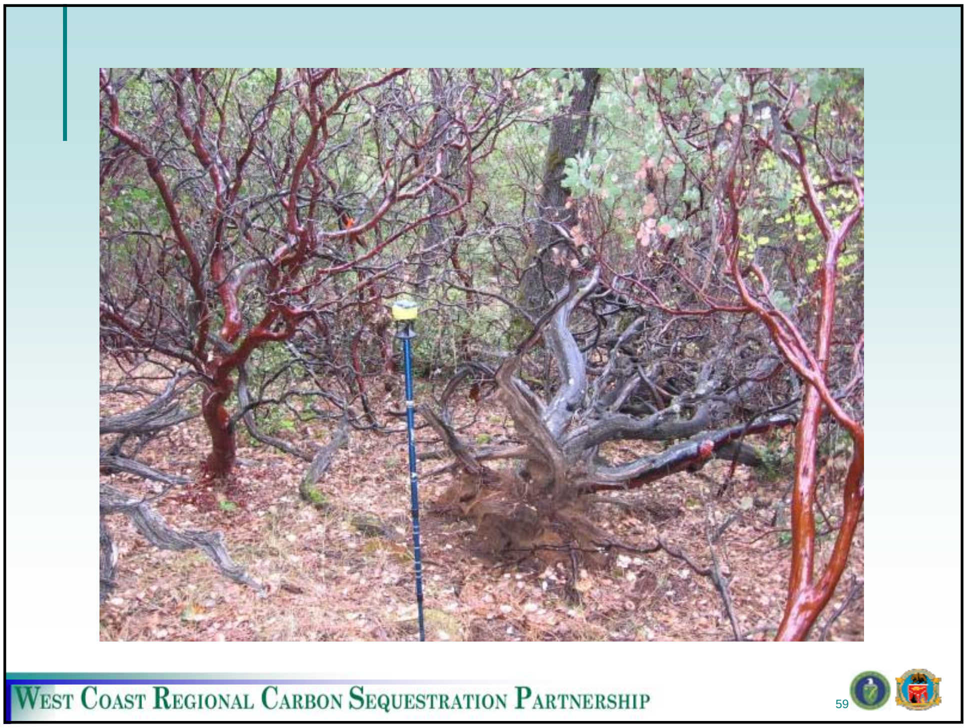
NO WEED CONTROL | **WEED CONTROL**

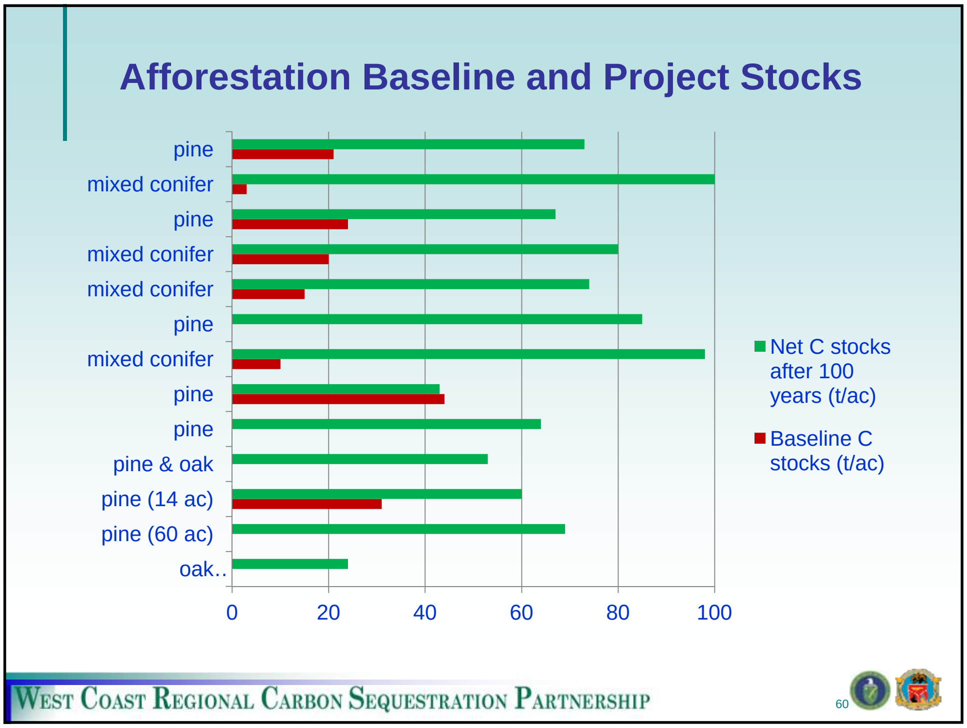
For the first 10 to 15 years both sites have equal amounts of total carbon, so there is a long wait to re-coup investment even though long term carbon/climate benefits are huge: Brush/burn/brush etc. cycle vs. Fire resilient forest w/ large trees



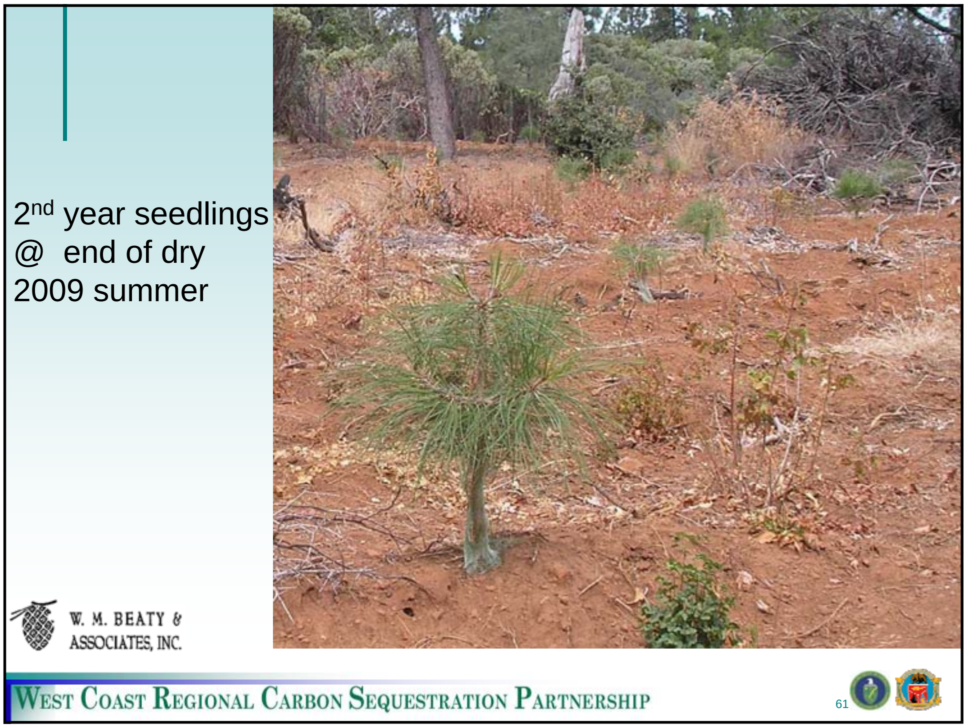
Mature PP forest = High carbon storage + resilient to fire

89 year-old Show Plantation



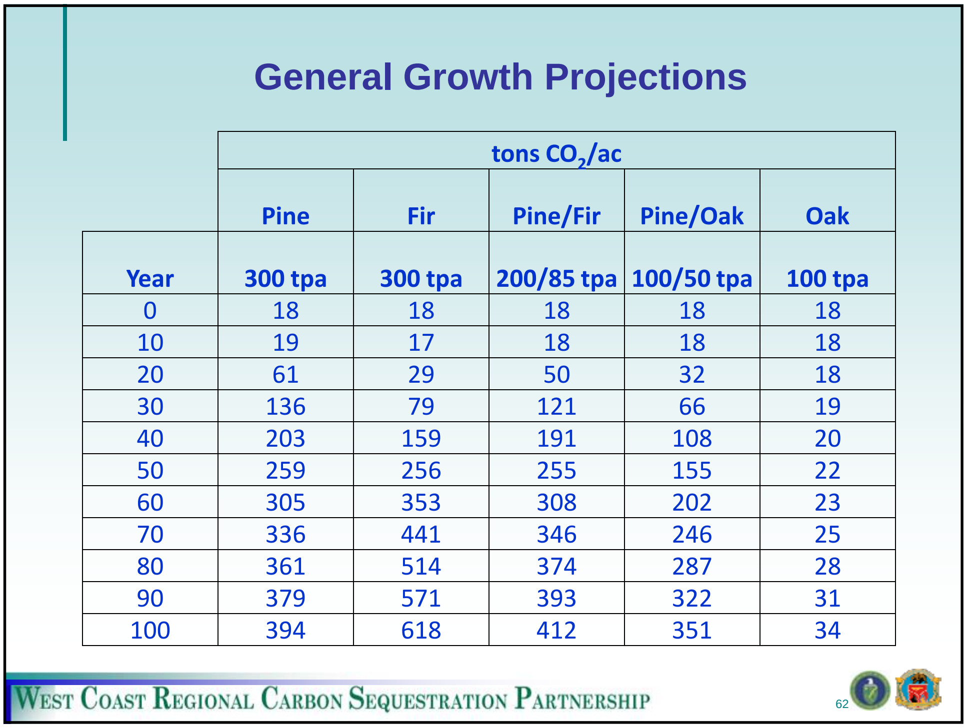


Afforestation Baseline and Project Stocks



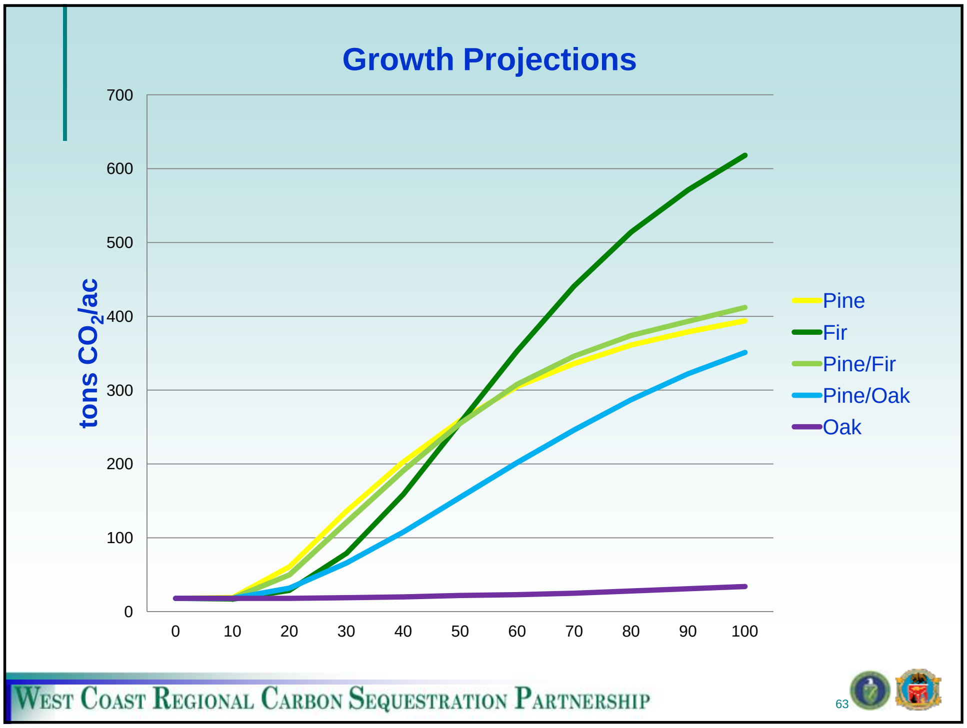
2nd year seedlings
@ end of dry
2009 summer

W. M. BEATY &
ASSOCIATES, INC.

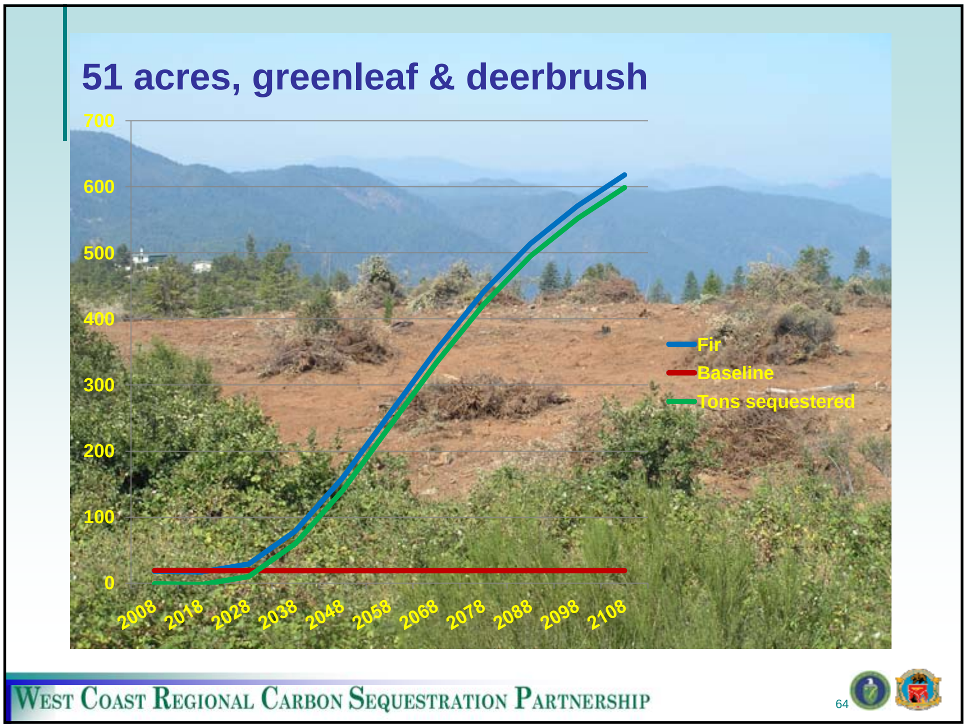


General Growth Projections

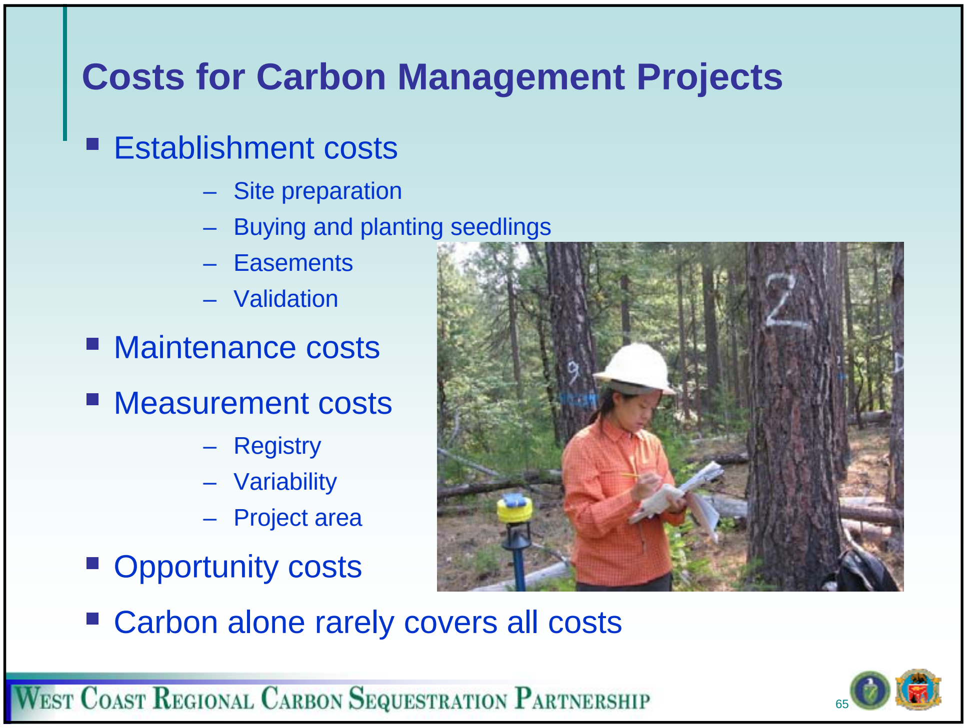
	tons CO_2/ac				
	Pine	Fir	Pine/Fir	Pine/Oak	Oak
Year	300 tpa	300 tpa	200/85 tpa	100/50 tpa	100 tpa
0	18	18	18	18	18
10	19	17	18	18	18
20	61	29	50	32	18
30	136	79	121	66	19
40	203	159	191	108	20
50	259	256	255	155	22
60	305	353	308	202	23
70	336	441	346	246	25
80	361	514	374	287	28
90	379	571	393	322	31
100	394	618	412	351	34



Growth Projections

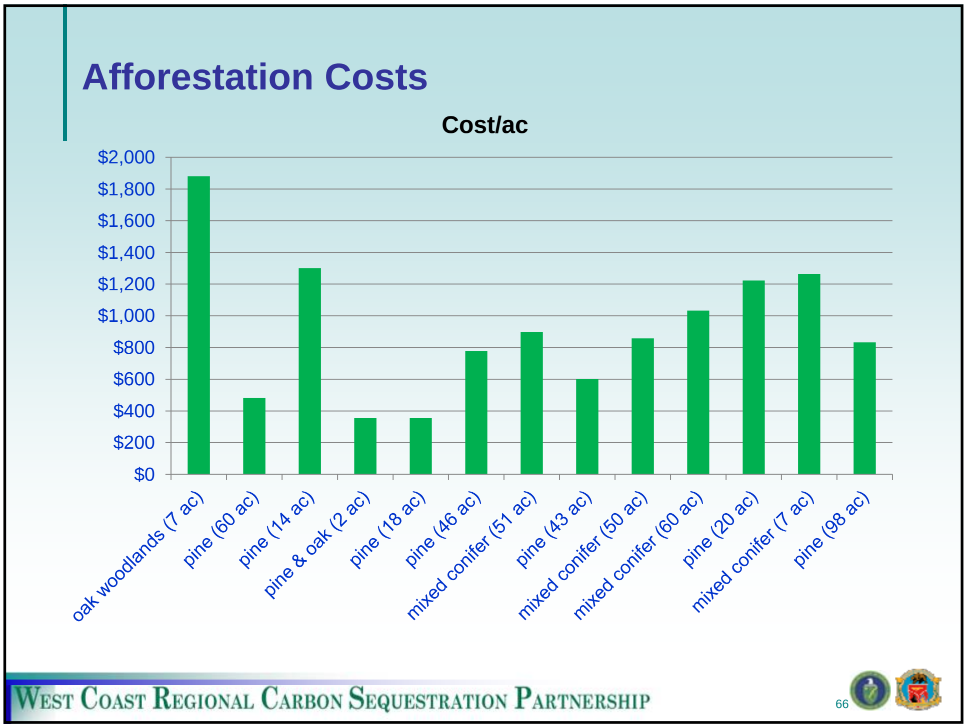


51 acres, greenleaf & deerbrush



Costs for Carbon Management Projects

- Establishment costs
  - Site preparation
  - Buying and planting seedlings
  - Easements
  - Validation
- Maintenance costs
- Measurement costs
  - Registry
  - Variability
  - Project area
- Opportunity costs
- Carbon alone rarely covers all costs

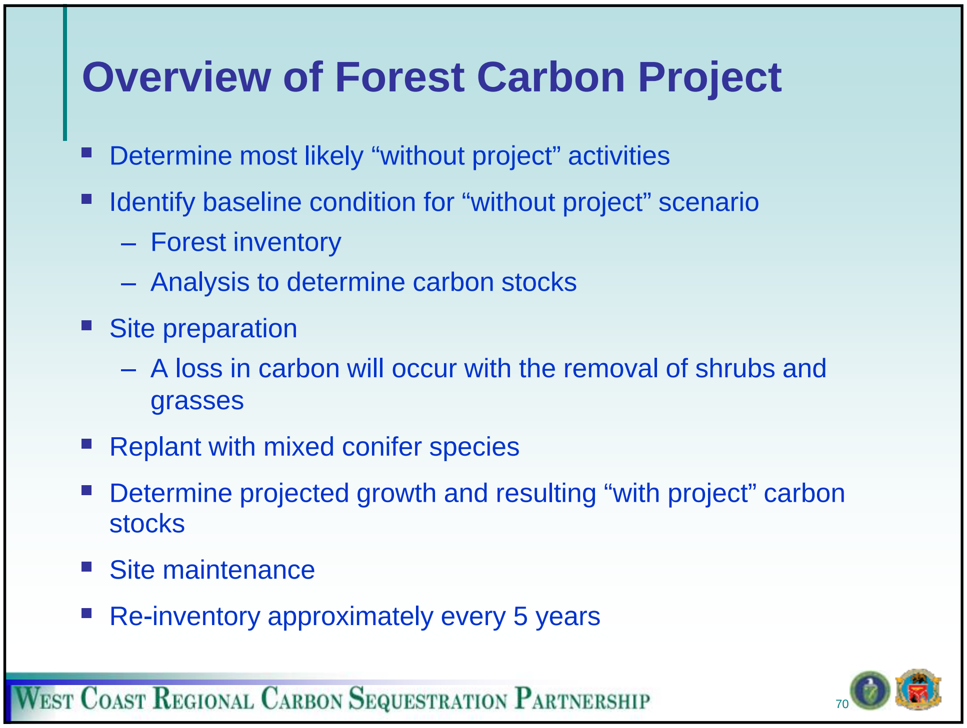


Afforestation Costs

14 acres, manzanita baseline,
$1,300/ac,
ponderosa pine planted

46 acres,
manzanita baseline, $778/ac,
Ponderosa pine planted

60 acres,
recent burn, $482/ac
Ponderosa pine
planted



Overview of Forest Carbon Project

- Determine most likely “without project” activities
- Identify baseline condition for “without project” scenario
  - Forest inventory
  - Analysis to determine carbon stocks
- Site preparation
  - A loss in carbon will occur with the removal of shrubs and grasses
- Replant with mixed conifer species
- Determine projected growth and resulting “with project” carbon stocks
- Site maintenance
- Re-inventory approximately every 5 years

Contact info

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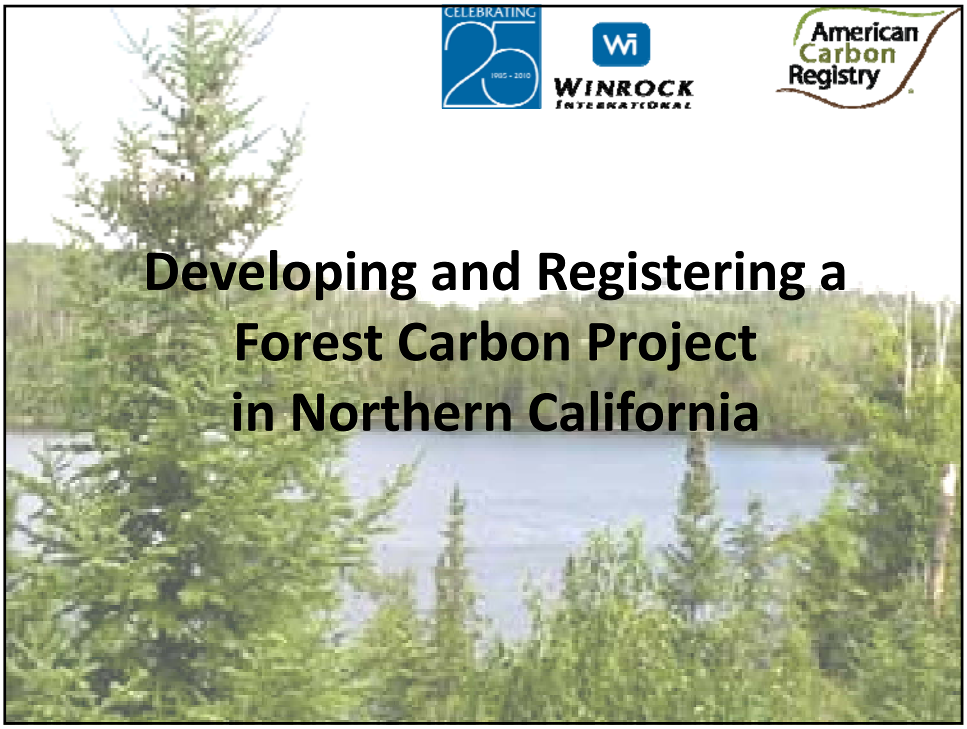
bobr@wmbeaty.com

Katie Goslee
Winrock International
kgoslee@winrock.org



Developing and Registering a Forest Carbon Project in Northern California

Outline

1. What is an offset?
    - Offset quality criteria
    - What does an offset “registry” do?
2. Developing and registering a forest carbon project
    - Focus on ACR and CAR
3. Legislative and market update

American Carbon Registry

What is an offset?

- Greenhouse gas emission reduction or removal used to compensate for emissions that occur elsewhere
- Project-based GHG reductions occurring in unregulated sectors, used by regulated entity for compliance
- Measured change vs. a baseline scenario
- Specific project type and vintage

American Carbon Registry

Voluntary and pre-compliance offsets

Voluntary
  - Value based on perceived quality
  - Buyers want “the story” behind the project
  - Marketing or reputational benefit
  - Regulatory approval not necessary
  - May not be verified, registered or retired
  - Variable quality

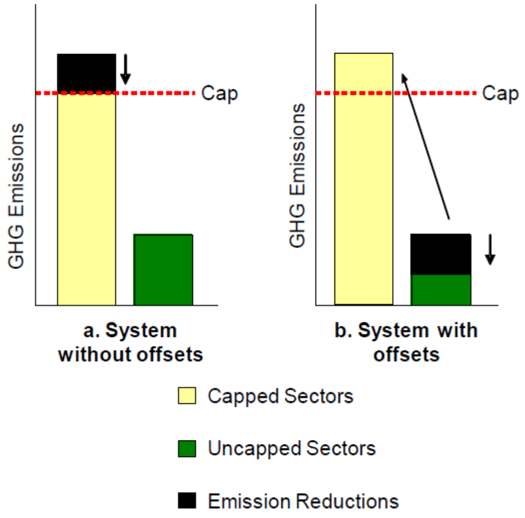
Pre-compliance
  - Value based on compliance recognition
  - Registered in approved early action program
  - Meet rigorous set of standards
  - Independently verified
  - Players want to gain experience, hedge against future requirements, help shape regulations

What is cap-and-trade?

Market-based mechanism to efficiently reduce emissions

- Government sets declining cap on emissions
- Program administrator (EPA, CARB) creates allowances and distributes via allocation or auction
- Each year capped entities must hold allowances = prior year emissions
- Compliance:
  - Reduce GHG emissions at covered facilities
  - Purchase allowances from other regulated entities
  - Purchase allowances from Government at auction
  - Purchase offsets

Offsets in cap-and-trade



American Carbon Registry

Offset quality criteria

Additional	Reductions are beyond regulations, beyond common practice, beyond business-as-usual
Real	After-the-fact, measurable GHG reductions
Permanent	Atmospheric benefit is permanent, or reversal risk is assessed and mitigated to make non-permanent offsets fungible with other offsets, on-system reductions and allowances
Net of leakage	Emission increases outside project boundary, due to project, are mitigated
Verified	Reductions are verified by an approved, accredited third party Rules complied with and GHG assertion is without material discrepancy
Serialized	Transparent accounting and tracking ensures same reduction used only once

American Carbon Registry

What does a registry do?

- Publish/approve standards, methodologies, tools
  - Public consultation and scientific peer review (ACR)
  - Stakeholder work groups (CAR)
- Act as gatekeeper on quality
  - Set standards and certify they have been met
  - Sellers know what is required, buyers have confidence offset is real/has compliance value, public has confidence in results
- Provide transparent serialized tracking of issuances, transactions, retirements
- Make project documentation publicly accessible
- Oversee third-party verification

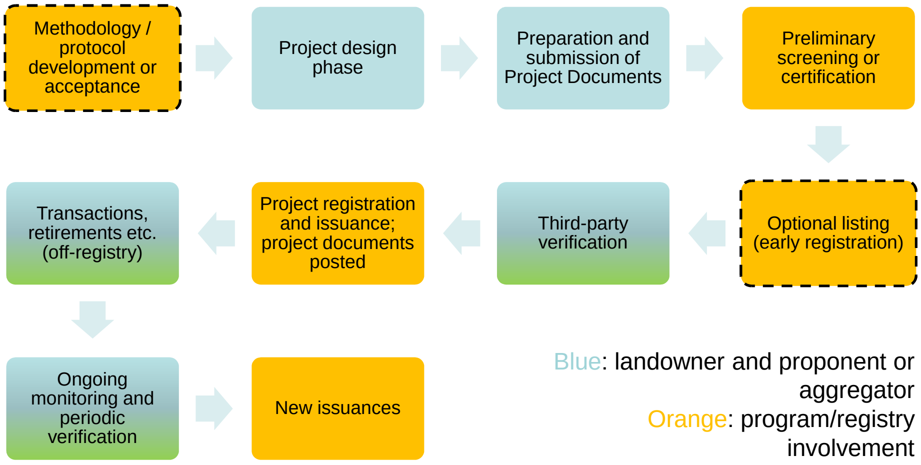
American Carbon Registry

- First U.S. private voluntary GHG registry
  - Founded 1997 by Environmental Defense Fund and Environmental Resources Trust
  - 30 million tons issued
- Pioneered system of transparent on-line reporting and serialization of verified project-based offsets – now the industry standard
- Joined Winrock International in 2007
  - Founded 1984 as a "public benefit corporation" under Arkansas state law

What does developing a forest carbon project mean to you?

- Steps in the process
- Key players and their roles
- Basics of ACR and CAR forest carbon protocols
- Eligible activities
- Additionality
- Permanence and risk mitigation
- Aggregation

Steps in the process



Methodology / protocol development or acceptance

Project design phase

Preparation and submission of Project Documents

Preliminary screening or certification

Optional listing (early registration)

Third-party verification

Project registration and issuance; project documents posted

Transactions, retirements etc. (off-registry)

Ongoing monitoring and periodic verification

New issuances

Blue: landowner and proponent or aggregator
Orange: program/registry involvement
Green: third-party involvement

Parties involved

Party	Basic roles
Landowner	•Title to lands; offset title until transferred to proponent or buyer •May be required to sign long-term agreement •May have monitoring, verification, risk mitigation obligation
Proponent	•Project design, interface with registry •Take offset title, incur costs, market offsets… many models •May have monitoring, verification, risk mitigation obligation
Aggregator	•Aggregate landowners to spread transaction costs and diversify risk •Educational and organizational role
RPF	•Project design assistance
Offset program or registry	•Publish/approve protocols •Gatekeeper on quality •Transparent serialized tracking •Oversee verification
Verifier	•Third-party auditing against requirements of program •Opinion on whether GHG assertion is without material discrepancy
Offset buyer	•Entity purchasing and using offsets for voluntary, pre-compliance, or speculative purposes

American Carbon Registry

Basics: ACR and CAR

	ACR	CAR
Scope	Worldwide	United States Mexico, Canada in future
Land ownerships	Private, all public, Tribal	Private and public (non-federal) for reforestation and IFM; private for avoided conversion
Eligible activities	•Afforestation/Reforestation •Improved Forest Management •Reducing Emissions from Deforestation (Avoided Conversion)	•Reforestation •Improved Forest Management •Avoided Conversion •Urban Forestry
Minimum term	40 years from start date	100 years after last credits issued
Risk mitigation	Buffer contribution (any ERTs) Insurance and other financial options	Buffer reserve

American Carbon Registry

Basics: ACR and CAR

	ACR	CAR
Agreement with	Proponent	Landowner
Additionality	"Three-prong test" or performance standard	Performance standard approach Automatic for reforestation Based on baseline stocks for IFM
Crediting period (baseline validity)	20 years for A/R and most IFM	100 years
Other requirements		Sustainable harvesting, "natural forest management," age classes, max. 40-acre clearcuts…
Verification	By independent third-party verifiers accredited by ANSI for relevant sectoral scope	

American Carbon Registry

Afforestation/Reforestation

- Establishing, increasing and restoring vegetative cover through the planting, sowing or human-assisted natural regeneration of woody vegetation
- Targets eventual establishment of forest
- Carried out on marginal agricultural or rangelands, brush fields, buffer areas, windbreaks, etc.
- Not cleared of forest in last 10 years solely to implement A/R project
  - Exceptions for fire, natural disturbance, brush removal for site preparation

American Carbon Registry

Improved Forest Management

- Activities to reduce GHG emissions and/or enhance GHG removals, implemented on lands designated, sanctioned or approved for forest management
  - Extending rotation lengths in managed forest
  - Increasing forest productivity by thinning diseased or suppressed trees
  - Managing competing brush and short-lived forest species
  - Increasing buffers or other set-asides
  - Increasing the stocking of trees on understocked areas
  - Increasing carbon stocks in harvested wood products
  - Improving harvest or production efficiency
  - Shifting from shorter- to longer-term wood products

Additionality

- GHG reductions and removals exceed those that would have occurred under current forestry laws and regulations, current forest industry practices, and under a business-as-usual scenario
  - Regulatory surplus and exceeds performance standard
  - Three-prong test:
    - Regulatory surplus
    - Exceeds common practice for area, forest type, similar landowners
    - Faces at least one implementation barrier: financial, technological, institutional

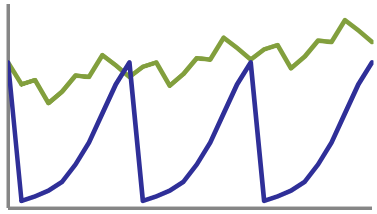
Baselines and additionality

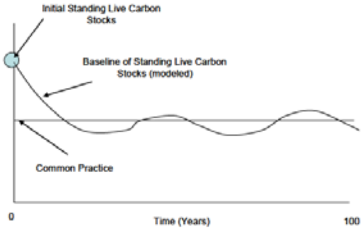
Project-specific

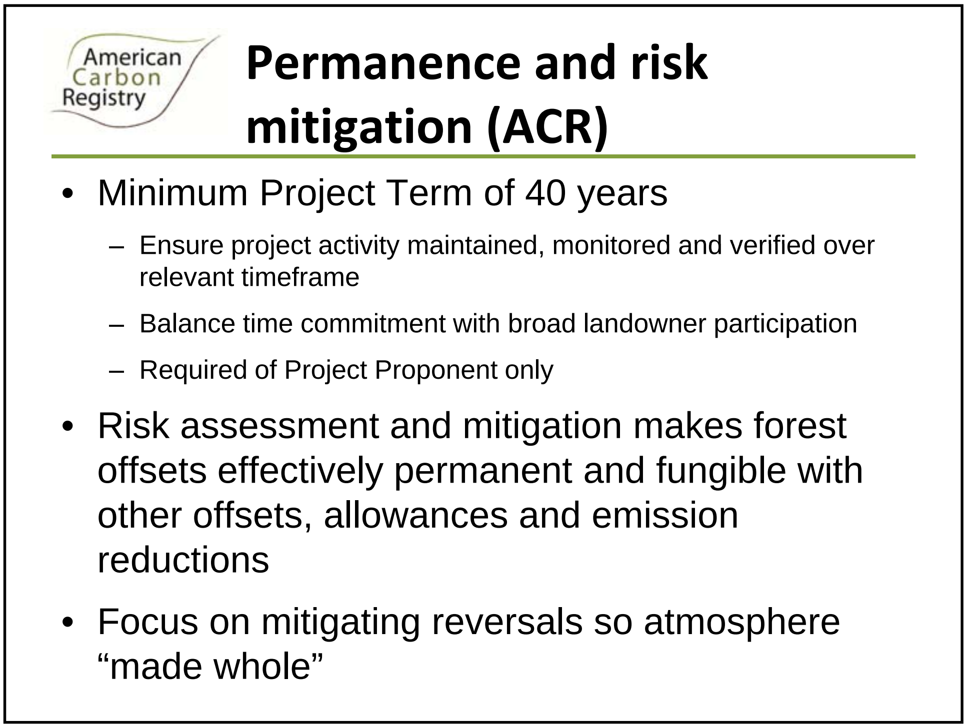
- More subjective, open to gaming
- Less efficient project approval process
- Rigorous tools available
- Less danger of over-crediting

Performance standard

- Less subjective
- Efficient to apply
- Heavy up-front data requirements
- Potential for over-crediting without under-crediting to balance

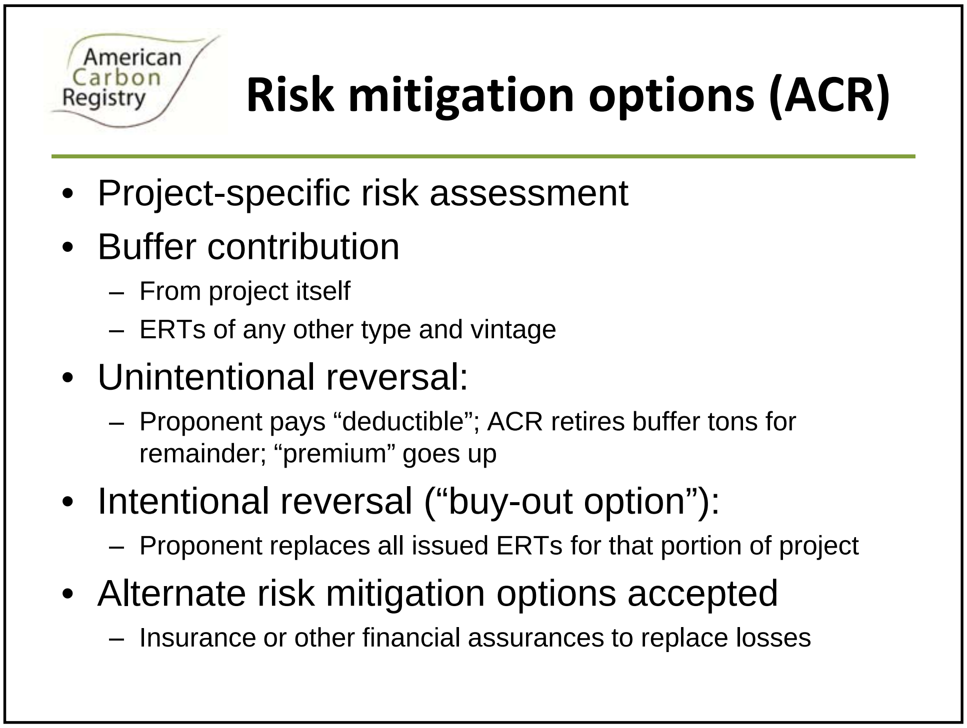






Permanence and risk mitigation (ACR)

- Minimum Project Term of 40 years
  - Ensure project activity maintained, monitored and verified over relevant timeframe
  - Balance time commitment with broad landowner participation
  - Required of Project Proponent only
- Risk assessment and mitigation makes forest offsets effectively permanent and fungible with other offsets, allowances and emission reductions
- Focus on mitigating reversals so atmosphere “made whole”



Risk mitigation options (ACR)

- Project-specific risk assessment
- Buffer contribution
  - From project itself
  - ERTs of any other type and vintage
- Unintentional reversal:
  - Proponent pays “deductible”; ACR retires buffer tons for remainder; “premium” goes up
- Intentional reversal (“buy-out option”):
  - Proponent replaces all issued ERTs for that portion of project
- Alternate risk mitigation options accepted
  - Insurance or other financial assurances to replace losses

Permanence and risk mitigation (CAR)

- PIA obligation of 100 years after last credits
  - Project monitoring, verification, reversal liability, harvest guidelines and “natural forest management”
  - Required of landowner (and successors, heirs, assigns, and new owners)
  - Superior to all other claims unless additional buffer contribution made
- Buffer CRTs canceled in event of reversals
  - Avoidable vs. unavoidable reversals
  - >1:1 penalty for any avoidable reversal before 50 yrs
- Focus on monitoring carbon stocks on site

Aggregation guidance (ACR)

- Key for transaction cost efficiencies (inventory, monitoring, verification) and risk diversification
- Agreement is still with Proponent (here aggregator)
  - Proponent commits to reversal risk mitigation, including exit of participating landowners
- For inventory and monitoring, precision targets applied at overall project level
  - ±10% of the mean at 90% confidence
  - Use stratification; does not require plots on every landholding
- Verification (reasonable assurance; ±5% materiality) also at project level
  - Risk-based approach and not all properties necessarily visited

Aggregation guidelines (CAR)

- “Aggregate” capped at 5,000 acres, 2 or more Forest Owners
- Each Forest Owner still has own PIA, liability for reversals, CAR account, baseline inventory, annual reports, etc.
- Aggregator provides services; *may* act as agent in transactions
- Goals:
  - Fewer plots to achieve ±5% at 90% confidence sampling error
  - Only half of properties verified each 6-year interval
- Constraints on leaving aggregate

Legislative and regulatory landscape

- No U.S. federal climate legislation
  - Scaling back from economy-wide cap-and-trade, to power sector cap-and-trade, to RES, to offshore oil etc., to nothing
  - Bills generally friendly to offsets, recognize cost containment and political value… but no bill
- EPA proceeds with regulation under Clean Air Act
  - Endangerment finding, mobile sources, stationary sources
  - Offsets and other market mechanisms unclear

American Carbon Registry

Eligible offset types (Stabenow and Kerry-Lieberman)

- Projects that reduce, flare or use methane:
  - Methane from mines, landfills, natural gas
  - Reduce fugitive emissions in oil & gas sector
  - Manure management, anaerobic digestion, waste aeration
- Projects that reduce CO_2 emissions or increase sequestration in agriculture, livestock, forestry, land use:
  - Afforestation/reforestation, improved forest management, reduced deforestation, urban forestry
  - Agricultural, grassland, and rangeland sequestration and management
  - Avoided conversion of grassland/rangeland/forest
  - Management/restoration of peatlands and wetlands
  - Conservation of marine coastal habitats
  - N_2O emission reduction (fertilizer production and/or use)
  - Biochar production and use
- Recycling and waste minimization
- Carbon Capture & Storage (with or without enhanced oil recovery)
- Destruction of ozone-depleting substances
- Small off-grid renewable electricity
- Projects reducing the GHG intensity of agricultural production

American Carbon Registry

"Qualified Early Offset Programs"

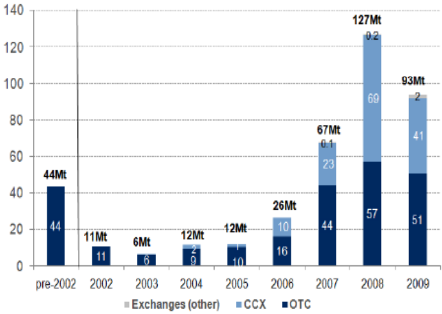
- Established before January 1, 2009
- Offset standards/methodologies/protocols must:
  - Be developed through public consultation or peer review
  - Require offsets be measurable, additional, verifiable, enforceable, permanent
  - Be made available to the public
- Require verification by accredited verifier
- Publicly accessible registry, serialized tons
- Financial assurance requirements
- No program involvement in project development

Legislative and regulatory landscape

- Focus shifts (back) to states and regional programs
- California AB32 cap-and-trade rule by end 2010
  - Proposition 23
- WCI released final cap-and-trade design
  - Not all original members participating
- Offsets seen as key
  - No clarity yet on which protocols will be recognized
  - Forestry a safe bet

Market landscape

- Marked decline in transaction volumes and prices
  - Voluntary activity down
  - Pre-compliance demand awaiting more clarity
  - U.S. carbon market players temporarily close U.S. desks
  - Scandals in CDM market
  - Uncertainty in post-Kyoto negotiations



Still… forest carbon remains a relatively safe bet

- Protocols are well established
- Generally cost-effective → offsets at an attractive cost per ton
  - Large potential supply
  - Attractive to both voluntary and pre-compliance buyers
- State and regional programs likely to recognize
  - Key to register on an established program
  - ACR, CAR, possibly VCS, possibly others
- Has become central to federal discussions

➢ Project development timeframe may be a year, more or less… pays to start now

Further Information

Nicholas Martin
Chief Technical Officer, American Carbon Registry

nmartin@winrock.org
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(703) 842-9500

American Carbon Registry

Protocol development: ACR and CAR

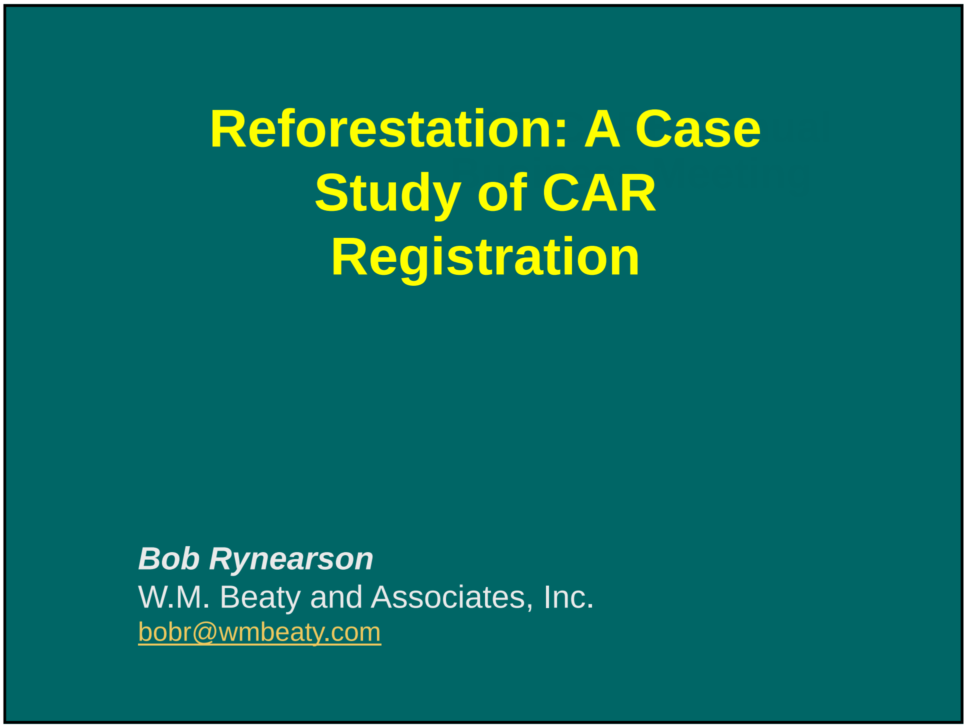
	ACR	CAR
Established	1997 (Merged with Winrock 2007)	2008 (CCAR established 2001)
Protocol development process	•Both external (bottom up) and internal •Public consultation •Scientific peer review •Final approval and publication	•Top-down only •Protocol scoping •Multi-stakeholder workgroup •Public comment •Board adoption
	•Transparently developed, regulatory-quality protocols meeting criteria of federal legislation **•State and regional approvals in process**	

American Carbon Registry

Protocols (existing and in progress)

ACR	CAR

•Forestry
  •AR
  •IFM
  •REDD
•N_2O from fertilizer
•Livestock methane
•Landfill methane
•Fugitive methane in oil & gas sector
•Improved grazing land management
•Wetland restoration and avoided loss
	•Forestry
	  •Reforestation
	  •IFM
	  •Avoided conversion
	•Urban forestry
	•Landfill methane
	•Livestock methane
	•Coal mine methane
	•Organic waste digestion
	•Ozone-depleting substances
	•Agriculture sector protocols under consideration



Reforestation: A Case Study of CAR Registration

Bob Rynearson
W.M. Beaty and Associates, Inc.
bobr@wmbeaty.com

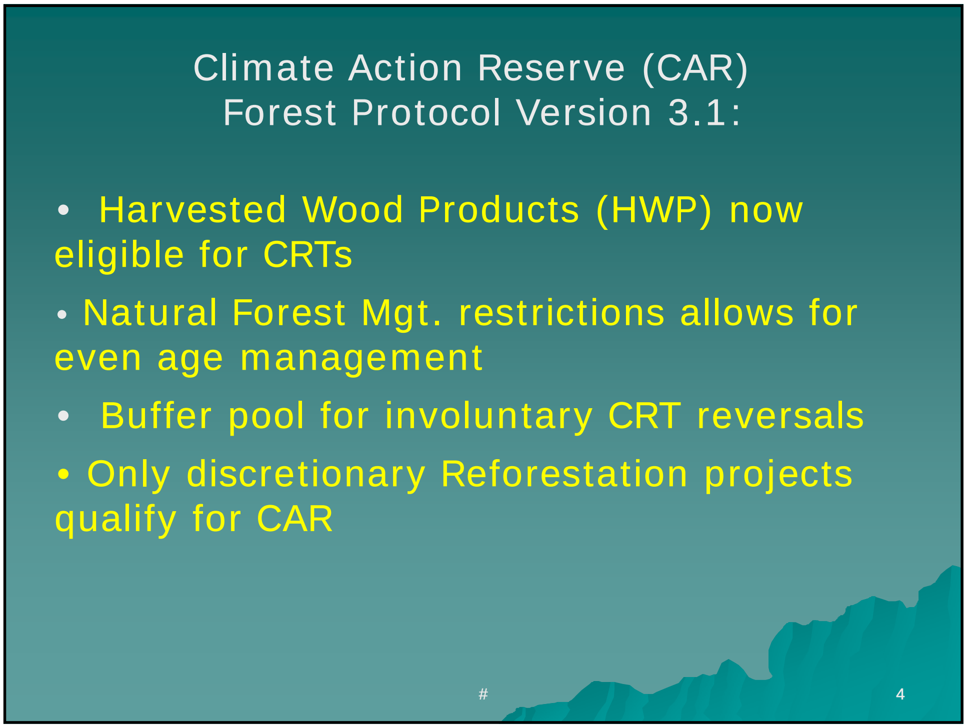
W.M. Beaty & Associates, Inc. Climate Action Registry (CAR) Reforestation Projects

- 4 Reforestation Projects totaling 16,470 acres
- sizes: 191 acres to 11,637 acres
- 191 acres reforestation after clearing old brushfield
- 16,279 acres reforestation after wildfire
- Very early stages of registration w/ CAR
- Also exploring other registries e.g. ACR
- Maybe a 5th project for a 2008 wildfire on > 2,100 acres?

Climate Action Reserve (CAR)
Forest Protocol Version 3.1

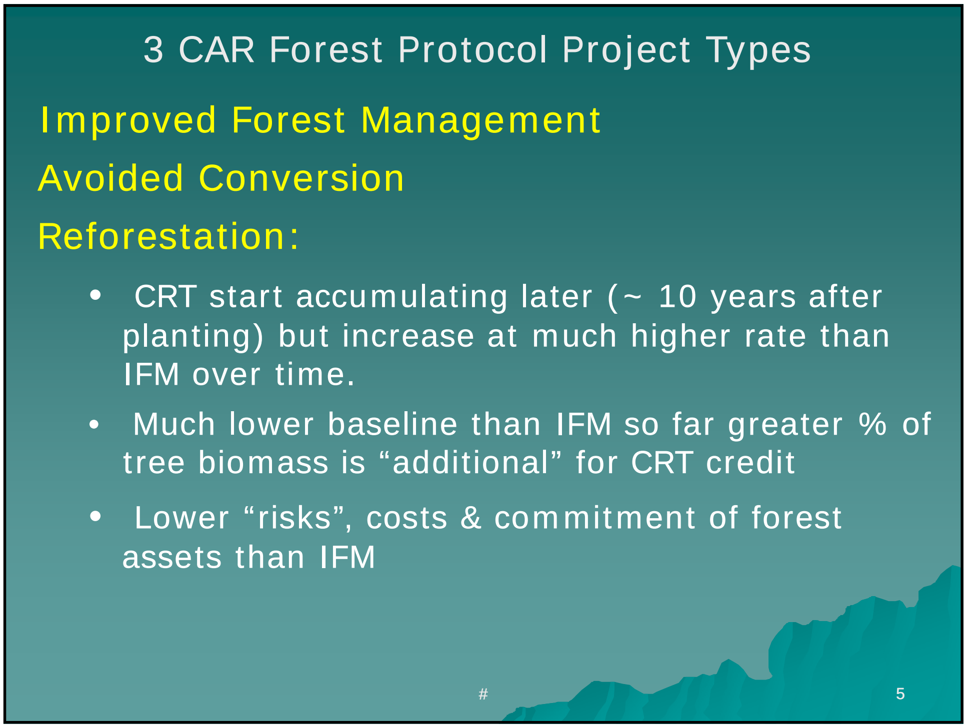
www.climateactionreserve.org

- Conservation Easement not required.
However, requires a 100 Yr PIA
- 1:1 buy out to terminate Reforestation PIA
- Reforestation Project no longer required to be unstocked for 10 years
- For Reforestation Projects: verification can be postponed until Climate Reserve Tonnes (CRTs) are registered



Climate Action Reserve (CAR)
Forest Protocol Version 3.1:

- Harvested Wood Products (HWP) now eligible for CRTs
- Natural Forest Mgt. restrictions allows for even age management
- Buffer pool for involuntary CRT reversals
- Only discretionary Reforestation projects qualify for CAR



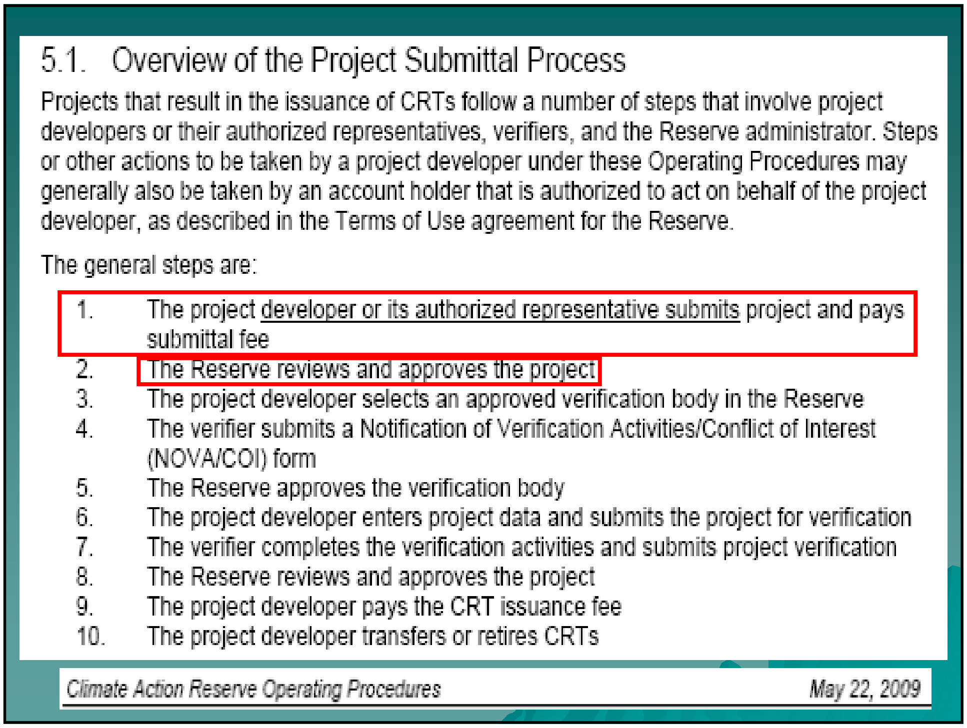
3 CAR Forest Protocol Project Types

Improved Forest Management

Avoided Conversion

Reforestation:

- CRT start accumulating later (~ 10 years after planting) but increase at much higher rate than IFM over time.
- Much lower baseline than IFM so far greater % of tree biomass is “additional” for CRT credit
- Lower “risks”, costs & commitment of forest assets than IFM

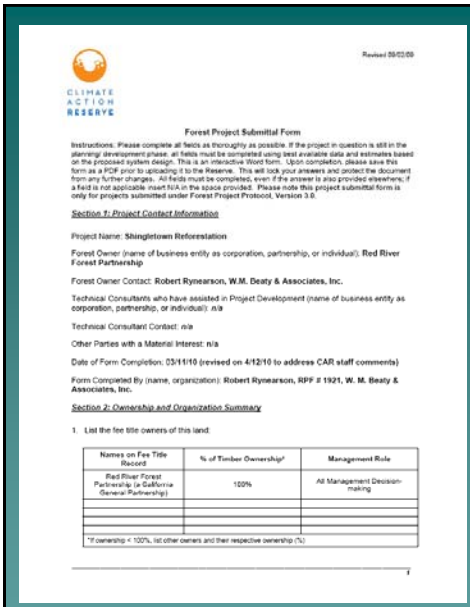


5.1. Overview of the Project Submittal Process

Projects that result in the issuance of CRTs follow a number of steps that involve project developers or their authorized representatives, verifiers, and the Reserve administrator. Steps or other actions to be taken by a project developer under these Operating Procedures may generally also be taken by an account holder that is authorized to act on behalf of the project developer, as described in the Terms of Use agreement for the Reserve.

The general steps are:

1. The project developer or its authorized representative submits project and pays submittal fee
2. The Reserve reviews and approves the project
3. The project developer selects an approved verification body in the Reserve
4. The verifier submits a Notification of Verification Activities/Conflict of Interest (NOVA/COI) form
5. The Reserve approves the verification body
6. The project developer enters project data and submits the project for verification
7. The verifier completes the verification activities and submits project verification
8. The Reserve reviews and approves the project
9. The project developer pays the CRT issuance fee
10. The project developer transfers or retires CRTs



Revised 09/03/09

CLIMATE
ACTION
RESERVE

Forest Project Submittal Form

Instructions: Please complete all fields as thoroughly as possible. If the project in question is still in the planning/ development phase, all fields must be completed using best available data and estimates based on the proposed system design. This is an interactive Word form. Upon completion, please save this form as a PDF prior to uploading it to the Reserve. This will lock your answers and protect the document from any further changes. All fields must be completed, even if the answer is also provided elsewhere; if a field is not applicable insert N/A in the space provided. Please note this project submittal form is only for projects submitted under Forest Project Protocol, Version 3.0.

Section 1: Project Contact Information

Project Name: **Shingletown Reforestation**

Forest Owner (name of business entity as corporation, partnership, or individual): **Red River Forest Partnership**

Forest Owner Contact: **Robert Rynearson, W.M. Beaty & Associates, Inc.**

Technical Consultants who have assisted in Project Development (name of business entity as corporation, partnership, or individual): *n/a*

Technical Consultant Contact: *n/a*

Other Parties with a Material Interest: **n/a**

Date of Form Completion: 03/11/10 **(revised on 4/12/10 to address CAR staff comments)**

Form Completed By (name, organization): **Robert Rynearson, RPF # 1921, W. M. Beaty & Associates, Inc.**

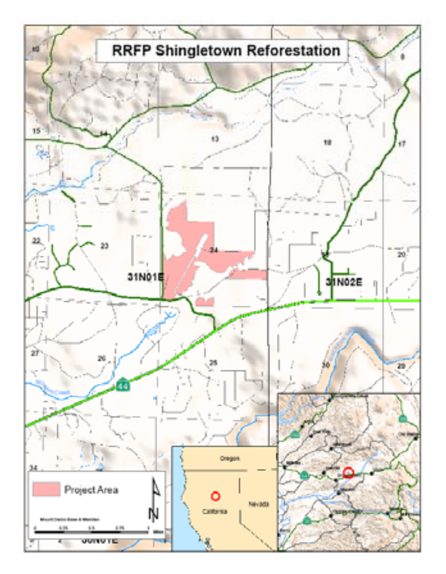
Section 2: Ownership and Organization Summary

1. List the fee title owners of this land:

Names on Fee Title Record	% of Timber Ownership*	Management Role
Red River Forest Partnership (a California General Partnership)	100%	All Management Decision-making

*If ownership < 100%, list other owners and their respective ownership (%)

1

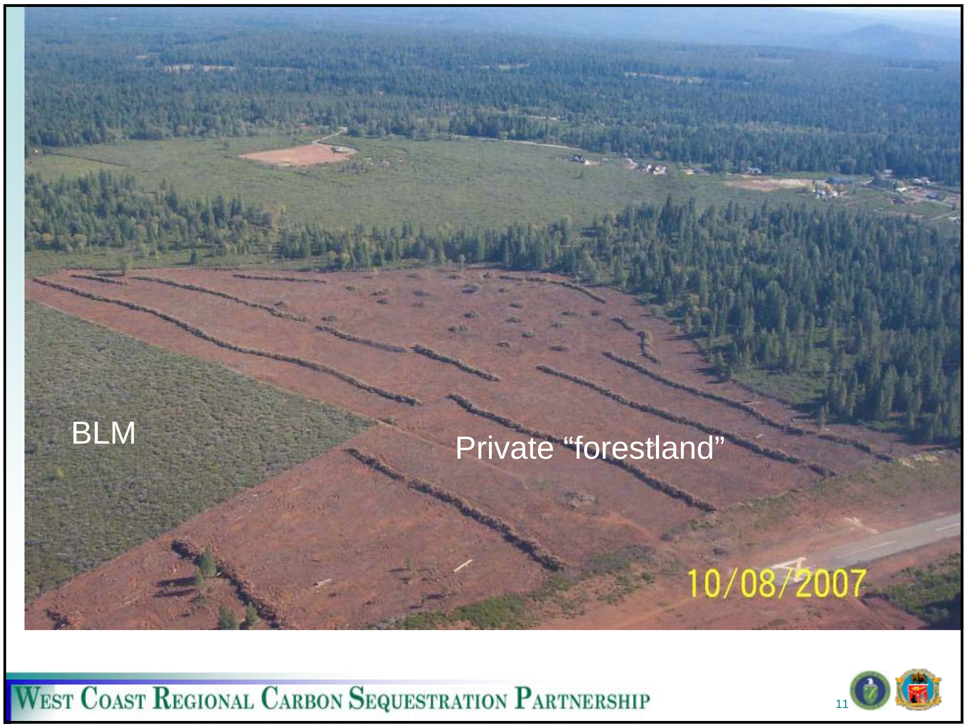


http://www.climateactionreserve.org/how/projects/

- **140 year-old brush site**
- **Forest soils, deep but low AWC**


BLM (cleared & planted in 1980's w/out weed control & failed)
Project Area
Cleared 2007
& Planted 2008
2008 WBA Photo
1:6,000

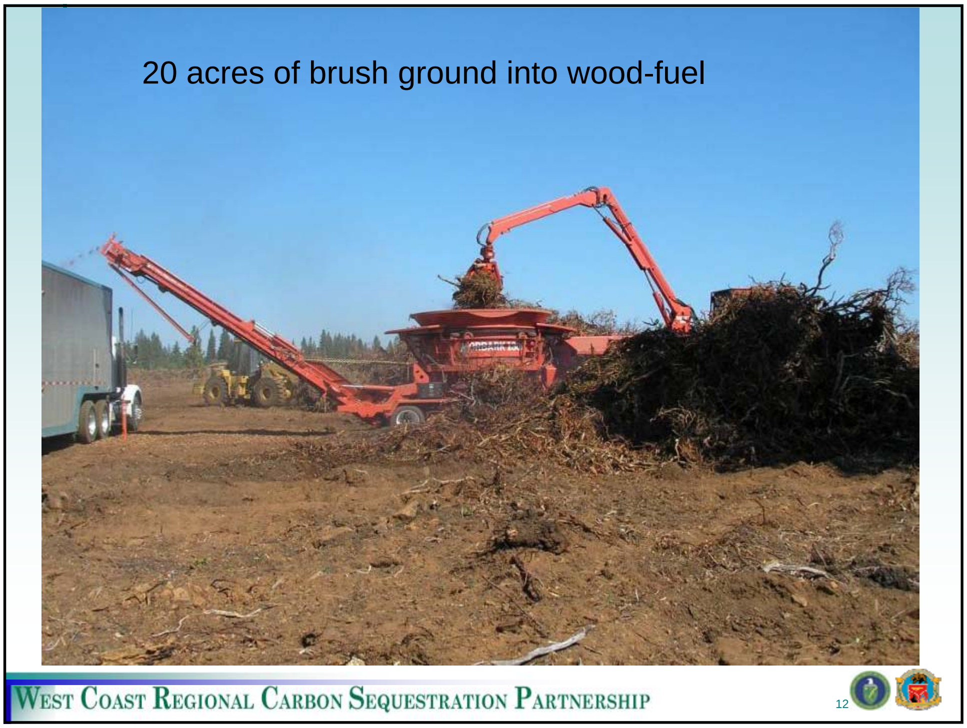

D7 Cat w/ Brushrake



BLM

Private “forestland”

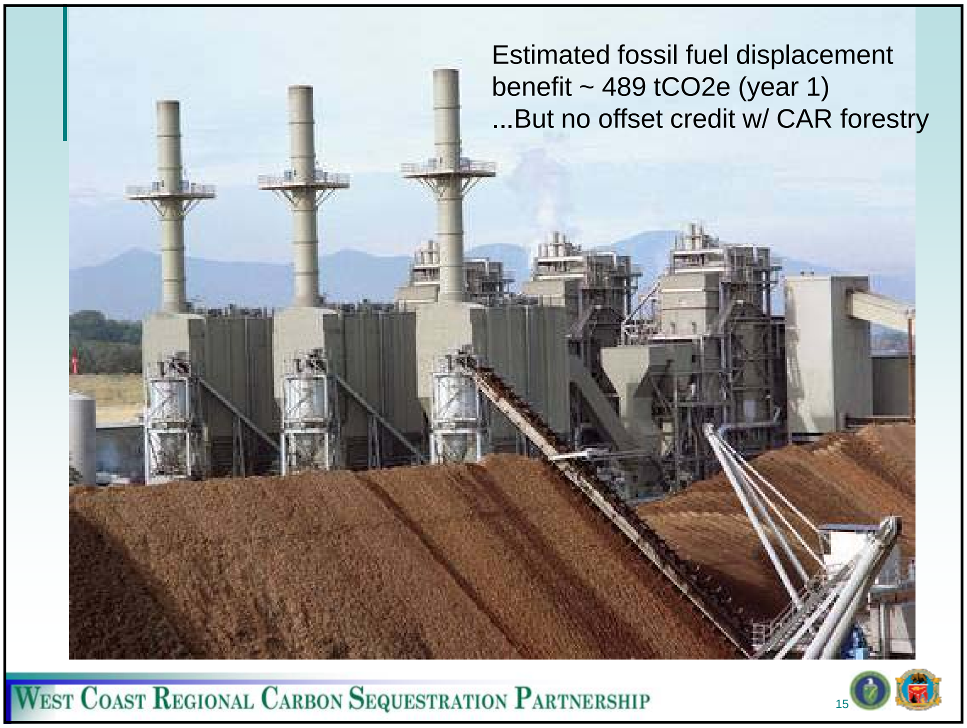
10/08/2007



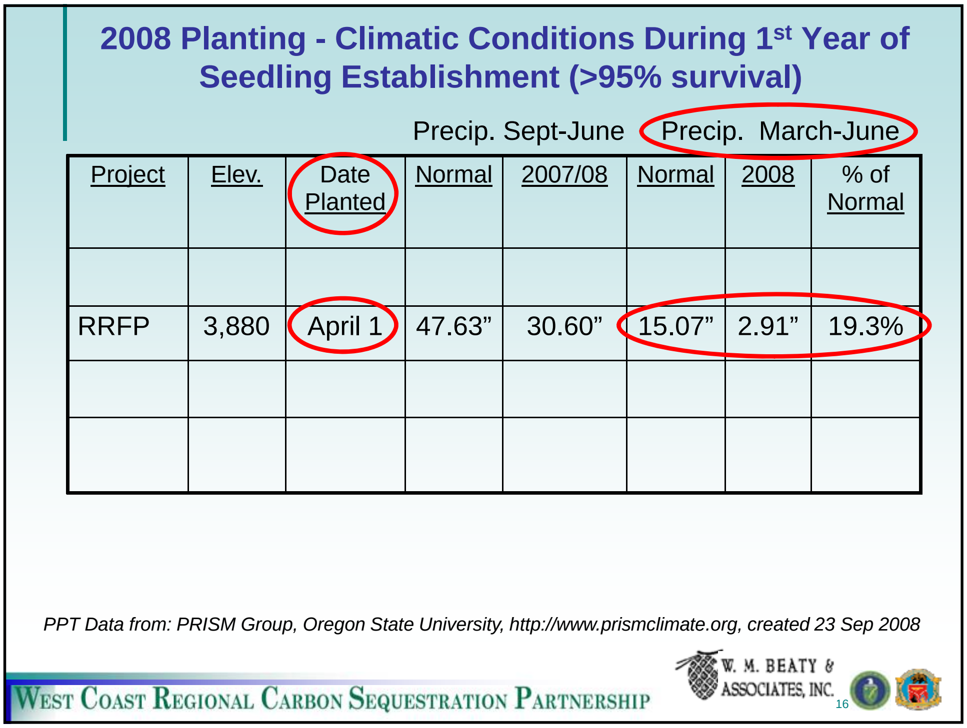
20 acres of brush ground into wood-fuel

WEST COAST REGIONAL CARBON SEQUESTRATION PARTNERSHIP

WEST COAST REGIONAL CARBON SEQUESTRATION PARTNERSHIP



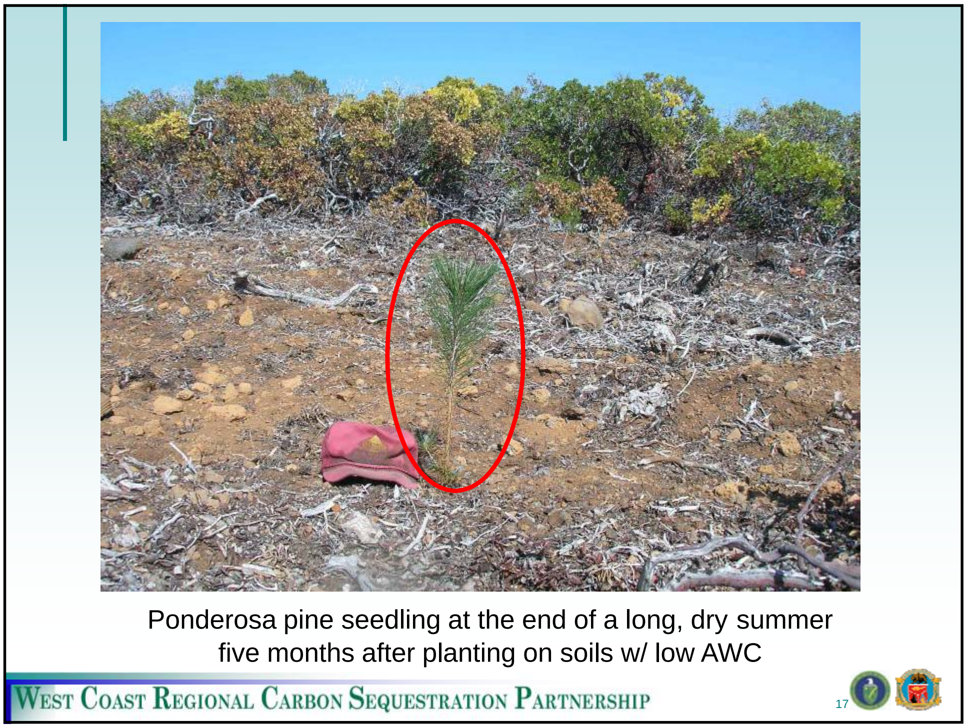
Estimated fossil fuel displacement benefit ~ 489 tCO2e (year 1)
...But no offset credit w/ CAR forestry



2008 Planting - Climatic Conditions During 1st Year of Seedling Establishment (>95% survival)

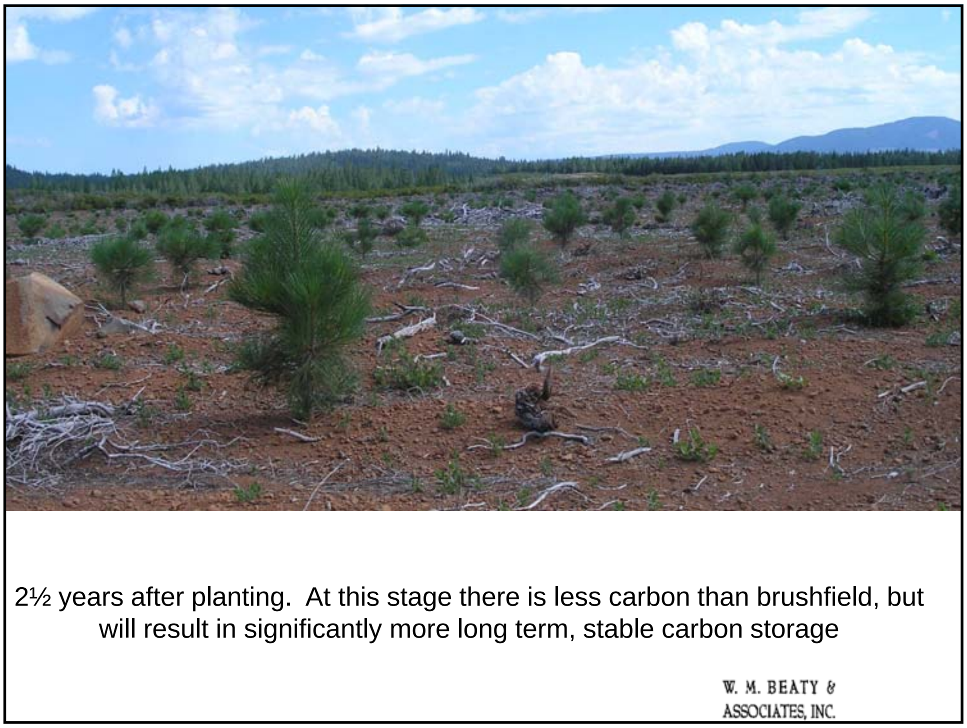
			Precip. Sept-June		Precip. March-June		
Project	Elev.	Date Planted	Normal	2007/08	Normal	2008	% of Normal
RRFP	3,880	April 1	47.63”	30.60”	15.07”	2.91”	19.3%

PPT Data from: PRISM Group, Oregon State University, http://www.prismclimate.org, created 23 Sep 2008



Ponderosa pine seedling at the end of a long, dry summer
five months after planting on soils w/ low AWC

WEST COAST REGIONAL CARBON SEQUESTRATION PARTNERSHIP



2½ years after planting. At this stage there is less carbon than brushfield, but
will result in significantly more long term, stable carbon storage

W. M. BEATY &
ASSOCIATES, INC.

15 YEAR-OLD PLANTATION

Established after wildfire in Northeastern California

Both areas were planted after the same wildfire but:

NO WEED CONTROL

WEED CONTROL

For the first 10 to 15 years both sites have equal amounts of total carbon, so there is a long wait to re-coup investment even though long term carbon/climate benefits are huge: Brush/burn/brush etc. cycle vs. Fire resilient forest w/ large trees

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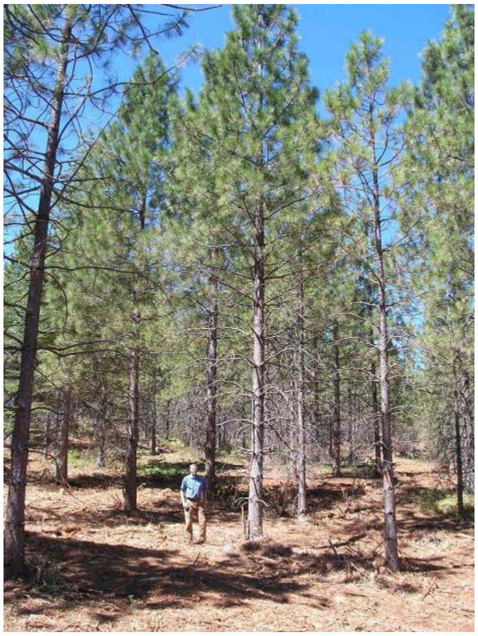
28 year old pine plantation north of Shingletown

After pre-commercial thin



W. M. BEATY &
ASSOCIATES, INC.

42 year old USFS pine plantation – 135 trees / acre
Challenge Experimental Forest

42 year old USFS pine plantation @ 1,210 trees / acre
Challenge Experimental Forest

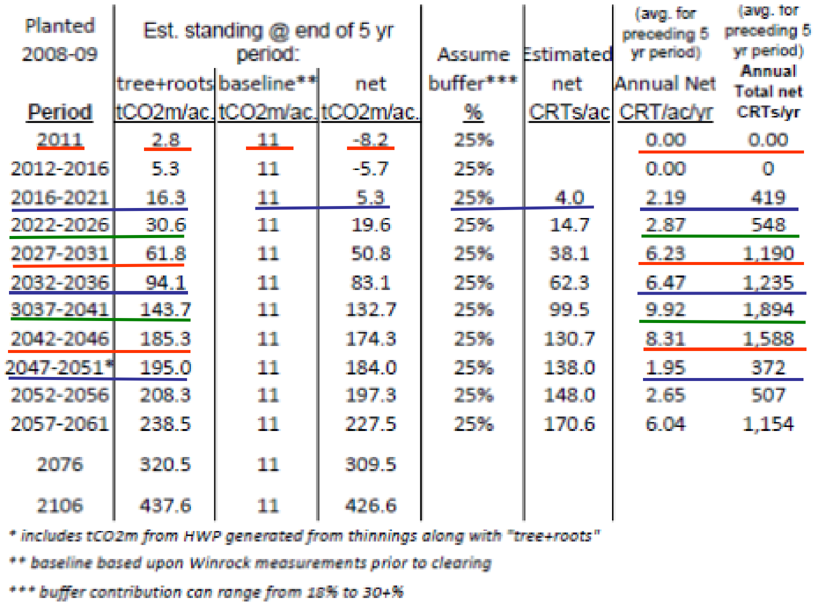
5-year Growth Increments

89 year-old USFS Plantation near McCloud

Managed mature pine forest = High carbon storage + resilient to fire

Very Rough Estimates based on modeling, CRTs sold on actual

Shasta Co. **Project 191 Acres**



Planted 2008-09 Period	Est. standing @ end of 5 yr period: tree+roots tCO2m/ac.	baseline** tCO2m/ac.	net tCO2m/ac.	Assume buffer*** %	Estimated net CRTs/ac	(avg. for preceding 5 yr period) Annual Net CRT/ac/yr	(avg. for preceding 5 yr period) Annual Total net CRTs/yr
2011	2.8	11	-8.2	25%		0.00	0.00
2012-2016	5.3	11	-5.7	25%		0.00	0
2016-2021	16.3	11	5.3	25%	4.0	2.19	419
2022-2026	30.6	11	19.6	25%	14.7	2.87	548
2027-2031	61.8	11	50.8	25%	38.1	6.23	1,190
2032-2036	94.1	11	83.1	25%	62.3	6.47	1,235
3037-2041	143.7	11	132.7	25%	99.5	9.92	1,894
2042-2046	185.3	11	174.3	25%	130.7	8.31	1,588
2047-2051*	195.0	11	184.0	25%	138.0	1.95	372
2052-2056	208.3	11	197.3	25%	148.0	2.65	507
2057-2061	238.5	11	227.5	25%	170.6	6.04	1,154
2076	320.5	11	309.5				
2106	437.6	11	426.6				

** includes tCO2m from HWP generated from thinnings along with "tree+roots"*

*** baseline based upon Winrock measurements prior to clearing*

**** buffer contribution can range from 18% to 30+%*

Cost & Revenue "Guesstimates" through 2036
For 191 acre project in Shasta County

Costs:

Establishment 2007-2010:	$109,000	$570/ac
Follow up release 2010 & 2011:	$ 19,000	$100/ac
Misc. plantation maint.:	$ 20,000	$105/ac
Subtotal	$148,000	$775/ac
Inventories/annual reporting:	$ 26,000	$136/ac
CAR submittal & annual fees:	$ 14,000	$ 71/ac
CAR Variance fee:	$ 1,500	$ 8/ac
Initial partial Verification:	$ 16,000	$ 84/ac
4 Verifications @ 6 yr. intervals:	$ 80,000	$419/ac
Subtotal	$137,000	$712/ac
TOTAL	**$285,000**	**$1,492/ac**

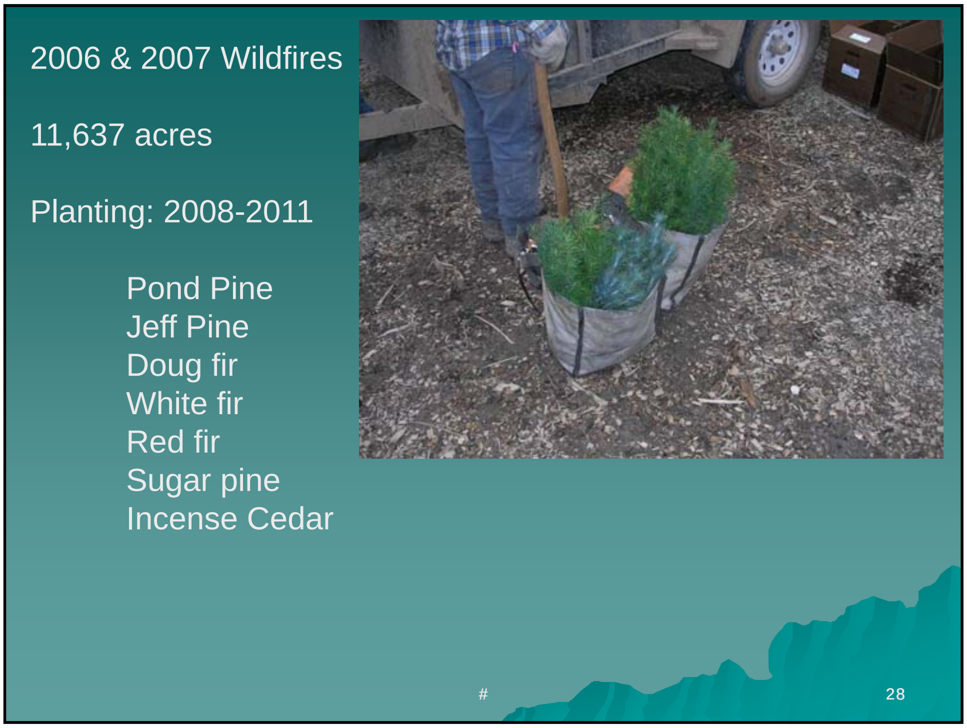
Cumulative Project Revenue through 2036:

@ $6.50/CRT = $110,00 $575/ac

@ $15.00/CRT = $254,350 $1,331/ac

@ $25.00/CRT = $423,900 $2,220/ac

2007 Wildfire
Red River Forests > 11,000 acres

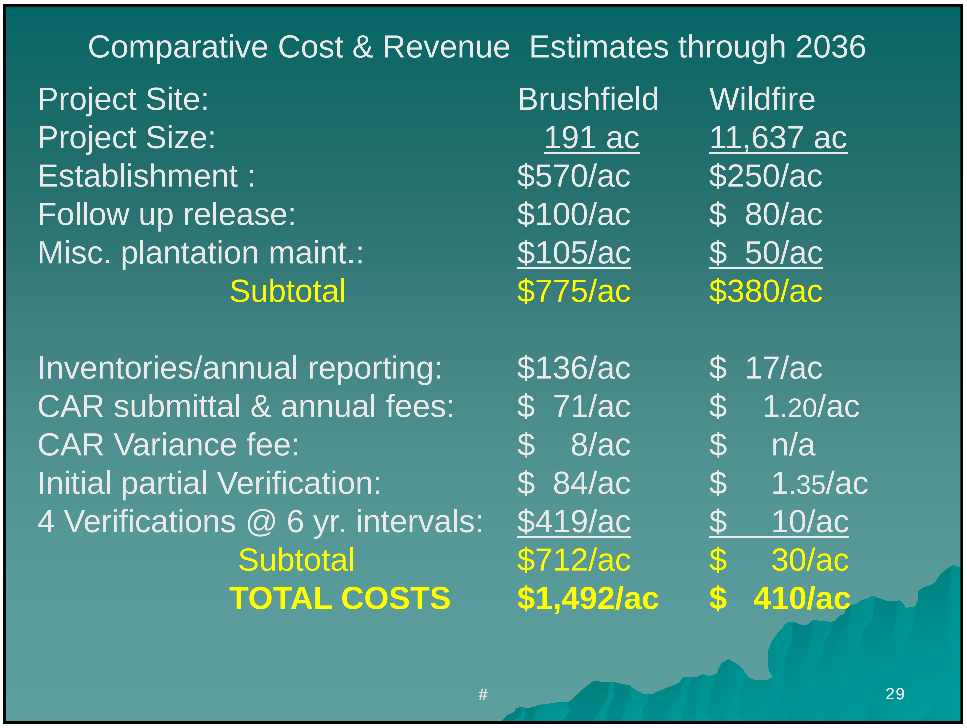


2006 & 2007 Wildfires

11,637 acres

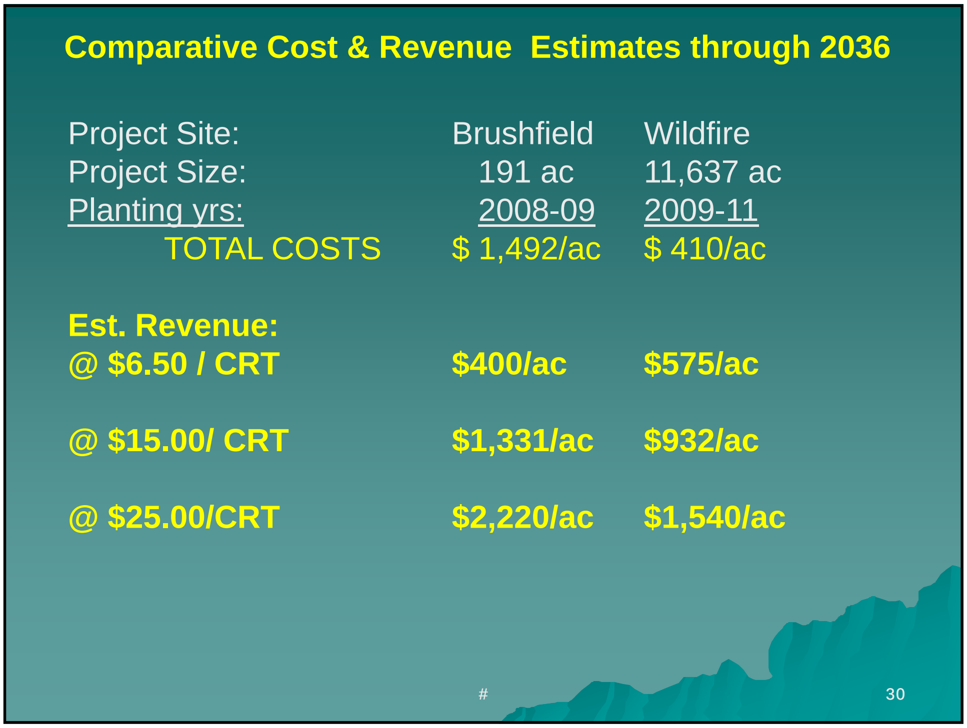
Planting: 2008-2011

- Pond Pine
- Jeff Pine
- Doug fir
- White fir
- Red fir
- Sugar pine
- Incense Cedar



Comparative Cost & Revenue Estimates through 2036

Project Site:	Brushfield	Wildfire
Project Size:	191 ac	11,637 ac
Establishment :	$570/ac	$250/ac
Follow up release:	$100/ac	$ 80/ac
Misc. plantation maint.:	$105/ac	$ 50/ac
Subtotal	$775/ac	$380/ac
Inventories/annual reporting:	$136/ac	$ 17/ac
CAR submittal & annual fees:	$ 71/ac	$ 1.20/ac
CAR Variance fee:	$ 8/ac	$ n/a
Initial partial Verification:	$ 84/ac	$ 1.35/ac
4 Verifications @ 6 yr. intervals:	$419/ac	$ 10/ac
Subtotal	$712/ac	$ 30/ac
TOTAL COSTS	**$1,492/ac**	**$ 410/ac**



Comparative Cost & Revenue Estimates through 2036

Project Site:	Brushfield	Wildfire
Project Size:	191 ac	11,637 ac
Planting yrs:	2008-09	2009-11
TOTAL COSTS	$ 1,492/ac	$ 410/ac
Est. Revenue:		
@ $6.50 / CRT	**$400/ac**	**$575/ac**
@ $15.00/ CRT	**$1,331/ac**	**$932/ac**
@ $25.00/CRT	**$2,220/ac**	**$1,540/ac**

CONCLUSIONS

- Reforesting brush-fields and/or wildfire damaged areas provide significant long term carbon sequestration benefits
- Financial attractiveness for landowners is limited by:
  - High upfront reforestation costs
  - Revenue stream starts much later (10 to 30 years into the future)
  - High uncertainty in future market value of CRTs
  - Uncertainties in CAR protocol interpretation & verification costs
  - Very long term PIA (> 100 years)

Obstacles for small landowner CAR Reforestation Project

- No annual income from timber to support Project development costs which cannot be recouped for a decade or two for revenue from CRTs
- Higher per acre fixed costs for reforestation activities
- Very high per acre fixed costs for CAR registration & verification
- Uncertainties in CAR protocol interpretation & verification
- Obligations of PIA very cumbersome
- Limited availability to a seed bank, reforestation expertise etc.
- CAR's "one size fits all" species diversity requirements disqualify most projects or require an expensive "variance"
- Uncertainty in market value when CRTs accrue (10 to 30 years into future)

Any Questions?

89 year-old Show Plantation