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Preliminary Identification of Basic Science Needs and Opportunities

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Author

Benson, S.M.

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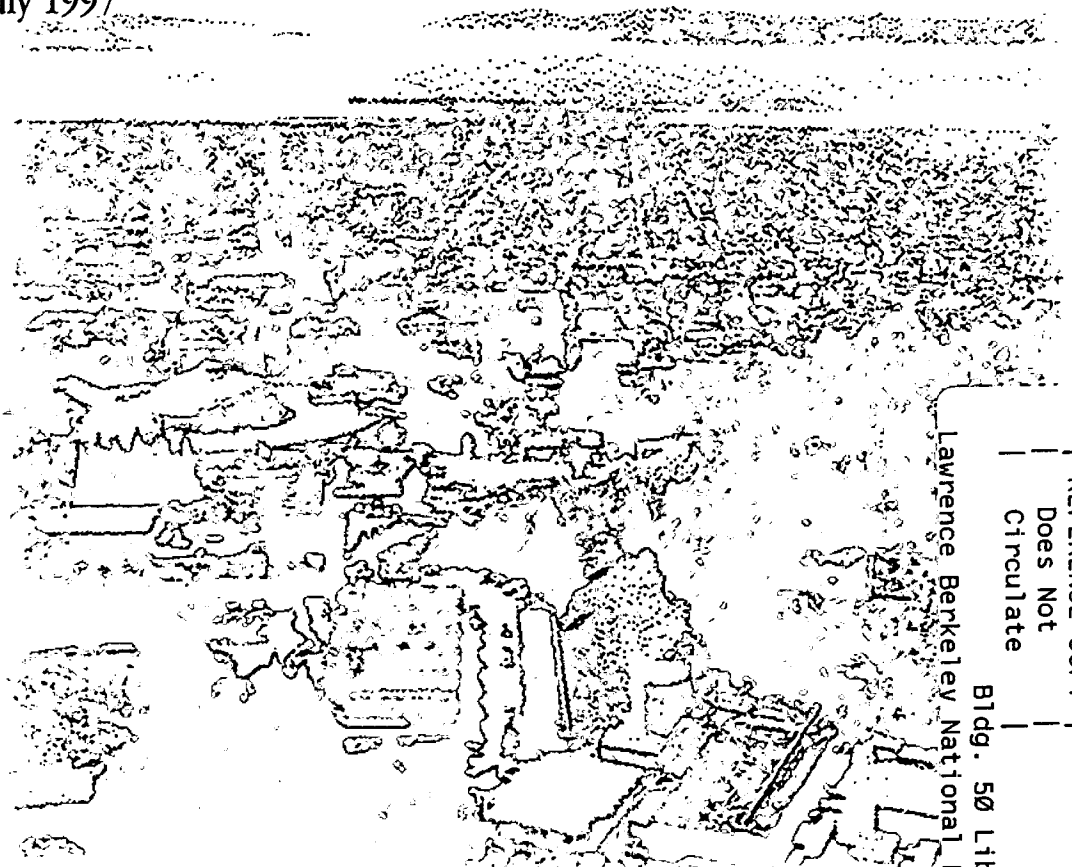
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Capturing and Sequestering Carbon By Enhancing the Natural Carbon Cycle: Preliminary Identification of Basic Science Needs and Opportunities

Sally M. Benson

Earth Sciences Division

July 1997



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**Capturing and Sequestering Carbon By
Enhancing the Natural Carbon Cycle:
Preliminary Identification of
Basic Science Needs and Opportunities**

**Summary Description of a
Workshop Organized by:
Dr. Sally M. Benson
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
Berkeley, CA 94720**

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Motivation for the Workshop

The Department of Energy's Office of Energy Research is sponsoring an assessment of fundamental research needs to support a national program in carbon management. The assessment is motivated by accumulating evidence that suggests that anthropogenic emissions of greenhouse gases such as carbon dioxide and methane are affecting the global and regional climate, and the belief that DOE's Office of Energy Research can contribute to the development of mid- to long-term solutions through a focused program of fundamental research in the appropriate areas. Projections of continuing increases in the atmospheric concentration of carbon dioxide and other greenhouse gases over the coming century raise many concerns regarding increased climatic, ecological, and economic impact. International and national pressure is increasing to take action now towards developing and implementing an effective carbon management strategy.

The Office of Energy Research has identified five areas where fundamental research could contribute significantly to a national carbon management strategy. These areas would build on existing programs, expertise, and research facilities, and include:

- Hydrogen production and fuel cells;
- Capture of carbon dioxide stack emissions and disposal through deep well or deep ocean disposal;
- Enhancing the natural carbon cycle to capture and sequester carbon;
- Improving the efficiency of energy production, conversion, and utilization; and
- Biomass production and utilization.

The purpose of this workshop was to bring together scientific experts in the natural carbon cycle in order to identify areas of fundamental research that are likely to lead to the development of mid- to long-term solutions for stabilizing or decreasing carbon dioxide and other greenhouse gases in the atmosphere.

Workshop Participants

Workshop participants included members of the academic and DOE National Laboratory research community. Disciplinary backgrounds of the participants encompass atmospheric modeling, marine geochemistry, isotope geochemistry, soil chemistry and microbiology, hydrology, microbial physiology, biogeochemical cycling, material science, chemistry, and forestry. A list of attendees for the workshop is provided in Appendix A.

Introduction

The purpose of the workshop was *to identify the underlying research needed to answer the following questions:*

1. Can the natural carbon cycle be used to aid in stabilizing or decreasing atmospheric CO₂ and CH₄ by:
 - Increasing carbon capture;
 - Preventing carbon from returning to the atmosphere through intermediate (<100 years) to long-term sequestration (> 100 years)?
2. What kind of ecosystem management practices could be used to achieve this?

The natural carbon cycle involves complex interactions among living organisms; degradation products of living organisms; the atmosphere; the oceans, rivers, and lakes; and the mineral constituents of the earth. The likely components of the natural carbon cycle that have a large enough capacity and exchange rate (flux) to capture and sequester carbon include:

- Oceans
- Forests
- Agricultural lands
- Grasslands, tundra, wetlands, and uncultivated lands
- Solid waste and waste waters

This workshop focused on identifying “targets of opportunity” for performing fundamental research that would contribute to an enhanced understanding of the natural carbon cycle and assist in developing management systems to capture and sequester carbon.

Figure 1 illustrates our concept for identifying “targets of opportunity.” Essentially, these targets meet three criteria: (1) the potential for carbon capture and sequestration is large (e.g., nominally 1 Gigatonne per year or more); (2) fundamental research is needed to develop the knowledge necessary to realize the target’s potential; and (3) the likelihood of success is reasonably good.

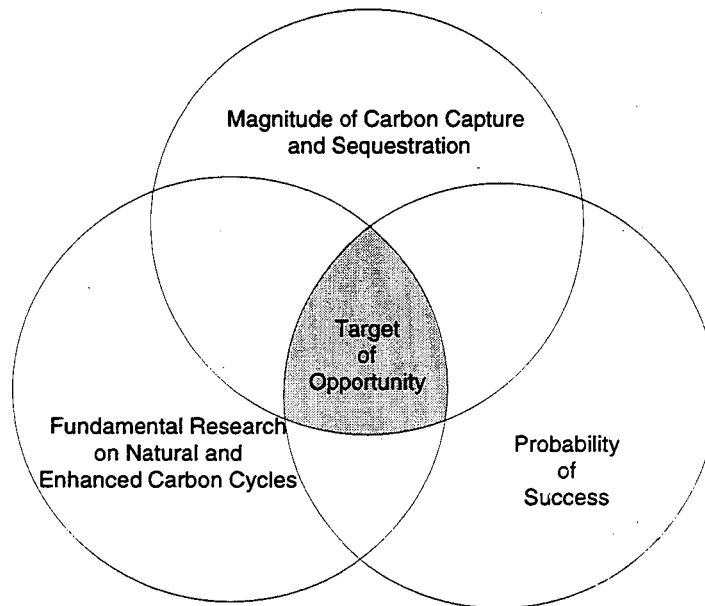


Figure 1. Model for identifying targets of opportunity for a fundamental research program in carbon management.

To assist in identifying components of the natural carbon cycle that could be enhanced, we first looked at currently available information on the size and fluxes of the major components of the cycle. Figure 2 provides a compilation of data on the inventory of the major pools of carbon actively involved in the carbon cycle (oceans, terrestrial biosphere, and atmosphere), and more importantly, on the magnitude of the annual fluxes between them. For comparison, the carbon emission caused by burning fossil fuels and the consequent annual increase in the atmospheric carbon inventory are also shown.

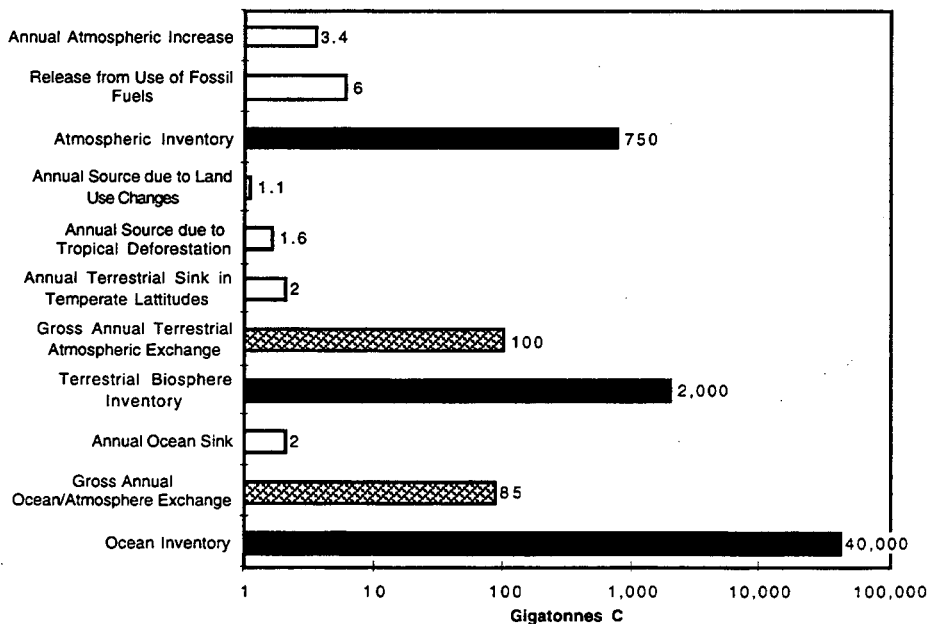


Figure 2. The major inventories and fluxes in the natural carbon cycle. Compiled from various sources.

Noteworthy is the observation that the inventory of carbon in the oceans (c. 40,000 GT) is large compared to the inventory in the terrestrial biosphere (c. 2,000 GT), which is in turn large compared to the atmospheric inventory (c. 750 GT). Even more important is to note that the annual exchange between the atmosphere and the oceans (approximately 60 GT) and the annual gross exchange between the terrestrial biosphere and the atmosphere (c. 100 GT) is large compared to the annual atmospheric increase (c. 3.4 GT) and fossil fuels emissions (c. 6 GT).

The large relative magnitude of these annual exchanges suggests that enhancing the natural carbon cycle presents a significant opportunity for stabilizing or decreasing atmospheric carbon (CO₂ and CH₄) concentrations. Opportunities are found in the oceans and terrestrial biosphere, as well as in solid/liquid waste processing. However, because of the central role that the natural carbon cycle plays in every aspect of the earth as we know it, there are important ecological, ethical, and economic considerations that must be addressed as part of formulating and pursuing a research agenda.

Ecological, Ethical, and Economic Considerations

Workshop participants unanimously agreed that it is essential to fully understand the nature and magnitude of local, regional, and global impacts associated with ecosystem management for carbon capture and sequestration. Deleterious impacts could include ecosystem changes with unintended negative consequences, unintended climatic feedback, and loss of biodiversity as well as economic impacts created by changing land and ocean productivity. The seriousness of each of these effects poses ethical considerations that must be addressed while the research agenda is being formulated. For example, we should ensure that ecological and biodiversity studies are performed in concert with experiments designed primarily to evaluate the effectiveness of a carbon management strategy. The participants recommend that assessing ecological, ethical, and economic considerations becomes an essential and central component of a carbon management research agenda.

Working Group Recommendations

The workshop participants were divided into three groups and given the charge to provide recommendations on the following:

- Identifying targets of opportunity for research
- Developing a rationale for why these targets are more important than others
- Developing a rough outline of the essential scientific components for each target of opportunity

Due to the limited time available, most of the emphasis was placed on identifying targets of opportunity. Further efforts are needed to more fully develop the rationale and the scientific components. In addition, one will have to identify and understand related research programs sponsored by DOE and other federal agencies. These programs provide an opportunity for cooperative and complementary research efforts.

In the following sections, recommendations for research are provided in three groupings.

Working Group 1: Terrestrial biosphere — including agricultural lands, grasslands, forests, tundra, and wetlands

Working Group 2: Oceans

Working Group 3: Methane — including solid and liquid waste

Working Group 1: Terrestrial Biosphere

Focus on:

- Carbon sequestration in soils and sediments
- Processes/mechanisms of exchange (fluxes)
- Factors controlling rate of exchange

Approaches:

- Integrated laboratory, field and modeling

Research Topics	Rationale	Scientific Disciplines
How do the interactions among the C, N, S, P, and water and energy cycles effect C-storage?	<ul style="list-style-type: none"> - Good starting research base - Fundamental question - Are critical controllers 	<ul style="list-style-type: none"> - Biogeochemistry - Hydrology
What is the nature of the dissolved forms of organic C and N in terrestrial systems — forms, origin, movement, stabilization, and degradation.	<ul style="list-style-type: none"> - Major fundamental research question - Pivotal in subsurface storage of carbon 	<ul style="list-style-type: none"> - Microbiology - Surface science - Organic geochemistry - Soil hydrology
Evaluation of soil conservation practices (tillage, fallowing, erosion control) and wetland preservation as facilitators of C-storage.	<ul style="list-style-type: none"> - Infrastructure already exists to make use of research findings - Enhance cost-effectiveness of existing practices and soil conservation programs 	<ul style="list-style-type: none"> - Agroecology - Soil conservation - Wetland biogeochemistry - Wetland ecology
Understand the processes involved in conversion of plant material to chemically and physically recalcitrant C.	<ul style="list-style-type: none"> - Very little is known - Return C to the sequestration state found prior to human activities 	<ul style="list-style-type: none"> - Soil microbiology - Organic geochemistry - Soil physical protection
Anthropogenic influences on the C-cycle (e.g., N, S, ozone).	<ul style="list-style-type: none"> - Major effects are already documented and shown to be significant - More fundamental understanding is needed to predict effects 	<ul style="list-style-type: none"> - Forestry - Tropospheric chemistry - Biogeochemistry - Biometeorology
Influence of climate change on the natural carbon cycle.	<ul style="list-style-type: none"> - Interannual and interdecadal variations hold important clues to large-scale climatic feedback processes. 	<ul style="list-style-type: none"> - All of the above
Mechanistic study of the chemical pathways by which nature transforms CO ₂ , as in photosystem I and other naturally occurring biomolecules.	<ul style="list-style-type: none"> - Most of these systems are still very poorly understood at a molecular level - Insight gained from studying these mechanisms could ultimately lead to practical solutions for sequestering CO₂. 	<ul style="list-style-type: none"> - Biochemistry

Table 1. Examples of recommended research topics that provide the fundamental understanding needed to enhance carbon storage in the terrestrial biosphere.

Working Group 2: Oceans

- Focus on:-
- Understanding and enhancing the carbon flux associated with the ocean's biogeochemical cycle
 - Processes/mechanisms of exchange (fluxes)
 - Ecological consequences of ocean fertilization

- Approaches:
- Integrated laboratory, field, and modeling

Research Topics	Rationale	Research Elements
Understanding the biogeochemical cycle of carbon in the ocean and its interactions with physical changes in ocean circulation	<ul style="list-style-type: none"> - A better understanding of the biologically driven aspects of the ocean carbon cycle is needed before a management scheme could be developed - Huge opportunity for carbon capture and long-term (>100 years) sequestration 	<ul style="list-style-type: none"> - Variability of carbon cycle components on daily, interannual, and event-driven time scales - New measurement techniques for observing the carbon cycle - Carbonate-forming phytoplankton - Phytoplankton – community dynamics and the link to food web carbon export - Paleoclimatic analysis of oceanic-atmosphere/CO₂ interactions
Enhancing ocean productivity	<p>Enhancing ocean productivity could lead to greater capture and sequestration of carbon by the following mechanisms:</p> <ul style="list-style-type: none"> - Increased air-sea transfer of CO₂ - Enlarged oceanic food web - Increased organic carbon sedimentation rates - Increased efficiency of particulate carbon export from surface waters - Decreased remineralization efficiency 	<ul style="list-style-type: none"> - Fertilization strategy <ul style="list-style-type: none"> • nutrient addition • delivery system • food-web response - Cultivation <ul style="list-style-type: none"> • capture efficiency • fuel source • food source - Ecological consequences of enhancing ocean productivity - Climate feedback

Table 2. Examples of recommended research topics that provide the fundamental understanding needed to enhance carbon capture and sequestration in the oceans.

Working Group 3: Methane — including solid and liquid waste emissions

The methane budget is provided in Table 3 below. The primary worldwide sources are rice cultivation, wetlands (produced from anaerobic decomposition of organic matter), ruminants, biomass burning, and landfills. Each year the majority of methane introduced into the atmosphere is decomposed by chemical or biological reactions, leaving only an annual increase of about 0.05 GT. While this is a small fraction compared to the annual atmospheric increase of CO₂, it is nevertheless significant due to the higher infrared absorbance of methane (equivalent to about 0.3 GT carbon as CO₂).

Research on reducing methane emissions is already being performed by international rice institutes, waste management associations and cattle associations. DOE can contribute to these efforts by coordinating or further expanding existing programs, particularly in the areas indicated in Table 4.

Source	Quantity (GT/year)	C-Equivalent (GT/year)
Worldwide production	0.5	2.9
Methane destruction (OH + soil absorption)	0.45	2.6
Atmospheric increase	0.05	0.3
Wetlands	0.1	0.6
Rice cultivation	0.1	0.6
Waste & landfills	0.04	0.2
Natural gas venting	0.02-0.04	0.1 - 0.2
Pipeline leaking	0.02-0.04	0.1 - 0.2
Coal crushing	0.02-0.04	0.1 - 0.2
Termites	0.02	0.1
Ruminants	0.08	0.5
Lakes & fresh waters	0.005-0.01	0.03-0.06
Clathrates	0.005-0.01	0.03-0.06
Biomass burning	0.05	0.3

Table 3. Methane budget (Source: I. Fung, personal communication).¹

¹ Since methane absorbs infrared radiation more efficiently than carbon dioxide, the equivalent impact due to atmospheric methane emissions is calculated by multiplying the methane emissions by 5.8.

Research Topics	Rationale	Research Elements
Better understanding of relationships between methanogens and methanotrophs with respect to competition and maintenance affected by changes in ecophysiological parameters such as moisture, temperature, Eh, etc.	Fundamental knowledge is needed to understand processes underpinning a wide range of environments that produce methane, including wetlands, rice cultivation, landfills and waste treatment systems	<ul style="list-style-type: none"> - Microbial community dynamics - Microbial physiology - Soil chemistry - Gene regulation - Competitive factors
Better understanding of soil absorption/consumption of methane	Soils are an important sink for methane and more needs to be understood about underlying mechanisms	Characterization of microbial population(s)/processes and ecophysiological condition for methane absorption/consumption
Clathrates – better understanding and increased knowledge of how and where they are formed	<p>Information is needed to resolve opposing theories about the location and existence of clathrates. For example:</p> <ul style="list-style-type: none"> - How are they formed? - How do they dissolve? - What are the effects of dissolution? - What are ways to capture CH₄? - How does CH₄ oxidize in the water column? 	<ul style="list-style-type: none"> - Organic geochemistry
Integrated advanced waste (solid and liquid) treatment plants that reduce carbon emissions	<p>Waste treatment processes are needed that either:</p> <ul style="list-style-type: none"> - do not produce methane, or - produce methane that can be used as a fuel source 	<ul style="list-style-type: none"> - Understand biochemical pathways for important waste treatment processes - Understand the rate limiting steps and environmental controls on key processes

Table 4. Examples of recommended research topics that provide the fundamental understanding needed to reduce methane emissions and enhance methane capture/conversion or sequestration.

Recommended Components of Carbon Management Research Program

Carbon Capture and Sequestration by the Terrestrial Biosphere

The carbon cycle in the terrestrial biosphere can be used to both capture and sequester CO₂. Important pools of organic carbon in the terrestrial biosphere are found above ground in biomass associated with forests, grasslands, wetlands, tundra, and agricultural lands, as well as in soils, roots, organic detritus, microorganisms and as dissolved organic carbon. The gross annual exchange of carbon with the terrestrial biosphere (c. 100 GT) attests to the efficiency of the carbon capture, which occurs largely by photosynthetic conversion of CO₂ to living plant matter. The efficiency of the terrestrial biosphere as a repository of organic carbon is evident from the 2,000 GT stored in the terrestrial biosphere, of which nearly 75% is stored in soils. The efficiency of both carbon capture and carbon storage suggests that enhancing these processes in the terrestrial biosphere offers a significant opportunity for stabilizing or decreasing atmospheric CO₂ concentrations. Some approaches for managing carbon in the terrestrial biosphere include:

Increasing photosynthesis: The only entry point for carbon to the terrestrial biosphere is via photosynthesis, whose rate is regulated by, inter alia, nutrient, temperature, precipitation, sunlight and atmospheric CO₂ levels. DOE has an existing program (FACE) to quantify the effects of higher CO₂ levels on photosynthesis. However, increasing photosynthesis if accompanied only by increased litterfall and increased decomposition, may accelerate carbon throughput without increasing storage. Studies on enhancing photosynthesis must be accompanied by studies to understand factors controlling decomposition rates and the transfer of carbon to slowly decomposing pools.

Increasing carbon capture and storage in agricultural lands: Soil carbon may be depleted by as much as 50% in agricultural lands, compared to precultivation levels². Restoration of one-half to two-thirds of the soil carbon in agricultural lands over a 50-year period could capture and store from 0.4 to 0.6 GT per year³. This option is appealing because the infrastructure already exists to make use of research findings that would enhance the cost-effectiveness of existing practices and soil conservation programs.

Increasing carbon capture and storage in degraded lands: As the result of poor soil management practices, a significant amount of the world's soils are too degraded to use for agricultural purposes or even for restoration of natural ecosystems. As the world-wide demand for food and appreciation for the importance of restoration of natural ecosystems grows, there will be more incentive to rehabilitate these lands. Increasing carbon capture and storage could be part of a rehabilitation plan. Estimates suggest that from 0.02 to 0.2 GT per year of carbon could be captured and stored in this way⁴ over a 50-year period.

Increasing carbon capture and storage in forests: Enhanced carbon capture and storage could occur in lower-, mid- and high-latitude forests through a combination of enhanced biomass production in existing forests, regeneration of forests on deforested or otherwise low-productivity lands, and agroforestry. The largest opportunity to contribute to carbon capture and storage is found in the lower latitudes, where extensive deforestation is occurring today. Enhanced reforestation techniques could accelerate the effectiveness of this approach.

Increasing carbon sequestration in wetlands: Wetlands are an important natural sink for carbon. Degradation of organic matter in wetlands is typically incomplete, leading to large concentrations of organic matter in wetland sediments. Enhancing the magnitude and

² Goudrian, 1990. Atmospheric CO₂, global carbon fluxes and the biosphere, in Theoretical Production Ecology: reflections and prospects. Pudoc, Wageningen, Simulation Monographs 34.

³ From IPCC Technical Paper I, Technologies, Policies and Measures for Mitigating Climate Change.

⁴ Ibid.

effectiveness of carbon capture and sequestration could be achieved by creating more wetlands or finding ways to enhance the natural sequestration process. Finding methods to suppress methane generation in wetlands (or prevent methane transport to the atmosphere) could also make this a more attractive option as methane is actually a more effective greenhouse gas than carbon dioxide.

Degradation of methane in soils: Since methane is also an important greenhouse gas and is part of the natural carbon cycle, methods to remove methane from the atmosphere or limit methane generation also should be evaluated⁵. Important sources of methane include rice cultivation, wetlands (produced from anaerobic decomposition of organic matter), ruminants, biomass burning, and landfills. Annually, some 0.5 GT of methane is introduced into the atmosphere, but nearly 90% of this is destroyed by oxidation in the atmosphere and decomposition in soils. Controlling decomposition in soils could stabilize or decrease atmospheric methane concentrations.

Integrated waste treatment plants that reduce carbon emissions: Solid and liquid waste treatment/disposal are a significant source of methane. Integrated advanced waste treatment systems that produce and capture methane provide the dual benefit of controlling methane emissions and providing a fuel source. Technologies that use algal biomass grown in high-rate ponds to enhance anaerobic treatment of waste also have the additional benefit of capturing carbon from the atmosphere. Nations developing their waste treatment infrastructure could immediately benefit from enhanced technologies. Scheduled infrastructure replacement in the developed nations could benefit from adoption of new technologies.

While each of these approaches holds promise for capturing or sequestering carbon, there are critical knowledge gaps that must be addressed before their respective benefits and drawbacks can be fully assessed. Capture and storage of carbon is transitory, and also depends critically on climatic conditions. Obtaining a better understanding of the transitory nature of the terrestrial carbon cycle and the fundamental biological, chemical, and hydrological mechanisms that control it are an important first step in such an ambitious undertaking. Below are some of the key research needs to address critical knowledge gaps.

Research Needs — Terrestrial Biosphere

Fundamental Understanding of Carbon Cycling in Soils: The cycling of carbon in soils involves the complex interaction among living and dead biomass, microorganisms, water, solutes, and mineral constituents of a soil. The organic matter in soil consists of a mixture of unaltered or partly altered plant material and microorganisms, organic acids, and humic substances. Turnover times for the various forms of carbon (the time that it takes to convert organic carbon to inorganic forms such as CO₂) vary from less than a year for microbial biomass to thousands of years for some of the humic and fulvic acids. If methods could be devised for creating large pools of carbon with very long turnover times, soils could provide a large repository for sequestering carbon. However, we have only a rudimentary understanding of the biogeochemical processes that control turnover times. Mechanistic studies at the molecular, micro, and meso-scales will provide the foundation for developing new technologies to capture and sequester carbon. Key fundamental research questions that could provide this knowledge are given below. The unique collection of spectroscopic, microscopic, analytical, and imaging technologies built and supported by DOE's Office of Energy Research are ideally suited to answering these questions.

- What are the forms of dissolved organic carbon and nitrogen in terrestrial systems? What are their molecular structures? How are they formed? How are they transported?

⁵ Molecule for molecule, methane absorbs infrared radiation nearly 20 times more efficiently than does carbon dioxide.

in soil systems? How stable are they? What environmental factors influence their stability? What are the degradation mechanisms?

- What are the processes involved in conversion of plant material to carbon containing compounds that are chemically and physically inert?
- How do the interactions among the carbon, nitrogen, sulfur, phosphorus, and water cycles affect carbon storage?
- What are the mechanisms by which methane is utilized and decomposed in soils? What is the relationship between methanogens and methanotrophs with respect to competition and maintenance as affected by changes in ecophysiological parameters such as moisture, temperature, Eh, pH, and availability of nutrients?

Understanding Mechanisms to Enhance Carbon Storage in Soils: Developing technologies for incorporating and storing more carbon in agricultural soils will require mechanistic understanding of the influence of soil cultivation and conservation practices on the carbon cycle. Examples of agricultural practices that could lead to enhanced carbon storage include incorporating post-harvest leaves and stems into soils, reducing tillage and aeration, reducing bare-soil fallowing, crop rotation, growing perennial crops or growing crops with large amounts of below-ground biomass (roots). Once more is understood about the influence of interaction of the carbon, nitrogen, sulfur, phosphorus, and water cycles on carbon cycle, modification of irrigation and fertilization practices may also provide options for enhanced carbon capture and sequestration. Mechanistic studies of the important physical, chemical and microbial processes at the micro and meso-scales are needed to guide follow-on experimentation at the pilot and field scales. Below are some of the key questions that must be addressed.

- What are the mechanisms by which agricultural practices such as tillage, fertilization, pesticide and herbicide application, crop rotation, irrigation fallowing, and erosion control influence carbon storage?
- Which of these practices or combinations of them will lead to enhanced carbon storage without unduly interfering with agricultural productivity or causing ecological harm?

Understanding the Influence of Climate Change and Anthropogenic Emissions on the Natural Carbon Cycle: The natural carbon cycle in the terrestrial biosphere is also influenced by anthropogenic emissions. There are data indicating both positive and negative feedbacks to carbon capture and sequestration caused by increased concentrations of atmospheric CO₂, nitrogen, ozone, and sulfur compounds. Moreover, climate changes created by anthropogenic emissions of greenhouse gases will lead to regional shifts in temperature and precipitation which will influence carbon capture and storage in the terrestrial biosphere. Understanding these feedbacks will be important for developing a comprehensive strategy for carbon management. Ecosystem-scale research underpinned by mechanistic studies of key processes is needed to understand anthropogenic influences on the natural carbon cycle.

Carbon Capture and Sequestration in the Oceans

The large exchange rates (c. 85 GT/year) and the large inventory of carbon (c. 40,000 GT) suggest that oceans may have the potential to capture and sequester significant quantities of CO₂. Deep ocean sequestration is particularly attractive because of the long residence times (hundreds of years) for waters below the thermal inversion. Nevertheless, there is considerable disagreement regarding the technical feasibility, viability and environmental consequences of manipulating the carbon cycle in the oceans to capture and seques-

ter more carbon — in part because the ocean carbon cycle is complex and in part because there is much we need to know before we could proceed with any assurance of success.

The exchange of carbon between the atmosphere and oceans is dependent on the gradient in CO₂ partial pressures as well as the rate of gas exchange across the air-sea interface. The CO₂ partial pressure in the surface waters is controlled by three primary mechanisms which are often referred to as the solubility pump, the biological pump and the carbonate pump. The solubility pump is driven principally by temperature variations in the water column. The biological pump results from photosynthetic production of planktonic organisms in surface waters and subsequent sedimentation of organic debris. The carbonate pump results from production and sedimentation of calcium carbonate by marine organisms. The complex interplay of these processes with ocean circulation can create either a sink or a source of CO₂, or perhaps both depending on the season. Improved understanding of these processes and how they vary on a daily, intra- and inter-annual time scale is an important component of understanding the natural carbon cycle — and an essential prerequisite to any management strategy for capturing and sequestering more carbon. Below are some of the key research needs to address critical knowledge gaps.

Research Needs - Oceans

Fundamental Understanding of the Carbon Cycle In the Ocean: Mechanistic investigations of the primary processes described above and their interactions with physical changes caused by ocean circulation are needed to develop a fundamental understanding of the carbon cycle in the ocean. In addition, more accurate and deployable methods are needed to measure CO₂ fluxes across the ocean/air interface, measure dissolved and particulate organic carbon and measure ocean productivity on the appropriate spatial and temporal scales. Integrated field, laboratory and modeling studies are needed to answer some of the key questions listed below.

- What are the forms of dissolved organic carbon in the ocean? What are their molecular structures? How are they formed? How are they transported? How stable are they? What environmental factors influence their stability? What are the degradation mechanisms?
- What is the nature of the particulate forms of organic carbon in the ocean? How stable are they? What environmental factors influence their stability? What are the degradation mechanisms?
- How variable are the components of the ocean carbon cycle components on daily, inter-annual, and event driven time scales?
- What is the dependency of the gas exchange rate on wind, stability and other parameters of the planetary boundary layer? What is the co-variation between gas exchange rate and the partial pressure of CO₂ in the surface waters?
- What is the community structure of the marine organisms that drive the biological and carbonate pumps? What is the relationship between the community structure and carbon export?
- What do paleoclimate studies reveal about the biogeochemical cycle in the oceans and its relationship to atmospheric CO₂ concentrations?

Fundamental Understanding of Mechanisms for Enhancing Carbon Capture and Sequestration: Increasing ocean productivity could lead to enhanced carbon capture and sequestration by some or all of the following mechanisms: increasing air-sea transfer of CO₂; enlarging the oceanic food web; increasing organic carbon sedimentation rates; increasing the efficiency of particulate carbon export from surface waters and; decreased remineralization

efficiency. Exploratory experiments have already been performed to stimulate ocean productivity by iron fertilization, but many more laboratory, field and modeling studies are needed to explore this and other strategies for enhancing ocean productivity — and to determine the effectiveness of enhanced biological productivity on carbon capture and sequestration. Below are some of the key questions that need to be addressed by theoretical, laboratory and eco-system scale research to develop a better understanding of the mechanisms for enhancing carbon capture and sequestration in the oceans.

- What are the optimal mechanisms for enhancing ocean productivity? What kind of nutrients could be added to the oceans to enhance productivity? How could these nutrients be delivered where and when they are needed? What will be the food-web response to nutrient additions? Where could nutrients be added to achieve the desired effect?
- Could the biomass cultivated in the oceans be harvested for food or fuel? How could it be captured without adverse ecological consequences?
- What are the ecological consequences of enhancing ocean productivity?
- What would be the climate feedback caused by enhancing ocean productivity?

Carbon Management Working Group
July 8, 1997
Lawrence Berkeley National Laboratory

Attendees:

Professor Roni Avissar
Environmental & Natural Resources
Cook Campus
Rutgers University
New Brunswick, NJ 08903

Dr. Marcelo Lippmann
Earth Sciences Division
Lawrence Berkeley National Laboratory
One Cyclotron Rd. M/S 90-1116
Berkeley, CA 94720

Dr. Sally Benson
Earth Sciences Division Director
Lawrence Berkeley National Laboratory
One Cyclotron Rd. M/S 90-1116
Berkeley, CA 94720

Asst. Professor Jeff Long
Dept. of Chemistry
B81 Tan Hall
University of California
Berkeley, CA 94720

Professor Jim Bishop
University of Victoria
Earth & Ocean Sciences
British Columbia, Canada

Professor Emeritus William Oswald
University of California, Berkeley
Richmond Field Station, Bldg. 112
1301 S. 46th St.
Richmond, CA 94804

Professor Mary Firestone
ESPM – Div. of Ecosystem Sciences
Hilgard Hall #3110
University of California
Berkeley, CA 94720

Dr. Miguel Salmeron
Materials Sciences Division
Lawrence Berkeley National Laboratory
M/S 66208
One Cyclotron Rd.
Berkeley, CA 94720

Professor Inez Fung
University of Victoria
Earth & Ocean Sciences
Room 296A
British Columbia, Canada

Dr. Jayant Sathaye
Environmental Energy Technology Div.
Lawrence Berkeley National Laboratory
One Cyclotron Rd. M/S 90-4044
Berkeley, CA 94720

Asst. Professor Allen Goldstein
ESPM – Div. of Ecosystem Sciences
Hilgard Hall #3110
University of California
Berkeley, CA 94720

Professor Garrison Sposito
ESPM – Div. of Ecosystem Sciences
Hilgard Hall #3110
University of California
Berkeley, CA 94720

Dr. Jennie Hunter-Cevera
Center for Environmental Biotechnology
Lawrence Berkeley National Laboratory
One Cyclotron Rd. M/S 90-1116
Berkeley, CA 94720

**ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY
ONE CYCLOTRON ROAD | BERKELEY, CALIFORNIA 94720**