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Investing in Resilience: Monetizing Carbon to Support Forest Restoration in California

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By

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Abstract

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The increasing frequency and severity of wildfire in California, exacerbated by climate change and historical forest management practices, underscore a critical need for increased forest management which reduces the risk of high severity fire. Currently, over $100 billion is needed to meet federal forest management goals outlined in the U.S. Forest Service Wildfire Crisis Strategy, but total, nonrecurring public funding is approximately $5 billion. To help fill this gap, state and federal agencies explicitly call for public-private partnerships to increase the diversity of funding sources. In this dissertation I evaluate the potential of carbon finance to fund forest management via the carbon benefits from utilizing low-value biomass and by monetizing increased forest carbon stocks from treatments which restore forest resilience. This dissertation helps to advance the field of biomass utilization by exploring ways to increase investment in biomass-based products and exploring the carbon benefits of a fire resilient forest structure, both novel contributions to the literature.

I employ a comprehensive set of methodological frameworks that integrate ecological, economic, and policy analyses to understand how carbon finance can support forest restoration goals in California. The methods used here include discounted cash flow analysis, life cycle assessment, and forest growth models. I reveal how forest management aimed at restoring fire resilience and biomass utilization can contribute to climate objectives. I further show that carbon revenue from biomass utilization and avoided wildfire emissions can contribute significant funding to forest restoration in the Sierra Nevada Mountains.

Themes emerging from this dissertation include: 1) The clear carbon benefits of biomass utilization and the pivotal role it can play in scaling forest restoration and closing funding gaps while generating profitable returns to investors. Fuels made from biomass have an Internal Rate of Return (IRR) of 19% and nonfuel products have an IRR of 13% in the baseline scenario, showing the potential for profitable investment in products utilizing low-value forest biomass. 2) Biochar production could turn low-value biomass into approximately 70 million carbon credits annually, provide IRRs as high as 10 – 30% to investors, and eliminate costs associated with pile-burning. While biochar has lower carbon benefits than other biomass-based products like hydrogen, biochar production is technologically mature and requires low capital expenditures, which can help to build biomass supply chains to unlock higher carbon benefit biomass utilization options. 3) The carbon benefits of restoring resilience and biomass utilization can pay for forest restoration in many instances, providing up to $4,000 per acre. However, to fully unlock markets for low-carbon intensity biomass-based commodities from low-value forest biomass, policy support for low carbon fuels and carbon markets will be crucial. Similarly, private investment will need rigorous predictive tools to forecast revenue from carbon markets, tolls which will need to be iteratively developed as the market evolves. This dissertation explores

the predictive tools necessary to estimate the impact of various policy and market scenarios on financial returns. Through this work, I hope to advance our ability to predict, and generate revenue from, the carbon benefits of forest restoration.

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1 INTRODUCTION

1.1 Background and Motivation

In California, 90% of the largest and most destructive fires have occurred since 2010. The 2018 Camp fire was the most destructive in state history, causing 85 fatalities and destroying over 18,000 structures. The 2020 August Complex fire burned over 1 million acres and is the largest in state history. The economic implications of these fires are enormous – the 2017-2018 fire season impact was estimated at $40 billion from direct damages, firefighting expenses, healthcare expenses, and economic disruptions. The 2021 Caldor Fire destroyed 440 homes worth $286 million, hazardous waste removal costs post fire were $96 million, and total firefighting costs were $271 million (Wara 2023). Throughout California and the nation, policy makers, private industry, and communities are scrambling to address the increasing extent and severity of wildfire.

Forests and fire have a long and complex history, shaped by both natural processes and human activities. Historically, wildfires were a natural part of California's forest ecosystems, playing a crucial role in maintaining ecological balance by clearing underbrush, promoting new growth, and maintaining biological diversity. Indigenous people used fire to manage the landscape for millennia, further influencing fire regimes (DellaSala et al. 2017; Perry et al. 2011; Hessburg et al. 2016; Knight et al. 2022). However, the relationship between humans and wildfires changed dramatically with European settlement. Extermination of indigenous fire practices and fire suppression policies enacted in the early 20th century, aimed at protecting the economic value of timber resources and human settlements, lead to a significant reduction in fire frequency. These policies, coupled with logging practices which targeted large diameter old growth trees and replaced them with monoculture plantations, have contributed to the accumulation of dense understory growth and overstocked, homogenous forest structure that created today's conditions ripe for high-severity wildfires (Hurteau et al. 2016; Collins, Everett, and Stephens 2011).
In response to the escalating wildfire crisis, California has established ambitious goals to increase forest resilience and complete fuel treatments on 1 million acres a year. Achieving these goals will require huge financial commitments - traditional funding strategies of congressional appropriations mixed with timber receipts will be inadequate, without an increase in public investment that far exceeds current funding for forest restoration. Current costs in the state of $2000 per acre or higher will require roughly $2 billion annually to achieve the goal of treating 1 million acres. At a national scale, the U.S. Forest Service strategy outlines a 10-year plan to treat up to 50 million acres of public and private lands (USFS 2022). Treating these acres will require at least $100 billion dollars, which far surpasses the approximately $5 billion total, nonrecurring current allocations from the federal government. Given the need for increased funding, both state and federal initiatives highlight the need for innovative public-private partnerships to bridge the funding gap.

Conservation finance which leverages carbon benefits of forest management offers one potential solution to addressing the funding shortfalls. By quantifying and monetizing the carbon benefits of utilizing low-value biomass and increasing carbon storage durability of more fire resilient forests, carbon finance offers a way to support and potentially expand forest management practices. Market-based approaches can incentivize private investment in forest restoration, turning ecosystem services into financial assets that can attract impact-oriented investors and provide capital needed to increase the pace and scale of restoration.

However, the credibility of the carbon market has increasingly come under scrutiny in the recent years. Lack of market transparency (Delacote 2024), scientifically inaccurate protocols (Badgley, Freeman, et al. 2022), unfounded assumptions regarding leakage rates (Haya et al. 2020), and oversimplified accounting practices have led to massive over-crediting with studies estimating that at least 30% to 82% of the credits in California's forest carbon offset program do not represent emission reductions (Badgley, Freeman, et al. 2022; Haya 2019; Haya et al. 2020). This issue is compounded by the design of forest carbon offset protocols in California's cap and trade program, which incentivize lengthened harvest rotations to increase forest carbon levels. These projects largely increase competition stress among trees and elevate fire risk in already overstocked forests, putting California Cap and Trade compliance offset markets in direct conflict with state wildfire prevention goals (Herbert et al. 2022). These carbon market critiques highlight that accurate baselines are one of the most critical components of measuring the carbon impact of forest carbon offsets and that traditional static baseline assumptions about economic and ecological factors tend to be inaccurate and overly simplistic.

Addressing the issues with carbon market creditability and quality requires refining methodologies for baseline creation and carbon accounting. Dynamic baselines that adapt to observed changes in surrounding forests can lead to more accurate carbon accounting and attribution of carbon benefits to specific practices (Fick et al. 2021; Haya et al. 2023). Dynamic baselines can also support the development of novel carbon contribution programs, which have emerged in response to carbon market critiques. Quickly evolving carbon contribution programs move away from carbon neutrality claims and reprioritize supply chain emission reductions. Remaining emissions are effectively self-taxed and the revenue is invested in projects with climate or social benefits. The shift is subtle, but carbon contribution programs reject the idea of equivalency between carbon emissions and carbon offsets, but instead acknowledge the harms caused by emissions and work to partially compensate those harms through direct investments in communities and nature. However, monitoring the impact of investments will be key to the success of carbon contribution programs (Blanchard, Anderegg, and Haya 2024). Dynamic baselines can increase the accuracy of monitoring carbon contribution program impact.

To date, carbon markets in forests have been designed to reduce risk for investors and project developers to the detriment of carbon benefit certainty, with protocols using fixed assumptions about ecological and economic assumptions to generate carbon credits ex-ante, based on predicted outcomes. Emerging dynamic baseline methods compare observed changes in a treatment area to changes in a similar reference region, allowing for the generation of credits ex-post, based on observed outcomes. These dynamic baselines coupled with ex-post crediting reduce climate risk and increase risk to project developers and investors, necessitating upfront capital for forest management before carbon credits are generated. This shift demands financial models which can accommodate delayed returns based on predictions about future ecological conditions, requiring developers and investors to bear the upfront costs and wait for outcomes to be verified before revenue flows. The success of such models hinges on their ability to manage risk effectively and incentivize upfront investment, which may include novel financial arrangements to mitigate the uncertainty of future carbon benefits.

While evolving quantification methods can increase rigor, certainty, and quality in the carbon market, fundamental questions about forest carbon offset projects will persist. Carbon stored in living systems has unique temporal characteristics that challenge equivalence between biogenic carbon storage and fossil fuel emissions (Galik and Jackson 2009; Carton, Lund, and Dooley 2021) and issues of permanence (Galik et al. 2022; Badgley, Chay, et al. 2022; Kaarakka, Rothey, and Dee 2023) which may not be appropriate to offsets for industrial emissions which have an immediate and lasting effects on atmospheric carbon levels (Carbon Market Watch 2023; Wu et al. 2023). Regardless of mechanisms, whether through traditional carbon offset programs or novel carbon attribution programs, payments made to forest managers that acknowledge and incentivize the multitude of ecosystem services forests provide will be critical to ensure the long-term viability of the ecosystems on which humanity depends. While analyses conducted for this dissertation do not employ a dynamic baseline approach, I propose methods to predict carbon sequestration rates and storage levels, which will be critical to successful scaling dynamic baseline approaches. Investors will be wary to provide project financing without clear predictions of carbon benefits and associated revenue over time.

The carbon benefits of forest restoration extend beyond the carbon sequestered in living trees. Utilizing low-value forest biomass – byproducts of forest management projects comprising treetops, branches, and small diameter trees – with appropriate environmental safeguards (Carbon Direct 2023) offers significant carbon benefits by leveraging the inherent photosynthetic potential of plants. Currently, removing or pile burning biomass after treatment increases carbon emissions and represents a substantial expense, up to $118 per ton biomass (Swezy, Bailey, and Chung 2021), money which could otherwise be spent on treating additional acres. Roughly, 10 bone dry tons of low-value biomass are generated per acre. Simply reducing the costs associated with disposing of this biomass could save up to $1,200 per acre based on numbers from Swezy, Bailey, and Chung (2021) and stimulating markets for biomass could generate additional revenue beyond simply cost savings. Converting biomass into products such as fuels and biopower or storing biogenic carbon in biochar and wood vaults further reduces carbon emissions associated with treatment and offers carbon removal benefits. Technologies such as biochar and wood vaults, which are both relatively technologically mature and market ready, can absorb large quantities of low-value biomass from forest thinning in an ad hoc and flexible manner that more capital-intensive products like fuels currently cannot (Elias et al. 2024).

Developing a robust and transparent biomass feedstock supply chain is essential for scaling high-carbon-benefit products like transportation fuels with carbon capture and sequestration (CCS). Feedstock contracts specifying timing, type, location, and biomass volume are necessary if woody-biomass based fuels is to become a reality. Biomass derived fuels can offer extensive carbon benefits (D. L. Sanchez et al. 2015), support statewide carbon neutrality goals by 2045 (Baker et al. 2020), and increase revenue for forest restoration (Cabiyo et al. 2021).

Developing low-value biomass supply chains can also provide critically needed project funding via traditional and carbon markets at the initiation of a project. Carbon revenue in the initial years of a project from biomass utilization is highly complementary with carbon revenue generated from avoided wildfire emissions via dynamic baseline, which generate revenue after a project is completed and carbon benefits can be observed and measured (Verra 2024; 2023; The Nature Conservancy 2022). But to weave together carbon income from highly temporally disparate sources, accurate predictive tools will be essential. These tools must account for the stochastic nature of wildfire and intricate carbon dynamics of forest management. Concurrently, the development of innovative financial instruments such as green bonds will be integral to leveraging diverse and novel sources of funding for restoration.

Bridging the multi-billion-dollar funding gap for forest restoration in California and throughout the U.S. requires impact-oriented investments into forest management. To unlock these novel investments, a broad range of methods are needed to effectively link predictions of forest carbon benefits with the needs of investors, requiring interdisciplinary tools and frameworks. This dissertation leans on perspectives from ecosystem services, forestry, finance, and industrial ecology to bridge the gap between investors and forest management. The complexity of the problem and the questions posed here demand linking methods such as stand level forest and statistical modeling to predict forest carbon levels over time, life-cycle analysis to calculate impacts of biomass utilization, and discounted cost flow analysis to predict financial returns of investments into carbon beneficial practices.

My goal in this dissertation is to advance the prediction and monetization of carbon benefits associated with forest restoration. Through these projects I have demonstrated the potential for investment into technology which uses low-value forest biomass as a feedstock such as transportation fuels, biopower, and biochar and the ability to link these products with both voluntary and compliance markets. I have also explored novel statistical methods for predicting the carbon impacts of restoring resilience to forests at highest risk for wildfire and the potential to bundle together carbon income from biomass utilization and avoided wildfire emissions. Through this work, I hope to contribute to the development of financially viable and ecologically sound funding strategies to enhance resilience in fire-prone forests.

1.2 Dissertation goals, research questions, structure, and thesis

The central question of this dissertation asks: what is the potential for carbon benefits from forest restoration to generate new funding streams? This dissertation aims to demonstrate the feasibility of industries for innovative wood products derived from low-value forest biomass and explore the potential to monetize the avoided wildfire emissions associated with restoring resilience to forests, defined as a forests ability to rebound after a disturbance such as wildfire while retaining its structure and function (M. P. North et al. 2022).

Below is a structured overview of the dissertation, detailing the contributions from each chapter. This work is interdisciplinary, combining perspectives from ecosystem services, carbon markets, forestry, ecology, and finance to create a carbon focused response to increasing funding for forest management. The methodological frameworks employed in these chapters include scenario analysis, discounted cost flow and financial analysis, market and policy analysis, lifecycle analysis, and stand level forest treatment modeling. This melding of methodologies reflects the complexity of rigorously integrating forest restoration with carbon finance. Stand level forest modeling enables projecting the impact of forest treatment over time, life cycle analyses capture the carbon dynamics of wood products, and financial analyses translates carbon benefits into tangible terms of investors.

Scientifically rigorous methods including those used in this dissertation are needed alongside financial innovation to monetize the carbon benefits of forest restoration with durability and relative certainty. Monetizing carbon is achievable and likely critical to securing the funding necessary for comprehensive forest restoration to support state climate and forest resiliency goals, but there are limitations to carbon finance and the instances in which it is appropriate. This dissertation helps to articulate key barriers and viable opportunities to unlock revenue from carbon benefits.

Specifically, it explores the carbon dynamics of biomass utilization and the potential to generate revenue from emerging markets for biomass. Biomass can displace higher carbon intensity feedstocks, but minimal investment has been made in the space. Lower capital expenditure technologies – those which require lower amounts of initial investments to build, may be able to help develop biomass supply chains and financial analysis can help encourage capital investments into companies making innovative products from biomass. Finally, this dissertation projects the carbon dynamics of restoring resilience to forests and explores whether the carbon benefits of biomass utilization and avoided wildfire emissions can generate enough revenue to pay for forest restoration.

1.2.1 Chapter 1: Financial analysis of innovative wood products and carbon finance to support forest restoration in California

Published in *Forest Products* (Elias et al. 2023).

Chapter 1 explores the challenge of biomass utilization and the potential for investment into innovative wood products which can utilize low-value biomass to make climate beneficial products. Specifically, it explores the return on investment of fuel and non-fuel products in a range of market and policy scenarios. To determine the potential of developing additional sources of revenue from low-value biomass, 12 different products are explored and several key questions are asked:

1. What is the carbon benefit of using low-value biomass to produce these products?
2. What is the economic feasibility of producing these products from low-value biomass?
3. How do different levels and types of carbon incentives affect economic feasibility?

I find that stimulating investment into markets for low-value biomass—such as tops and branches of trees, small trees, and dead trees—will add value to forest raw materials and provide additional revenue streams to pay for forest restoration. I evaluate the investment potential of products made from low-value biomass using a discounted cash-flow analysis of several possible forest products including fuels and non-fuels under various climate policy and market scenarios. I demonstrate the carbon benefits provided by these products, attributed to their substitution for fossil-fuel feedstocks and long-term carbon storage. My work finds that there is an opportunity to develop several highly profitable products, most notably fuels, many of which are eligible for energy and climate policy programs such as California's Low Carbon Fuel Standard and the federal Renewable Fuel Standard. Nonfuel products have an average internal rate of return (IRR) of 13 percent, whereas fuels have an average IRR of 19 percent in our baseline scenario. Although products ineligible for government incentives are generally less profitable, income from the voluntary carbon market greatly increases the IRR. Fostering investment into these products can encourage critically needed funding for forest management while developing a high-impact carbon removal solution enabled by state, federal, and voluntary climate initiatives. Based on this analysis, effective climate policy has the potential to facilitate forest restoration efforts in California.

1.2.2 Chapter 2: Market analysis of coupled biochar and carbon credit production from wildfire fuel reduction projects in the Western U.S.

Published in *Biofuels, Bioproducts, and Biorefining* (Elias et al. 2024).

Building on chapter 1, chapter 2 continues to explore the challenge of biomass utilization from forest restoration project. This chapter specifically explores biochar, which has a growing carbon credit market and is an immediately technologically feasible use case for low-value biomass. With the goal of understanding the potential for coupling forest restoration with biochar and carbon credit production, we answer the following questions for the state of California and the Western U.S:

1. What is the potential supply of woody biomass from forest restoration projects throughout California and the Western United States?
2. What is the current generation capacity for coupled biochar and carbon offset production in California? How many carbon credits could be generated given different production scenarios?
3. What is the potential demand for carbon credits coupled with biochar production?
4. What is the financial viability of different biochar production systems? How do fluctuations in carbon credit price, biochar price, and feedstock costs affect viability?
5. What is the potential for investment in biochar production?

I find that biochar production which utilizes woody biomass specifically from wildfire fuel thinning projects as a feedstock can financially contribute to much-needed fuel thinning projects. Each coupled biochar and carbon credit production system has positive returns in certain scenarios. Light upgrades to existing biopower facilities have the highest returns, with Internal Rates of Return generally between 10-30%. Mobile biochar production often had the lowest returns. However, land managers can subsidize mobile biochar production up to \$150 - \$300 USD per tonne biochar and still save money as compared to pile burning low-value biomass, while additionally generating approximately one carbon credit for every two bone dry tonnes of low-value biomass turned to biochar. The investment potential for biochar production from low-value forest biomass in the Western U.S. is over \$20 billion USD at current carbon prices. This investment could generate approximately 70 million carbon credits annual – roughly the same number currently generated globally by all forestry and agricultural carbon projects. The critical barrier to industry growth is the lack of transparent biomass supply chains which enable long-term contracting for feedstock, production schedules, and investment. Moving forward, there are three potential pathways for the biochar industry to scale and utilize biomass from forest management and fuel thinning projects. Either 1) the carbon market will need to sustain high carbon prices, 2) a subsidy or other mechanism will need to decrease the cost of feedstock biomass, or 3) production will need to take advantage of economies of scale to bring down biochar prices while increasing production.

1.2.3 Chapter 3: Carbon finance for fire-adapted forest management in California

In preparation for *Frontiers in Forests and Global Change* (Elias et al. 2024 in preparation).

Chapter 3 builds on the two previous chapters by exploring the carbon dynamics and potential for carbon finance to restore fire resilience to forests. Forest managers throughout California face the challenge of restoring forest resilience of fire-prone forests in an era of climate change and escalating wildfire risks while navigating financial constraints. Carbon finance can potentially play a role in supporting forest treatment by leveraging the carbon benefits of both avoided wildfire emissions and biomass utilization. In this chapter, I explore the carbon dynamics associated with restoring resilience to high fire risk forest plots and examine potential carbon revenue generated via avoided wildfire emissions and biomass utilization. The key questions explored are:

1. What are the carbon dynamics associated with restoring resilience to the American River watershed?
2. What is the value and certainty of different sources of carbon benefits?

I find that restoring a resilient forest structure in the American River watershed can generate up to $9850 per hectare ($4000 per acre) in carbon revenue from avoided wildfire emissions and biomass utilization, potentially fully funding forest management. Employing a dynamic baseline framework, this study assesses the impacts of restoring resilience to high-risk forests with thinning and prescribed fire. These practices show an initial carbon cost, but ultimately increase carbon storage compared to a no-treatment scenario by 86 Mt CO_2e per hectare (35 Mt CO_2e per acre) over 25 years, with market-ready biomass utilization options adding another 6 - 23 CO_2e benefit per hectare (2 - 9 CO_2e per acre). Treatment enhances carbon stability by shifting carbon storage from dense, overcrowded small trees to more dispersed, fire-resilient large trees and reduces fire severity (flame length) by 78% five years post-treatment. Compared to pretreatment levels, treatment decreases the number of trees on the landscape by 74% while increasing carbon storage by 6% at the end of the 25-year simulation. To reduce investor risk and generate carbon revenue from these treatments, treatments at scale and accurate predictive tools will be crucial. To maximize certainty of carbon benefits, dynamic baselines and ex-post carbon crediting will be critical. This study shows that carbon revenue from traditional markets or novel carbon attribution programs can help close the funding gap for forest restoration in California while underscoring the need for innovative conservation finance mechanisms to support ecosystem resilience and climate mitigation goals.

2 CHAPTER 1: Financial Analysis of Innovative Wood Products and Carbon Finance to Support Forest Restoration in California

Published in the journal *Forest Products (Elias et al. 2023)*.

2.1 Preface

Chapter 1 is a coupled carbon and financial analysis of several products which can be made from non-merchantable biomass, a costly by product of forest thinning projects. The analysis begins by quantifying the carbon benefit of utilizing waste biomass from forest thinning to create a range of fuel and non-fuel products and then performs a discounted cash flow analysis in different policy and market scenarios to identify the potential profitability of each product. In forest management throughout fire-prone forests, dealing with non-merchantable forest biomass represents a significant cost. Finding revenue generating alternatives to pile burning non-merchantable forest material would decrease per acre forest treatment costs and increase pace and scale of forest restoration. The work in this chapter was published in the journal *Forest Products* as an article titled, "Financial analysis of innovative wood products and carbon finance to support forest restoration in California," and is included with permission of my co-authors Bodie Cabiyo, John Dees, Phil Saksa, and Daniel L. Sanchez. This paper was completed in partnership with Blue Forest, a close research and industry partner, and was used to help launch the California Wildfire Innovation Fund (CWIF). CWIF is first of its kind climate investment fund that seeks to generate competitive financial returns while reducing fire risk. The fund targets investments in emerging opportunities across the forest restoration, wood utilization, and wildfire mitigation sectors, with particular emphasis on industries and projects that create value from non-merchantable woody biomass and achieve long terms carbon storage and sequestration outcomes. CWIF was created in partnership with CSAA Insurance Group. This work was funded by a CalFire Forest Health Research Grant.

2.2 Introduction

In California, 90% of the largest and most destructive fires in recorded history have occurred since 2010. CalFire fire suppression expenditures have increased as well, topping $1 billion for the first time in both 2020 and 2021, in contrast to average yearly expenditures of $167 million between 2000-2005. Although fire is a natural and necessary process in the Sierra Nevada and many other dry western forests, the increasing extent and severity of wildfires threatens the resilience of both social and ecological systems (Barros et al. 2018).

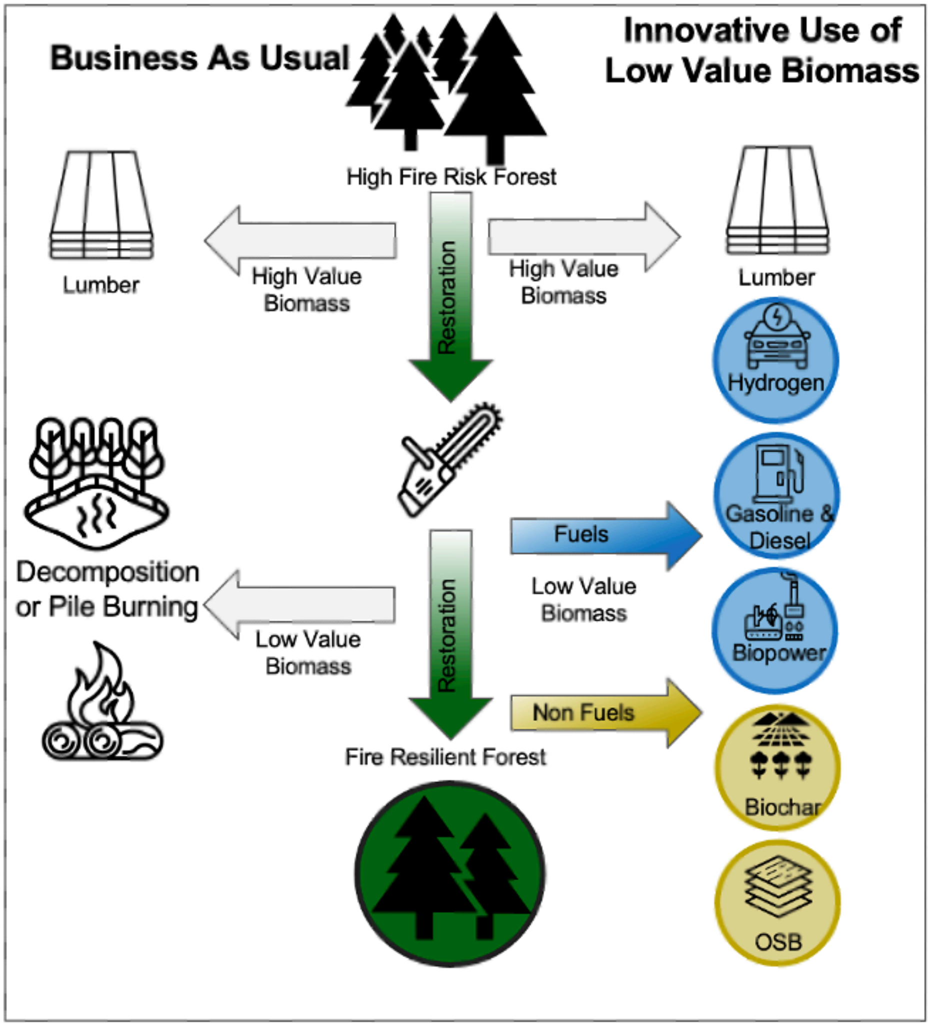
The increasing severity of the wildfires throughout California has been caused by management decisions such as fire exclusion which have in turn been exacerbated by climate change. These factors have created younger, denser, and more homogenous forests which are susceptible to high severity, stand replacing fires (Collins, Everett, and Stephens 2011; Lydersen and Collins 2018; McIntyre et al. 2015). These management impacts have been amplified by a lengthening fire season and increasing occurrence of extreme fire weather (Jain, Fried, and Loreno 2020), shifting seasonality of precipitation (Swain 2021), and increasing temperature (J. D. Miller et al. 2009).

To increase the resilience of the Sierra Nevada and other Dry Western Forests to ensure the continuity of ecological function and ecosystem benefits to human populations, a substantial increase in forest management is needed. Oftentimes, this management takes the form of mechanical and hand thinning of dense, overcrowded forest stands followed by the reintroduction of low severity burning. With approximately 50 million acres in need of treatment ("Confronting the Wildfire Crisis" 2022) at an average cost of at least $1,000 per acre (Chang 2021),the current need of $50 billion is roughly 100 times higher than Forest Service preventative treatment allocations, which was $0.5 billion in 2017 (U.S. Forest Service 2016).

California's Forest Action Team and the State of California have a goal to reduce wildfire risk on 1 million acres of combined public and private land (Forest Climate Action Team 2018). To achieve these goals, the plan calls for fuel reduction treatments, timber harvests, and expanded use of harvested wood products. Management, including mechanical thinning and prescribed fire, can reduce the risk of high severity wildfire while providing multiple benefits (Kalies and Yocom Kent 2016; Stephens, Battaglia, et al. 2020). To fund forest management on public land historically, congressional appropriations have been combined with receipts from timber sales. However, treatment is often costly on both public and private lands even when the sale of merchantable sawlogs is possible. In many cases, the effectiveness of fuel treatments is dependent on the removal of small trees, which generally are low-value and do not have viable markets. Income from markets for small trees, residues from forest management, and other forms of low-value biomass could provide much needed revenue to scale forest restoration, but market demand is currently limited. As a result of lackluster market demand, large amounts of low-value biomass are left to decay or are burned after treatment, releasing their carbon to the atmosphere. Developing and fostering markets for low-value biomass such as branches, small trees, dead trees, and tops can increase the funding available for forest management.

Utilizing low-value biomass as a feedstock to create innovative wood products is highly beneficial from a carbon removal or abatement perspective (Bergman et al. 2014; Baker et al. 2020; Cabiyo et al. 2021). These carbon benefits primarily accrue from the substitution for fossil fuel feedstocks in products like transportation fuels as well as from the long-term storage of carbon in products like building materials and biochar. These substitution and storage benefits can be financially leveraged through incentive programs like California's Low Carbon Fuel Standard (LCFS) ("Low Carbon Fuel Standard," n.d.), the Federal Renewable Fuel Standard (RFS) ("Renewable Fuel Standard Program" 2015), 45Q tax credits (Internal Revenue Service 2021), and the voluntary carbon market to increase the profitability of these innovative wood products.

Figure 1: Innovative Wood Products
Non-merchantable woody biomass generated during forest restoration is currently left in the forest to decompose or burn. However, that biomass could be used to create a range of carbon beneficial fuel and non-fuel products.



In this study, we examine the financial viability of a range of fuel and non-fuel products that can be made from low-value biomass in three different carbon incentive scenarios. These products are categorized as fuel and non-fuel products (see Figure 1). Non-fuel products included are oriented strand board (OSB), biochar from a mobile pyrolysis unit, and biochar produced in a centralized facility. The fuel products included are pyrolysis fuels, Fischer-Tropsch fuels, Fischer-Tropsch fuels with CCS, hydrogen, hydrogen with CCS, renewable natural gas, renewable natural gas with CCS, biopower, and biopower with carbon capture and sequestration (BECCS) (see Table 1 for acronyms and definitions). Biopower and BECCS are considered fuels because the electricity is assumed to power electric vehicles, making both biopower and BECCS eligible for LCFS credits in California. These products vary in terms of market readiness, but represent a range of possible products which can be made from low-value wood.

To determine the potential of increasing funding for forest management by developing additional sources of revenue from low-value biomass, we examine twelve different products and ask several key questions:

1. What is the carbon benefit of using low-value biomass to produce these products?
2. What is the economic feasibility of producing these products from low-value biomass?
3. How do different levels and types of carbon incentives affect economic feasibility?

To answer these questions, we conduct a financial analysis incorporating carbon incentives using existing voluntary carbon market credits as well as existing State and Federal policies in California.

2.3 Methods

We examine twelve innovative wood products in this study, divided into non-fuel products and fuel products. These products are amongst the most promising identified by the State's Joint Institute for Wood Products Innovation (D. Sanchez and Gilani 2022). The carbon benefit of using biomass as a feedstock is first assessed based on existing literature. We then perform a discounted cash flow analysis for each product. Each of these wood products is technically feasible and rely on different forms of low-value biomass. OSB for example, requires small-diameter (pulpwood) logs while the production of hydrogen can utilize mixed biomass including tops, branches, leaves, and bark. This analysis is agnostic to the type of feedstock necessary and uses the term feedstock interchangeably between pulpwood, wood chips, and other forms of low-value biomass. It is also assumed that all facilities have enough feedstock to meet yearly requirements and the feedstock costs used represents delivered costs.

Table 1: Acronyms and definitions of common terms.

Term	Meaning	Description
Fuel Products		Fuel descriptions adapted from Baker et al. (2020).
FT Fuels	Fischer-Tropsch Fuels	Formation of liquid transportation fuels (gasoline and diesel) from the gasification of biomass followed by Fischer-Tropsch syntheses. The final products are typically gasoline and diesel blend stocks identical to their fossil-derived counterparts.
FT Fuels + CCS		Fischer-Tropsch Fuels produced with carbon capture and sequestration incorporated.
RNG	Renewable natural gas	Produced by upgrading biogas or syngas into a product which can supplement or replace traditional natural gas.
RNG + CCS		RNG produced along with the capture and sequestration of CO_2 emitted during production.
Hydrogen		Formed from syngas by converting carbon monoxide and water into CO_2 and hydrogen.
Hydrogen + CCS		Hydrogen has a high potential quantity of CO_2 which can be captured because the fuel produced (hydrogen) does not contain carbon. This is in part why hydrogen + CCS has the largest carbon benefits of the products modelled.
BECCS	Bioenergy with carbon capture and storage	Creating electricity from biomass and capturing and storing the carbon, removing it from the atmosphere.
Pyrolysis Fuels		Thermochemical conversion which decomposes biomass in gas, liquid, and solid products. Bio-oil is upgraded into liquid transportation fuels (gasoline and diesel).
Non-Fuel Products		
Biochar		Material obtained from the pyrolysis of biomass in an oxygen-limited environment.
OSB	Oriented Strand Board	Building material formed by compressing adhesives and layers of wood strands in specific orientations, similar to particle board.
Incentive Programs		
45Q	Section 45Q of the Internal Revenue Code	Tax credit ($10-$50) for each metric ton of carbon captured and sequestered, depending on type of geologic storage.
RFS	Renewable Fuel Standard	Congressionally created program designed to reduce greenhouse gas emissions and expand renewable fuels sector.
LCFS	California Low Carbon Fuel Standard	State created program to decrease the carbon intensity of transportation fuels.
Abbreviations		
CAPEX	Capital Expenditures	Major long-term expenses such as physical assets, buildings, equipment, and vehicles.
OPEX	Operational Expenditures	Day-to-day expenses including salaries, rent, utilities, and costs of production.
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model	Analytical tool that conducts a Life Cycle Analysis by simulating the energy use and emission outputs of various vehicles and fuels.
IRR	Internal Rate of Return	Method for calculating an investment's rate of return. The IRR estimates a project's breakeven discount rate, indicating profitability potential.
RIN	Renewable identification number	Credit generated each time a gallon of renewable fuel is produced per the Renewable Fuel Standard (RFS)
CCS	Carbon capture and sequestration	Technologies which capture and compress CO_2 from industrial processes then inject the compressed CO_2 in deep geologic formations.

2.3.1 Carbon Benefit Analyses

To determine the carbon benefit of utilizing biomass to create each product, we rely on published values, primarily from Cabiyo et al. (2021), to model the cradle-to-grave and well-to-wheels carbon benefit of biomass utilization. The system boundaries are drawn such that we assess carbon emissions and benefits across four life cycle categories: 1) *transportation emissions* 2) *production emissions* - accounts for all direct and upstream emissions from fossil fuels used onsite in handling and conversion of biomass. Biogenic carbon emissions are treated as neutral, as it is assumed these wastes would have returned carbon to the atmosphere via degradation or burning (see Discussion). 3) *substitution of carbon-intensive products* - assumes 1:1 replacement and emissions avoidance of conventional electricity and fuels in the California context, and 4) product end of life - includes combustion of final fuels and decay of recalcitrant and long-lived forest products. Data from the Greenhouse Gasses, Regulated Emissions, and Energy Use in Transportation (GREET) model are used for all process and substituted fuels and electricity. Products and co-products are assumed to displace incumbent sources of emissions where appropriate (described below). For a full accounting of scenario outputs, see Table 5. Biomass-derived electricity is assumed to displace the average distributed California grid in 2019 with an emissions factor of 224 $kgCO_2e/MWh$. Renewable natural gas (RNG) is assumed to displace a mix of North American natural gas with an average emissions factor of 73.9 gCO_2e/MJ, which includes both extraction and eventual combustion. All woody feedstocks are assumed to be 50% C by mass. Carbon benefit is the sum of all non-biogenic emissions minus avoided emissions and storage. Carbon benefits were calculated in terms of tC benefit per bone dry ton of woody biomass.

2.3.2 Scenario Descriptions

Transport and harvest - Feedstock harvest and transport emissions are consistent across pathways. We assume a 90-mile average travel distance by heavy duty diesel truck with a 16-ton payload, accounting for backhaul. The truck has a fuel economy of 7.17 mi/gal loaded and 9.03 mi/gal backhaul.

The centralized pyrolysis biochar scenario assumes a slow pyrolysis system based on Lehmann (2015) where 35% of feedstock carbon ends up in the biochar, 30% goes to pyrolysis oil, and 35% to the syngas fraction. As in Lehmann, we assume bio-oil and syngas are combusted for heat and power in the facility. The operation generates net power for export to the grid at a rate of 0.31 MWh/ metric ton of feedstock. The power export is assumed to displace the average distributed California grid. The process requires auxiliary diesel fuel and natural gas at a rate of 2.09kg/t and 3.1 kg/t of feedstock, respectively. Relying on updated emissions factors from the GREET model, diesel and natural gas contribute ~8 $kgCO_2e/t$ and ~10 $kgCO_2e/t$ of feedstock respectively. Combustion of biogenic fuels (syngas and pyrolysis oil) is assumed to yield net zero CO_2e emissions. Carbon storage in biochar assumes that 85% of the carbon is recalcitrant while 15% is labile, with half-lives of 300 years (k_{recalc} = -0.002) and 20 years (k_{labile} = -0.035), respectively. Carbon remaining sequestered in biochar is assessed at the 100-year time horizon, with ~68% remaining. The fraction of carbon remaining at 100 years is described by the two-pool model in equation 1.

Equation 1: % C remaining at 100 years = (labile % * $\exp(100k_{labile})$) + (recalcitrant % * $\exp(100k_{recalc})$)

The mobile pyrolysis biochar scenario follows the analysis of the case 2 “no dryer” scenario in Thengane et al (2020). However, Thengane assumes a dry basis carbon content of 46% in the feedstock. For consistency, we recalculated the results from Thengane assuming 50% carbon content. In this scenario, 32% of feedstock carbon is retained in the biochar. Pyrolysis oil and syngas fractions are combusted and emitted. There is no power generation assumed in this scenario. Propane is combusted as auxiliary fuel at a rate of 38 t/t feedstock. The emissions factor for propane is obtained from the GREET model at a rate of 0.59 $kgCO_2e/kg$ propane combusted. The biochar carbon in this scenario is assumed to be 93% recalcitrant and 7% labile. The half-lives assumed are the same as in the slow pyrolysis scenario. ~74% of the carbon in the biochar is assumed to remain after 100 years (see equation 1 above).

The renewable natural gas scenarios, both with and without carbon capture and sequestration (CCS), are based on a life cycle assessment performed by the Gas Technology Institute (GTI) ("Low-Carbon Renewable Natural Gas (RNG) From Wood Waste" 2019) for the California Air Resources Board (CARB). All assumptions from Tables 19 and 20 of that report remain unchanged save for the emissions credits awarded for net power exported to the grid, the quantity of CO_2e captured in the CCS case, and feedstock harvest and transport. As in the previous scenarios, we substitute our feedstock and harvest emissions for those used in the GTI report. The emissions intensity of the California average grid is used to calculate credits for displaced grid power at a rate of 85 kj/MJ of RNG in the no-CCS case and 45 kj/MJ RNG in the CCS case. We use grid emissions factors from a more recent GREET model, as described earlier in this section. We also explicitly model the parasitic load for compression of captured CO_2e and deduct that load from the available power export at a rate of 200 kWh/tCO_2e in the CCS case. We update the carbon content of feedstock assumption to 50% for consistency which changes the balance of CO_2e available for capture. The CI of RNG in the non-CCS case is ~20gCO_2e/MJ (vs 16 gCO_2e/MJ in the GTI report) and in the CCS case -42 gCO_2e/MJ (-77gCO_2e/MJ in the GTI report). Process emissions do not include electricity credits in the results section. Rather, the substitution benefit is the combined effect of displaced grid power and displaced conventional natural gas using the GREET emissions factor described previously.

2.3.3 Baseline Economic Scenario and Discounted Cash Flow Analysis

To establish baseline economic scenarios for each product (see Table 2), we incorporate published techno-economic analyses to compile the initial capital expenditures required to build manufacturing facilities, the yearly operating expenditures, and the yearly feedstock required to achieve production targets.

Table 2: Baseline scenario economic assumptions. See Table 1 (above) for complete acronyms.

	Baseline (USD)	Unit
Feedstock	$60	Bone Dry Ton (BDT)
LCFS	$100	Ton CO_2e
RIN	$0.91	Gallon Gasoline Equivalent (GGE)
45Q	$50*	Ton CO_2e
Voluntary carbon market - Biochar	$90	Ton CO_2e
Voluntary carbon market - OSB	$30	Ton CO_2e
Electricity (50MW BECCS)	$120	Megawatt Hour (MWh)
Electricity (3MW Biopower)	$195	Megawatt Hour (MWh)
OSB	$224	3/8" Thousand Square Feet (MSF)
Biochar	$425	Ton
Diesel	$2.25	Gallon
Gasoline	$2.25	Gallon
Hydrogen	$1.40	Kilogram (KG)
RNG	$11.00	Million Metric British Thermal Unit (MMBTU)

* Policy cliff scenario is assumed. 45Q is discontinued after 12 years in accordance with current legislation.

Income from primary products, coproducts, and applicable carbon incentives (LCFS, RFS, 45Q, and voluntary carbon market) are incorporated into yearly revenue (see Tables 3 and 4). Carbon incentives modeled include income from California's Low Carbon Fuel Standard (LCFS), the Federal Renewable Fuel Standard (RFS), 45Q carbon capture and sequestration tax credits, and voluntary carbon market credits, as applicable. After costs and revenue are calculated, the Internal Rate of Return (IRR) is calculated for each product over a 20-year timeframe to create high, low, and baseline carbon incentive scenarios. A construction period of one year is assumed for each product and full production of primary products and generation of carbon incentives is assumed to start in year two. Existing literature is used to build the baseline economic (Table 2) and baseline technological assumptions (Table 4) scenarios for each product including OSB ("California Assessment of Wood Business Innovation Opportunities and Markets (CAWBIOM). Phase II Report: Feasibility of Potential Business Opportunities" 2015), biochar from a mobile pyrolysis unit (Thengane et al. 2020), biochar produced in a centralized facility (Lehmann and Joseph 2015), pyrolysis fuels (W. Li et al. 2017), Fischer-Tropsch fuels (Liu et al. 2011), Fischer-Tropsch fuels with CCS (Liu et al. 2011), hydrogen (Sarkar and Kumar 2009), hydrogen with CCS (Sarkar and Kumar 2009), renewable natural gas ("Low-Carbon Renewable Natural Gas (RNG) From Wood Waste" 2019), renewable natural gas with CCS ("Low-Carbon Renewable Natural Gas (RNG) From Wood Waste" 2019), biopower ("California Assessment of Wood Business Innovation Opportunities and Markets (CAWBIOM). Phase II Report: Feasibility of Potential Business Opportunities" 2015), and biopower with carbon capture and sequestration (BECCS) (Bhave et al. 2017).

The manner in which carbon incentive programs are incorporated into the financial analysis are intended to be as realistic as possible and aligned with current policy, per Sanchez and Gilani (2022). For a comprehensive list of the carbon incentives incorporated into the baseline financial analysis of each product, see Table 4. The baseline carbon incentive scenario for each product (Table 2) attempts to capture current market prices for all primary products and carbon incentives keeping high volatility in mind. The LCFS price used for the baseline scenario ($100 per ton CO_2e) takes into consideration the yearly average from 2020 of $200 per ton CO_2e, the yearly average from 2021 of 178 per ton CO_2e, and transactions averaging $92 per ton CO_2e in the third quarter of 2022. ("Weekly LCFS Credit Transfer Activity Reports," n.d.). RIN credit pricing in the baseline scenario ($0.91 per ton CO_2e) represents the median transaction price over the between 2016-2021. The median was used given the stability of the RIN market as compared to the volatility in the LCFS market. The baseline scenario assumes that half of the feedstock originates on private land and half on public land; currently feedstock originating on federal land is not eligible for RIN credits (D. Sanchez and Gilani 2022). Thus, only half of the feedstock utilized generates RIN credits. 45Q tax credits are assumed to be $50 per ton CO_2e (Jones and Sherlock 2021) with the policy lapsing after 12 years. Voluntary carbon market pricing for OSB ($30 per ton CO_2e) is based on the prices for similar credits being sold by Puro.earth (Puro.earth, n.d.) in 2022 while pricing for biochar carbon credits ($90 per ton CO_2e) is based on the NASDAQ price index for biochar carbon credits ("Carbon Removal Price Indexes," n.d.). Market rates for primary products including biochar (Thengane et al. 2020), OSB ("California Assessment of Wood Business Innovation Opportunities and Markets (CAWBIOM). Phase II Report: Feasibility of Potential Business Opportunities" 2015), electricity (K. Li 2022; "Bioenergy Market Adjusting Tariff (Senate Bill 1122)," n.d.; "Electricity Monthly Update"

2022), RNG ("Natural Gas Monthly" 2022), gasoline and diesel ("Gasoline and Diesel Fuel Update" 2022), and hydrogen ("Global Hydrogen Review 2021" 2021) are highly variable by region, plant size, and production method. The assumptions in this analysis (Table 3) are based on recent market trends and attempt to capture realistic baseline prices for each primary product. Income from carbon incentives is assumed to occur the same year the primary product is generated. Each year that products generating carbon benefits is produced, additional income is captured in the discounted cost flow analysis.

2.3.4 Carbon Incentive Scenario Analysis

Two scenario analyses are conducted which examine high and low carbon incentive scenarios (see Figures 2 and 3) over a 20-year timeframe. Each scenario examines high and low assumptions for LCFS, RIN, 45Q, and voluntary carbon markets separately while holding all other variables and carbon incentives constant at the baseline (see Table 3). Certain scenarios examine the effect of current policy hypothetically not being renewed (policy cliff), such as the LCFS low carbon incentive scenario, while others examine the effect of a drop in market price, such as the voluntary carbon market price. Policy cliffs are created based on the current legislation and informed by the authors' expert opinions. The assumptions for each scenario are listed explicitly in Table 3. LCFS pricing in the high carbon incentive scenario is $125 and in the low carbon incentive scenario is $100 but terminates after 10 years. The low RIN scenario assumes all feedstock originates on public land and is thus not eligible for RIN credits while the high scenario is $3.04, which is the 95th percentile of RIN pricing between 2016 – 2021. 45Q tax credits pricing is dependent on how the CO_2e is sequestered. The low carbon incentive scenario assumes a price per ton CO_2e of $35 with the policy lapsing after 12 years, in line with current legislation. The high carbon incentive scenario assumes a price per ton CO_2e of $50 with the policy being renewed for the 20 years used in this analysis. Voluntary carbon market price for both biochar and OSB is informed by recent market ranges (Puro.earth, n.d.; "Nasdaq Carbon Removal Marketplace and Technologies," n.d.).

Table 3: carbon incentive scenario assumptions.

Key Variable	**Low**	**Baseline**	**High**	**Unit**
Feedstock	$40	$60	$120	Bone Dry Ton (BDT)
LCFS	$100*	$100	$125	Ton CO2e
RIN	$0	$0.91	$3.04	Gallon Gasoline Equivalent (GGE)
45Q	$35*	$50*	$50	Ton CO2e
Voluntary Carbon Market - Biochar	$20	$90	$120	Ton CO2e
Voluntary Carbon Market - OSB	$15	$35	$45	Ton CO2e

* Policy cliff scenario is assumed. LCFS discontinued after 10 years. 45Q discontinued after 12 years. RIN is assumed to be continuously present or absent at given prices. Policy assumptions built to best reflect current legislation; see Methods.

2.3.5 Sensitivity Analyses

To understand how fluctuations in cost and income affect the baseline economic scenarios, a sensitivity analysis is conducted by increasing and decreasing various parameters by 40% in increments of 10%. The parameters analyzed included feedstock cost, operational expenditures (OPEX), capital expenditures (CAPEX), price of the primary product, carbon benefit, LCFS price, RFS price, and 45Q credit for each eligible product. The associated percent changes in IRR are displayed in Figures 4 and 5.

Table 4: Technological assumptions.

	CapEx (million)	OpEx per ton feedstock (excludes feedstock costs)	Annual Feedstock Requirement (Bone Dry Tons)	Annual Capacity		Monetized Products	Eligible Carbon Incentives	Baseline Internal Rate of Return	Baseline Net Present Value (million)
Fuel Products									
Biopower	$27	$57	30,000	3	Megawatts	Electricity and Steam	LCFS	4%	$-3
Biopower + CCS	$1,059	$9	829,000	50	Megawatts	Electricity	LCFS	14%	$972
FT Fuels	$1,086	$94	1,176,359	23.1 Million 39.3 Million	Gallons Gasoline Gallons Diesel	Gasoline, Diesel, and Electricity	LCFS, RIN	6%	$72
FT Fuels + CCS	$1,106	$109	1,176,359	23.1 Million 39.3 Million	Gallons Gasoline Gallons Diesel	Gasoline, Diesel, and Electricity	LCFS, RIN, 45Q	17%	$1287
RNG	$509	$96	310,610	2.9 Billion	Cubic Feet	Renewable Natural Gas	LCFS, RIN	-4%	$-299
RNG + CCS	$519	$112	310,000	2.9 Billion	Cubic Feet	Renewable Natural Gas	LCFS, RIN, 45Q	9%	$164
Hydrogen	$267	$98	620,500	51.8 Million	Kilograms Hydrogen	Hydrogen	LCFS	17%	$317
Hydrogen + CCS	$283	$113	620,500	51.8 Million	Kilograms Hydrogen	Hydrogen	LCFS, 45Q	51%	$1395
Pyrolysis Fuels	$340	$3	656,416	33.3 Million 24.3 Million	Gallons Gasoline Gallons Diesel	Gasoline and Diesel	LCFS, RIN	35%	$1,106
Non-Fuel Products									
Biochar Mobile	$0.74	$103	2,933	1350	Tons Biochar	Biochar	Voluntary Carbon Market	18%	1
Biochar Centralized	$21	$106	70,080	24,500	Tons Biochar	Biochar and Electricity	Voluntary Carbon Market	24%	42
OSB	$216	$332	334,500	475	Million square feet	Oriented Strand Board	Voluntary Carbon Market	13%	163

2.3.6 Feedstock Price Assumptions and Price Analysis

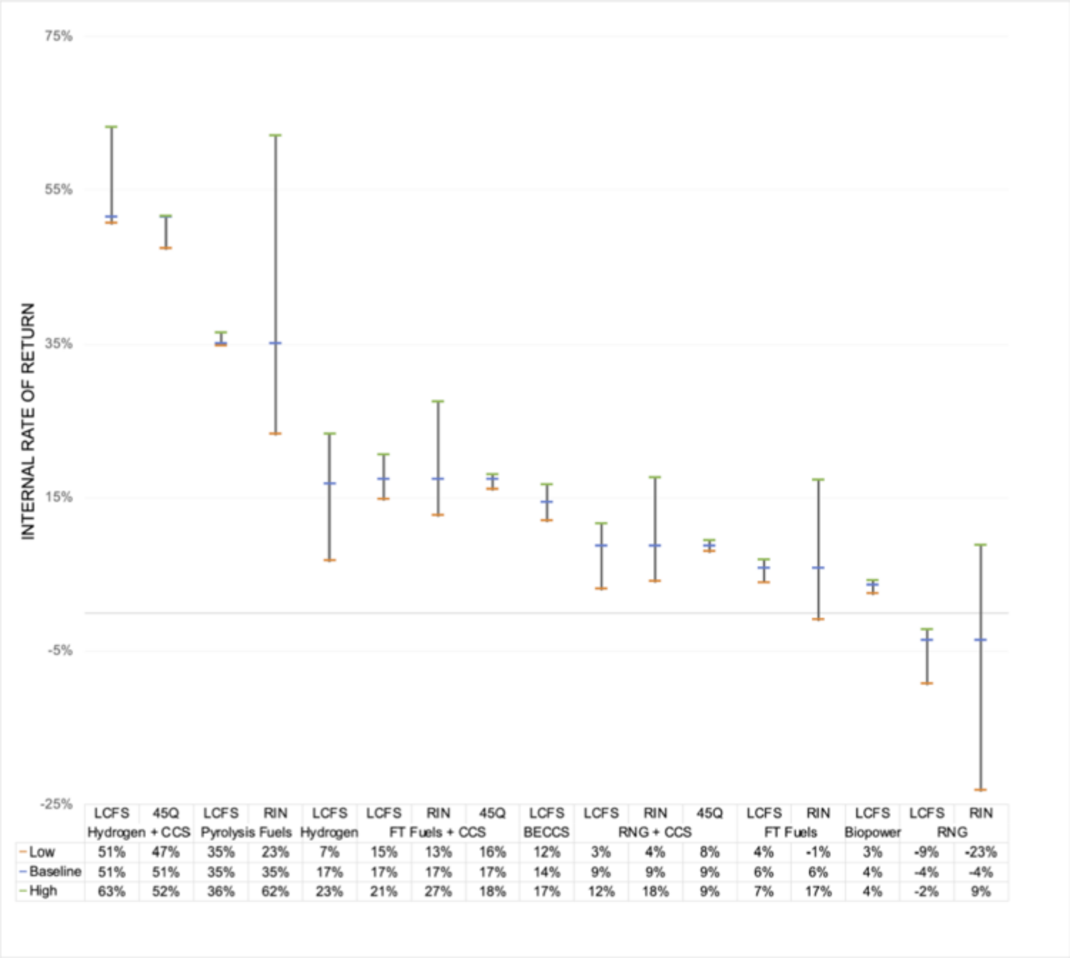
Feedstock costs are generally broken down into collection/ processing and transportation in the literature. Costs associated with harvesting, chipping, and hauling low-value biomass to a production facility vary greatly. These costs will be impacts by the objective of the forest management - whether explicitly a harvest, a fuel reduction, or some combination - as well as equipment technology, harvest objective, site conditions, and haul distance all of which will in turn affect the delivered feedstock costs (Lord et al. 2006). The baseline feedstock cost assumption of $60 per ton is considered the average annual delivered cost per bone dry ton (BDT) and is based on ranges in the literature from California and Oregon between $45 to $70 (Springsteen et al. 2015), $55 to $120 (Swezy, Bailey, and Chung 2021), $35 to $65 ("California Biomass Utilization Facility Feedstock Supply Report" 2018), and $35 to $66 (Lord et al. 2006). The effect of fluctuations in feedstock price is captured in Figure 6, in which all other variables aside from feedstock cost are held constant at the baseline economic assumptions (Table 3) and feedstock cost assumed to have a low of $40 per BDT and a high of $120 per BDT.

2.4 Results

An analysis of the carbon incentive scenarios' financial impact on fuel products highlights hydrogen + CCS as a standout product in our assumed baseline scenario (see Figure 2). Hydrogen + CCS has the highest IRR of the fuel products, with an IRR of over 45% even in the low carbon incentive scenario, but importantly our modeling does not account for hydrogen storage and transport. Pyrolysis fuels are also highly profitable, with an IRR over 30% in the high carbon incentive scenario and an IRR over 20% in the low carbon incentive scenario, which assumes an absence of RIN credits or a discontinuation of LCFS credits after 10 years. Hydrogen does not have quite as high of an IRR, but is still between 7 - 23% in each of the carbon incentive scenarios.

The hydrogen + CCS facility we modeled is highly profitable and relatively market ready compared to some of the other fuels modeled. Although hydrogen + CCS is the standout product in this analysis many of the other fuel products have an IRR of 5% or higher in our baseline carbon incentive scenario, with the notable exception of renewable natural gas (without CCS) which had a negative IRR in each scenario and biopower which had an IRR below 5% in each scenario.

Figure 2: Fuel products carbon incentive scenarios. Depiction of the high, baseline, and low carbon incentive scenarios for each fuel product. The scenarios for each variable (LCFS, RIN, or 45Q) hold all other variables constant at the baseline scenario.



	LCFS	45Q	LCFS	RIN	LCFS	LCFS	RIN	45Q	LCFS	LCFS	RIN	45Q	LCFS	RIN	LCFS	LCFS	RIN
	Hydrogen + CCS		Pyrolysis Fuels		Hydrogen	FT Fuels + CCS			BECCS	RNG + CCS			FT Fuels		Biopower	RNG	
− Low	51%	47%	35%	23%	7%	15%	13%	16%	12%	3%	4%	8%	4%	-1%	3%	-9%	-23%
− Baseline	51%	51%	35%	35%	17%	17%	17%	17%	14%	9%	9%	9%	6%	6%	4%	-4%	-4%
− High	63%	52%	36%	62%	23%	21%	27%	18%	17%	12%	18%	9%	7%	17%	4%	-2%	9%

Our low carbon incentive scenario for fuels includes downward fluctuations in LCFS, RIN, and 45Q credit prices as those are the incentives over which policy has direct control. Due to the multiple sources of revenue, including state incentives as well as primary and secondary products, the IRR impacts from fluctuations in any one source of income were mediated by other income.

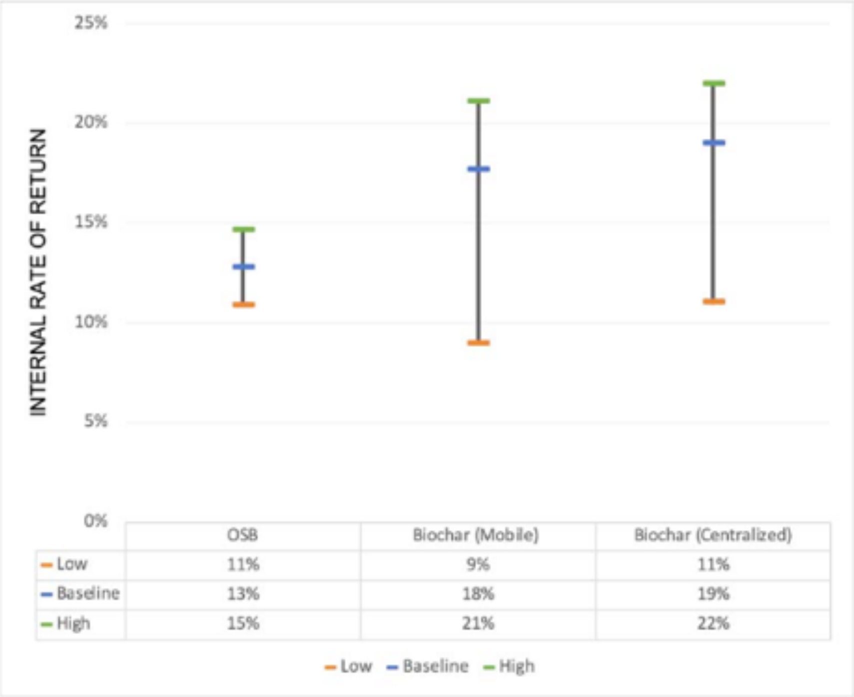
In this model, we build in realistic conservativeness wherever possible, such as including 50% contingency to CAPEX for fuels (excluding BECCS and biopower which received 30% contingency) and 30% contingencies for non-fuels. With that in mind, there are likely a number of unforeseen real-world costs that were not captured by the techno-economic analyses incorporated in this study due to the relatively low technology readiness of certain technologies.

An analysis of voluntary carbon market income on the IRR of non-fuel products (Figure 3) finds that biochar (mobile) has an IRR of 9% in the low carbon incentive scenario (\$20/ ton CO_2e) and 21% in the high carbon incentive scenario (\$120/ ton CO_2e) while biochar (centralized) has an IRR of 11% in the low carbon incentive scenario and 22% in the high scenario. OSB is minimally affected by income from the potential voluntary carbon market, going from 11% in the low scenario (\$15/ ton CO_2e) to 15% in the high scenario (\$45/ ton CO_2e) in part due to the lower carbon credit prices for OSB as compared to biochar.

The most carbon beneficial products are fuel products coupled with CCS (see Table 5). The substantial carbon benefit of fuels coupled with CCS is in large part due to the substitution benefit of using biomass in place of fossil fuels alongside the CO_2e captured and stored from the production processes, which is captured in our carbon benefits calculations. The least carbon beneficial product is biopower, due to a lack of carbon storage benefits and relatively small substitution benefits given the relatively high penetration of renewable energy in California's grid.

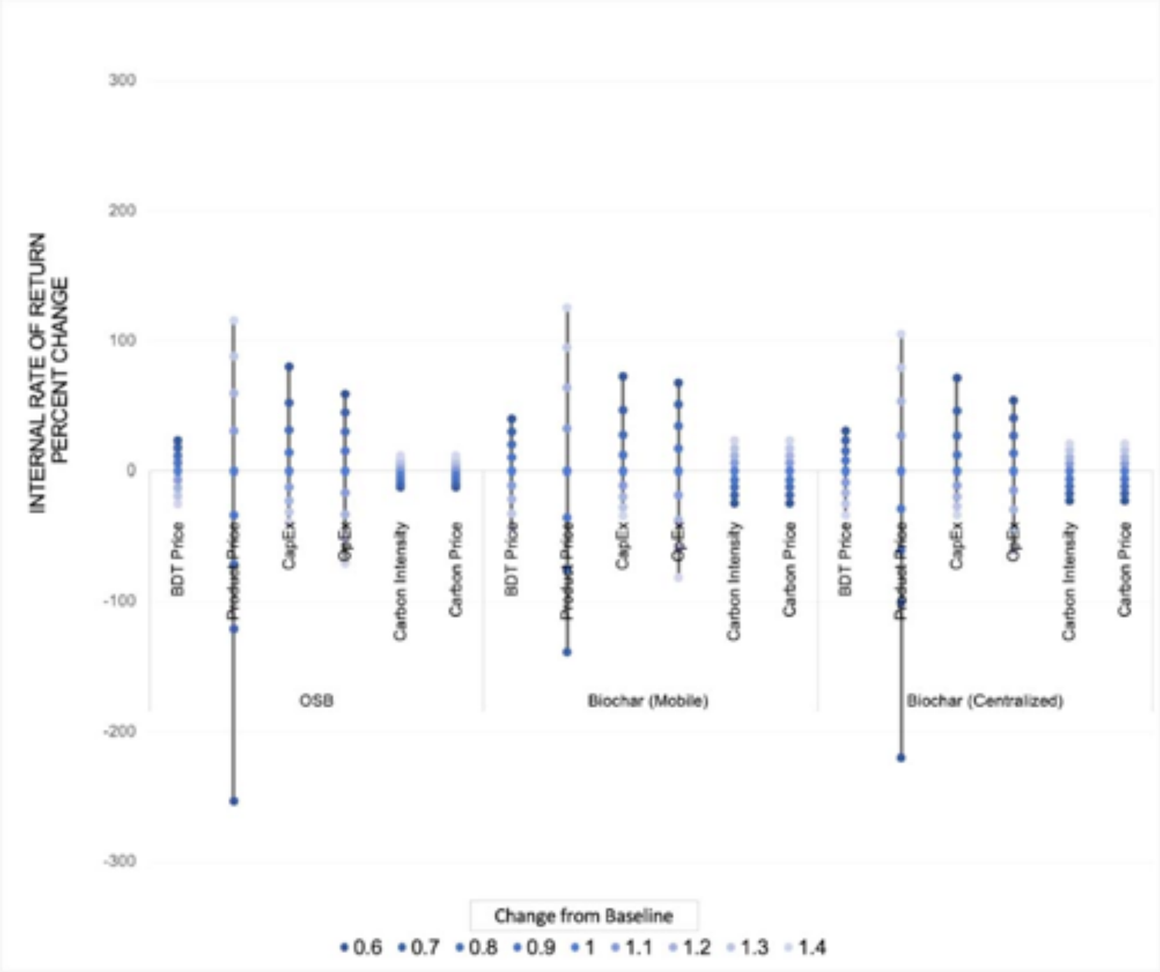
The sensitivity analysis of the wood products is divided into non-fuel and fuel products (see Figures 4 and 5). Non-fuel products are highly sensitive to many parameters. Primary product price (which excludes price for any coproducts) in particular has a high impact on the IRR. For example, a 20% decrease in product price from the baseline scenario decreases the IRR for OSB by 71%, biochar (mobile) by 75%, and biochar (centralized) by 60%. This likely reflects these products' reliance on market, rather than policy-derived, revenues.

Figure 3: Nonfuel products carbon incentive scenarios. Depiction of the high, baseline, and low carbon incentive scenarios for each nonfuel product. The inly incentive program examined for these products is voluntary carbon market.



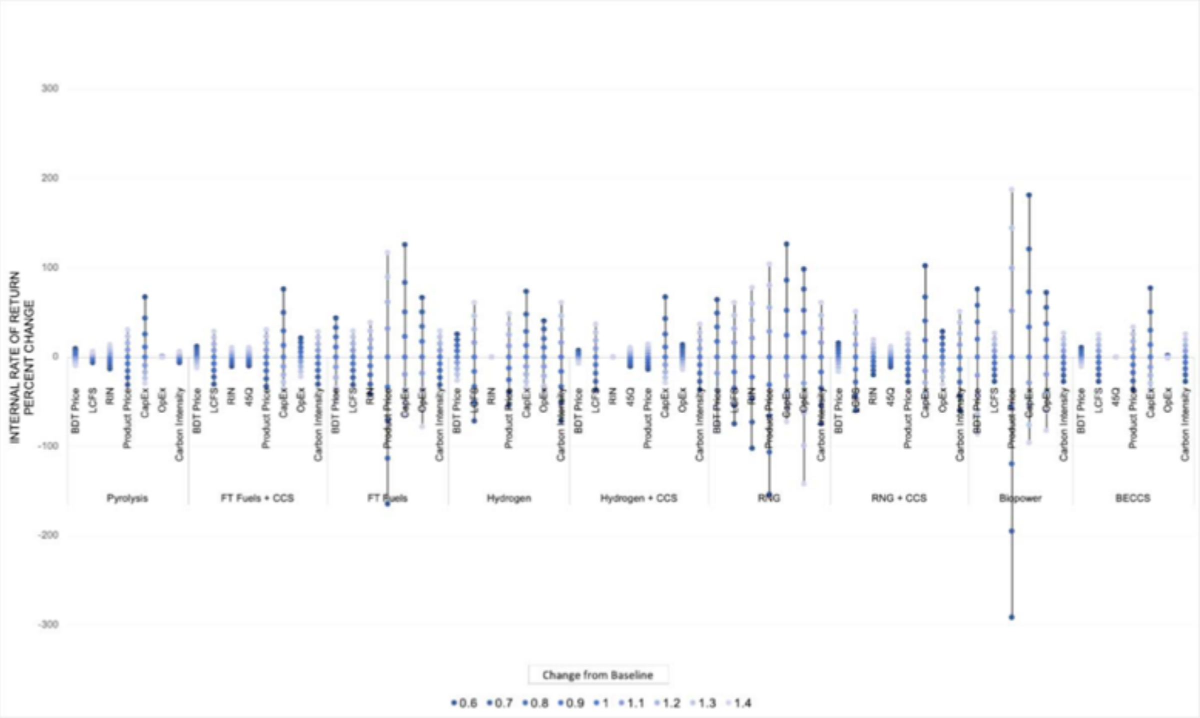
The IRRs for fuel products are generally less sensitive to fluctuations in primary product price than non-fuel products, with the notable exceptions of Fischer-Tropsch Fuels, renewable natural gas, and biopower (see Figure 6). For example, a 20% decrease in product price from the baseline scenario decreased the IRR for pyrolysis fuels by 16%, Fischer-Tropsch Fuels + CCS by 16%, hydrogen by 26%, hydrogen + CCS by 7%, renewable natural gas + CCS by 14%, and BECCS by 18%. For Fischer-Tropsch Fuels, renewable natural gas, and biopower, which are the products more sensitive to product price, a 20% decrease in product price from the baseline scenario decreases the IRR by 71%, 66%, and 120%, respectively. This decreased sensitivity is due in part to the multiple sources of income for many fuel products, particularly income from LCFS credits, RIN credits, and 45Q tax credits.

Figure 4: Nonfuel products sensitivity analysis. Depiction of the percent change of the internal rate of return (IRR) resulting from a change in the baseline assumptions in Table 2.



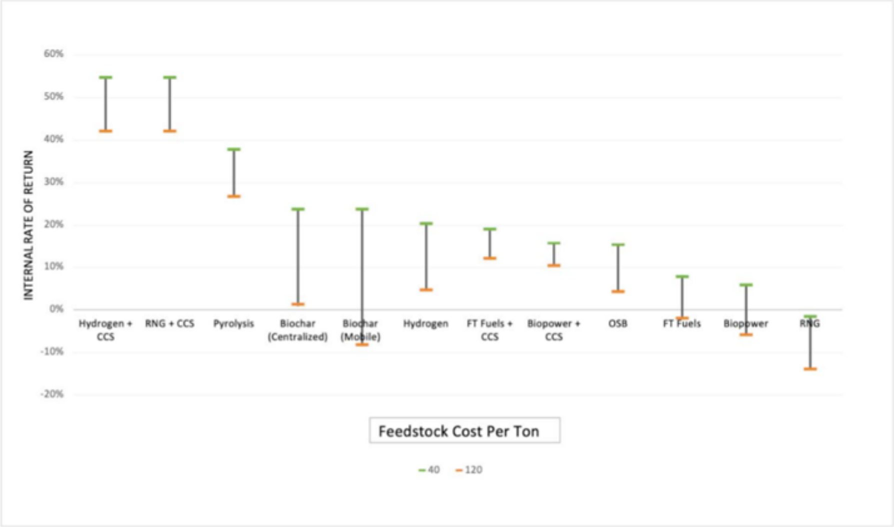
For the products which were eligible for programs like the LCFS and the RFS, fluctuations in the LCFS price in particular have a similar magnitude of impact on the IRR. A 20% decrease in the LCFS price from the baseline scenario decreases the IRR for pyrolysis fuels by 3%, Fischer-Tropsch fuels + CCS by 12%, Fischer-Tropsch fuels by 10%, Hydrogen by 25%, Hydrogen + CCS by 18%, renewable natural gas by 13%, and renewable natural gas + CCS by 19%. Fluctuations in RIN credit pricing have a similar, but lower magnitude, impact on the IRR.

Figure 5: Fuel products sensitivity analysis. Depiction of the percent change of the internal rate of return (IRR) resulting from a change in the baseline assumptions depicted in Table 2.



Fluctuations in carbon intensity, or the amount of greenhouse gasses released in the lifetime of a product, have a consistently high impact on the IRR, given that the number of LCFS or RIN credits received is determined by the carbon benefit calculated. RIN and LCFS credits were a significant source of income for eligible products – fuel products received an average of 49% of their income from carbon incentives. Fuel products, with the exception of pyrolysis fuels, biopower and BECCS, had a highly negative IRR when all carbon incentives were removed.

Figure 6: Feedstock cost analysis. Depiction of the range of internal rate of return (IRR) for each product examined resulting from high and low feedstock costs. All other variables help constant at the baseline described in Table 2.



Changes in the feedstock cost have a sizable impact on the IRR of many products (see Figure 6). However, even in the high-cost scenario ($120/ bone dry ton feedstock) hydrogen + CCS and renewable natural gas + CCS, have IRRs over 40%. In the baseline scenario of $60/ bone dry ton feedstock, biochar (mobile) and biochar (centralized) have high IRRs of 18% and 19% respectively, but are very sensitive to upward fluctuations in feedstock cost.

Table 5: Carbon benefits of each biomass product in terms of tons of carbon benefit / ton of carbon in feedstock. Storage includes landfilled wood and carbon in long-lived products. CCS storage benefits are included in process emissions.

Technologies		**Substitution**	**Process Emissions**	**Storage**	**Total**
Non-Fuel					
	OSB	0.94	-0.30	0.44	**1.08**
	Biopower + CCS	0.10	0.72	0.00	**0.82**
	Biochar (Centralized)	0.04	-0.03	0.36	**0.36**
	Biochar (Mobile)	0.00	-0.03	0.24	**0.21**
	Biopower	0.13	-0.02	0.00	**0.11**
Fuel					
	Hydrogen + CCS	0.80	0.85	0.00	**1.65**
	RNG + CCS	0.49	0.64	0.00	**1.13**
	Fischer-Tropsch Fuels + CCS	0.35	0.46	0.00	**0.81**
	Hydrogen	0.80	0.01	0.00	**0.81**
	Pyrolysis Fuels	0.63	-0.20	0.00	**0.44**
	RNG	0.51	-0.20	0.00	**0.31**
	Fischer-Tropsch Fuels	0.35	-0.13	0.00	**0.22**

2.5 Discussion and conclusion

Emerging fuel and non-fuel products utilizing low-value biomass as a feedstock can provide additional funding for critical forest restoration while helping to accomplish climate neutrality goals in California. In the baseline scenario, non-fuel products have an average IRR of 13% while fuels have an average of 19% IRR. Hydrogen + CCS and several other fuel products made from low-value biomass are still highly profitable at feedstock costs over $100 per ton under our assumptions, while non-fuel products have IRRs over 10% when feedstock costs are over $80 per ton. With a rough average of 10 tons of low-value biomass needing to be removed from each acre of overstocked forest (Rummer et al. 2005), these products could add a significant revenue source to forest management operations by providing new markets for low-value biomass. In certain scenarios, this additional income from low-value biomass may be able to single handedly pay for forest management, depending on the contractual arrangement between landowner and harvesting contractor.

However, the viability of both non-fuel and fuel products are dependent upon policy and market support in the form of consistent price support and the longevity of existing carbon incentive programs. Our analysis shows that non-fuel products like biochar and building materials like OSB need reliable markets, along with carbon and product prices, to ensure the profitability of their operations. For instance, a 20% change in the market price for each of these primary products created a 45% or greater decrease in the IRR. Biochar and other non-fuel products are clearly highly sensitive to market price for primary products and various price support systems may help to decrease risk and encourage investment in this space.

On the other hand, fuel products like hydrogen and other transportation fuels are less sensitive to changes in market price for primary products and are highly profitable with existing carbon incentives like LCFS, RIN, and 45Q credits. Here, policy certainty will be a key driver of deployment. For each fuel, an average of 49% of yearly income in our relatively conservative baseline scenario was directly from carbon incentives, with as much as 76% for hydrogen + CCS and renewable natural gas + CCS. The continued maintenance and expansion of these carbon incentives will help to send signals to the market to invest in these climate beneficial fuels.

In other instances, leveraging voluntary carbon credit markets can help to encourage these products. The centralized biochar facility we modeled had an IRR of 19% when carbon credits were $20 per ton and 34% when carbon credits reached $120 per ton. Interest in biochar has increased as a possible component of mine remediation products or as a soil amendment in agricultural, range, or forest lands. Moreover, demand for scientifically rigorous and demonstrably additional carbon credits is increasing and biochar carbon offsets could help to fill this demand, as seen in the carbon offset purchasing trends by Microsoft and other corporate carbon neutrality leaders (“Microsoft Carbon Removal - Lessons from an Early Corporate Purchase” 2021).

The carbon benefits of biochar and certain building materials like OSB can be monetized by creating credits through existing registries such as Puro.earth or Verra. LCFS and RIN credits can be generated by calculating the carbon intensity of the fuel created while working through the California Air and Resources Board and the Federal Environmental Protection Agency, respectively. The 45Q tax credit can be claimed under section 45Q of the U.S. Internal Revenue Code. In each of these instances, industry consultants can advise on how to best monetize the carbon benefits of these carbon beneficial products.

There are important limitations to this study. First, the capital expenditures used in this modeling are from published studies and may not represent the full costs that might be faced by a new facility. Higher capital costs as a result of high land costs and complex permitting processes in California, for example, may increase capital expenditures and reduce the IRR for specific products. We attempt to account for these unforeseen expenditures by adding a 50% contingency to CAPEX costs for fuels (except for biopower and BECCS, which have a 30% contingency) and 30% for non-fuels. Second, there are economic assumptions such as market price for primary products which may be inaccurate or fluctuate overtime. Third, we assume that sufficient feedstock is available and pricing is fixed in each scenario. Although current policies and increased forest management will generate enormous amounts of low-value biomass, the amount which is financially feasible to access will depend greatly on transportation distance and thus location of the wood products facility. The investability of any wood products facility will depend in part on the ability to write long-term feedstock contracts and ensure price stability. Lastly, we assume that biogenic carbon is neutral, in other words it is assumed that low-value biomass is sourced from forest residues, and that this carbon would have returned to the atmosphere via degradation or pile burning. This is a valid assumption in California, but may not be true in all forest management contexts.

With these limitations in mind, the technologies modeled in this study represent a mosaic of possibilities that could be implemented alongside one another to reinvigorate rural wood products and forest management industries. This study finds that there are several innovative wood products which warrant increased attention from private investors. The hydrogen + CCS and hydrogen facilities modeled are well aligned with current policy initiatives such as the California Energy Commissions' Clean Transportation Program, established by California AB 118.

A healthy and economically resilient wood products industry might be one which still incorporates traditional wood products such as dimensional timber while including innovative products like fuels which can add value to low-value biomass. Fostering markets for low-value biomass may enable the Forest Service and private landowners in California to manage landscapes for ecological resilience in the face of a changing climate.

3 CHAPTER 2: Market analysis of coupled biochar and carbon credit production from wildfire fuel reduction projects in the Western U.S.

Published in *Biofuels, Bioproducts, and Biorefining* (Elias et al. 2024)

3.1 Preface

Chapter 2 is an analysis of the potential to link low-value biomass generated from forest thinning with coupled biochar and carbon credit production in California and throughout the Western U.S. This analysis begins by estimating the annual low-value biomass supply and converting all of the low-value material into biochar and carbon credits. It then delves into a series of potential scenarios for coupled biochar and carbon credit production including the current capacity of biochar infrastructure, increases in industry capacity, and two different upgrades to biopower facilities which would yield biochar and carbon credits. It further explores the demand for biochar carbon credits through interviews, the profitability of biochar production in different market scenarios, and the total investment potential to convert all low-value biomass to biochar and carbon credits. This work was published in the journal *Biofuels, Bioproducts, and Biorefining*. It is included with permission of my co-authors Daniel L. Sanchez, Phil Saksa, Josiah Hunt, and Jonathan Remucal. This paper was completed in research partnership Blue Forest and the Climate Action Reserve as part of the development of U.S. and Canada Biochar Protocol which provides guidance on how to quantify, monitor, report, and verify the climate benefits from the production and use of biochar. It was funded by a USFS Wood Innovation Grant.

3.2 Introduction

Biochar can be made from a range of biomass materials - such as woody biomass from forest restoration projects, food and yard waste, and crop residues - and has promising applications in agriculture, forestry, and other industries (Brown, Wright, and Brown 2011; Woolf et al. 2010). While the biochar market in the United States has recently begun to grow due in large part to demand for the Carbon Dioxide Removal (CDR) credits generated from biochar production ("Puro.Earth Carbon Removal," n.d.), biochar sales are still limited by lack of demand, access to capital, and other market barriers (Thengane et al. 2021). Overall, forest biomass has higher feedstock transportation costs and less consistent supply chains then agricultural or sawmill waste, and as a result has not been used widely by producers to create biochar (Springsteen et al. 2015).

However, biochar also presents a unique opportunity to link forest thinning projects which reduce the risk of wildfire with a carbon beneficial use for low-value woody biomass, which can include logging slash, treetops, branches, and small diameter trees. The scientific consensus is that both large amounts of biomass need to be removed from forests in the Western U.S. to ensure long term resiliency in forests (Collins, Everett, and Stephens 2011; Lydersen and Collins 2018; McIntyre et al. 2015) and that there are several climate beneficial products, such as biochar, which can be made from low-value biomass (Elias et al. 2023; Baker et al. 2020). If biochar production is profitable or cost saving, it can also help to lower the cost per acre of forest treatment given the current cost associated with pile burning low-value material. Pile is the typical disposal method for low-value material, which can cost hundreds of dollars per acre while emitting carbon and smoke which can lead to local health impacts (California Council on Science and Technology and Blue Forest 2023). Currently, there is a need of well over $100 billion U.S. dollars (USD) to restore fire resilience to forests in the U.S. via fuels thinning (Chang 2021; "Confronting the Wildfire Crisis" 2022) and the influx of funding from federal legislation passed in 2022 covers only a small fraction of this need – roughly $5 billion ("Visualizing Federal Funding for Wildfire Management and Response," n.d.). Innovative wood products can help to close this funding gap (Cabiyo et al. 2021).

With the goal of understanding the potential for coupling forest restoration with biochar and carbon credit production, we answer the following questions for the state of California and the Western U.S (states west of the Rocky Mountains):

1. What is the potential supply of woody biomass from forest restoration projects throughout California and the Western United States?
2. What is the current generation capacity for coupled biochar and carbon offset production in California? How many carbon credits could be generated given different production scenarios?
3. What is the potential demand for carbon credits coupled with biochar production?
4. What is the financial viability of different biochar production systems? How do fluctuations in carbon credit price, biochar price, and feedstock costs affect viability?
5. What is the potential for investment in biochar production?

The findings from this work can be used as a starting place to guide investment in the biochar industry while providing an understanding of the feasibility of using woody biomass from forest restoration projects to create biochar and carbon credits.

3.3 Methods

This study explores key factors for establishing a biochar industry using -value biomass from forest thinning, including: 1) biomass supply and biochar-carbon credit coupling, 2) biochar and carbon credit production potential, 3) demand for biochar carbon credits, 4) profitability in various scenarios, and 5) total investment potential. The study is segmented into corresponding subsections across methods and results for clarity. All currencies are USD.

3.3.1 Annual low-value biomass supply and potential for coupled biochar and carbon credit production

We estimate the technical supply of non-merchantable forest biomass in bone dry tonnes (BDT), considering forest land treatment, biomass harvest, slash proportions, and wood products infrastructure capacity in California and the Western United States. Key assumptions are based on industry data (University of Montana 2016; McIver 2015) and conversions from Shelley (Shelley 2007). Table 6 details biomass supply assumptions, including merchantable timber harvest and wood products infrastructure capacity, with projections for the West extrapolated from regional statistics ("University of Montana Bureau of Business and Economic Research" 2013). Biochar production is presumed to have a 0.25 mass yield from woody biomass, with carbon credit estimations following IPCC (IPCC 2019), EBC (Schmidt, Kammann, and

Hagemann 2021), and Puro (Schimmelpfennig and Glaser 2022) methodologies with low estimated of 1.9 tonnes of CO_2 per tonne biochar produced and high estimated of 2.7 tonnes of CO_2 per tonne biochar produced. Increased low and high scenarios refer to the number of acres that are assumed to be treated in the scenario. The amount of biomass from each scenario is primarily a function of acres treated as well as the assumption made regarding the wood products industry capacity.

Formulas for Biomass Supply Estimations:
Current Low = (Total Merchantable Timber Harvest) / (Percent Merchantable Harvest per Acre) * Percent Low-Value Biomass per Acre
Current High = Acres Treated * Biomass Harvested per Acre - Current Industry Capacity [BDT]
Increased Low = Acres Treated * Low-Value Biomass per Acre
Increased High = Acres Treated * Biomass Harvested per Acre - Current Industry Capacity [BDT]

Table 6: Biomass supply assumptions regarding acres treated in each scenario (low vs. high), wood products industry, and biomass generated per acre.

Parameter	**Value**	**Source**
Biomass harvested per acre	20 Bone Dry Tonnes	Rummer et al. 2005
Merchantable biomass per acre	60%	Bill Stewart personal communication 2021
Non-merchantable biomass per acre	40%	Bill Stewart personal communication 2021
Total merchantable timber harvest [CA]	2.12 Million Bone Dry Tonnes	University of Montana 2016
Wood products infrastructure total capacity [CA]	3 Million Bone Dry Tonnes	University of Montana 2016 and McIver 2015
Wood products infrastructure total capacity [West]	18 Million Bone Dry Tonnes	*Estimated from University of Montana 2013 statewide harvest data
Current percent wood products infrastructure utilized	71%	University of Montana 2016 and McIver 2015
California acres treated		
Current low	NA	
Current high	250,000 Acres	Assumed
Increased low	500,000 Acres	Assumed
Increased high	1,000,000 Acres	Assumed
Western U.S. acres treated		
Current low	1,500,000 Acres	Assumed
Current high	1,500,000 Acres	Assumed
Increased low	2,000,000 Acres	Assumed
Increased high	4,000,000 Acres	Assumed

3.3.2 Biochar and carbon credit production capacity

We analyze current and potential biochar production capacities. Our assessment of California and the Western U.S. biochar and carbon credit potential is informed by producer surveys (Groot et al. 2018), projected capacity increases, and biopower facility upgrades. California's biopower comprises 26 facilities totaling 551 MW(McIver 2015), while the Western U.S. hosts 42 facilities with 893 MW("U.S. Energy Information Administration" 2023). We assumed proportional production based on the number of producers and region. Potential capacity increases are projected as proportional to current capacity. We examined 'light' and 'heavy' biopower facility upgrades for biochar production, with 'light' upgrades yielding less biochar. Upgrade eligibility and feedstock-to-biochar conversion rates were based on practitioner insight (Hunt, 2022, pers. comm, 25, 26).

Table 7: Biochar and carbon credit generation calculation inputs and parameters

Variable	**Assumption**		**Descriptions**	**Source**
	Light Upgrade	Heavy Upgrade		
BioCap	551		Total state biopower capacity (megawatts)	McIver 2015
BioElig	70%		Percent of the total state biopower (BioCap) eligible for upgrades	Assumption
CapFac	70%		Capacity factor of biopower production	Assumption
ElecGenEff	20%		Electrical energy generation efficiency	Assumption
MassYield (light)	2%	10%	Biomass to biochar generation efficiency	Hunt and Miles 2020
BioHeat	5.58		Heating value (mWh) per tonne biomass	Argonne National Lab 2021
CharHeat	6.11		Heating value (mWh) per tonne biochar	Argonne National Lab 2022
CharConvert	60%		Realizable energy content change	Intermediate output
EffCost	33.96%		Energy content percent change (wet basis 43% to 0%)	Forest Research 2022
TotFeed	2,200,000	2,500,000	Tons of biomass needed to fulfill statewide biopower demand	Intermediate output

Equations for Biochar and Carbon Credit Production:

Feedstock = (BioCap * BioElig * CapFac * 365 * 24)/ (BioHeat * ElecGenEff)
Feedstock is total amount needed to power existing and eligible biopower facilities.
BiocharYield = Feedstock * MassYield
BiocharYield is the amount of biochar which could be generated from upgrades to biopower facilities.
AddFeed = (BiocharYield*CharHeat)/(CharConvert*BioHeat)
AddFeed is the amount of additional feedstock needed to power upgrades to biopower facilities.
CharConvert = (Bioheat*(1-EffCost))/CharHeat
TotFeed = AddFeed + Feedstock

Carbon offsets from standalone and coupled biochar producers are calculated using IPCC (IPCC 2019), EBC (Schmidt, Kammann, and Hagemann 2021), and Puro (Schimmelpfennig and Glaser 2022) methodologies and range between 1.9 and 2.7 tonnes of CO_2 per tonne of biochar produced.

3.3.3 Carbon credit demand potential

Demand for biochar carbon credits was assessed through semi-structured, confidential interviews with carbon market experts representing five organizations, focusing on market perceptions, demand trends, pricing, and market drivers.

*3.3.4 Biochar production investment potential and market scenario analysis *

The market analysis draws on deconstructed techno-economic analyses (TEA) to establish financial projections, specifically Net Present Value and Internal Rate of Return, for each defined market scenario. For a 25 MW biopower plant's biomass requirements (Wiltsee 2000), we consider both light (Hunt and Miles 2020) and heavy (Friedenthal 2022) upgrade scenarios with alterations made in consultation with the original authors. The labor costs for these upgrades are predicated on an annual full-time employee cost of $132,500, adjusted for inflation (The Beck Group 2015). Our models incorporate mobile biochar production using a mobile system (Thengane et al. 2021) and centralized production in a large-scale facility (Friedenthal 2022). Carbon benefit calculations are aligned with Puro, EBC, and IPCC benchmarks, applying an average of 2.5 tonnes CO_2 per tonne of biochar for upgrade scenarios and 2.3 tonnes CO_2 for mobile and centralized systems, assuming 80% carbon content with 80% carbon durability over a century. To streamline analysis, we calculate a singular conservative figure, reducing model output complexity. Sensitivity analyses adjust key variables by 10% increments to evaluate a 40% swing in either direction on the Internal Rate of Return (IRR) for each system.

Financial viability for biochar and carbon credit production pairs four distinct system models with market scenarios, grounded in established techno-economic literature: a small-scale mobile unit in forest settings (Thengane et al. 2021), a stand-alone industrial setup (Friedenthal 2022), and two configurations of a 25 MW biopower facility, one with a light retrofit (Wiltsee 2000) and another with a heavy retrofit including three kilns for co-producing biochar and syngas for electricity (Friedenthal 2022). All references to these production systems are based on the specified sources, and economic assumptions are consistent with these models.

3.3.5 Level of investment needed

The investment impact of $100 million in biochar-carbon credit coproduction was calculated using capital expenditures and output of four production systems. The total investment required for Western U.S. biomass utilization was estimated by dividing total potential feedstock in the increased high scenario by each facility's annual requirements.

3.4 Results

3.4.1 Annual low-value biomass supply and the potential for coupled biochar and carbon credit production

Low-value biomass, often left behind from forest restoration and fuel thinning, is typically burned or left to decompose, releasing carbon and incurring costs for land owners (Springsteen et al. 2015). With increased state and federal restoration goals, surplus biomass will greatly increase. The amount of surplus varies by site and is influenced by market demand, tree characteristics, and management goals. We asses current and projected quantities of low-value biomass and the potential for biochar and carbon credit production while disregarding current production capacity limits (Table 8).

Table 8: Annual woody biomass supply and potential coupled biochar and carbon credit production under current levels of forest treatment and an increased scenario.

	Biomass Supply [million bone dry tonnes]		**Potential Biochar [million tonnes]**		**Potential Carbon Credits CO_2 [millions]**	
California	**Low**	**High**	**Low**	**High**	**Low**	**High**
Current [approx. 250,000 acres treated]	1	5	0.25	1.3	0.5	3.5
Increased forest management [500,000 - 1,000,000 acres treated]	8	22	2	5.5	4	15
Western U.S.						
Current [approx. 1,500,000 acres treated]	4	18	1	4	2	11
Increased forest management [2,000,000 - 4,000,000] acres treated	24	102	6	26	11	69

Sawmill capacity underpins the amount of non-merchantable biomass supply. Even considering a significant rise in wood product infrastructure (low supply estimate in increased management scenario), biomass supply will not constrain near-term biochar and carbon credit production. Maximum biochar and carbon credit outputs (Table 8) are theoretical technical ceilings and do not account for economic factors.

California's current biomass supply is between 1 and 5 million tonnes annually, potentially reaching 22 million tonnes to meet state targets. This could yield 250,000 to 1,300,000 tonnes of biochar now, and up to 5.5 million tonnes with state objectives. Carbon credit potential ranges from 500,000 to 3,500,000 currently and could rise to 15 million annually with targeted restoration.

Across the western U.S., annual slash production is between 4 and 18 million tonnes, with up to 102 million tonnes possible in an increased management scenario aligned with state and federal policies. Current biomass supply could produce 1 to 4 million tonnes of biochar and, with state goals, up to 26 million tonnes. Carbon credit production potential could climb from 2 to 11 million now to nearly 70 million with state restoration objectives.

3.4.2 Biochar and carbon credit production capacity

Current biochar production in California is difficult to quantify due to market opacity, but likely near or under 10,000 tonnes per year by a small number of firms (Thengane et al. 2021). However, recent and increasing demand for carbon dioxide removal credits has attracted startups and investors. Biochar is produced either by standalone mobile/centralized units or through co-generation with biopower. Table 9 outlines the biochar and carbon credit potentials from forest biomass, considering industry expansion or biopower modifications. These figures are conservative compared to the broader technical potential indicated in Table 8.

Table 9: Depiction of the current and potential biochar and carbon credit production in five different scenarios, as well as the amount of feedstock necessary to accomplish those upgrades.

	Feedstock Necessary [bone dry tonnes]	**Potential Biochar Production [tonnes]**	**Potential Credit Generation [tonnes CO_2, low estimate]**	**Potential Credit Generation [tonnes CO_2, high estimate]**
California				
Current stand-alone production	23,000	6,000	10,000	14,000
50% Industry capacity increase	36,000	9,000	15,000	21,000
100% Industry capacity increase	48,000	12,000	20,000	28,000
Biopower light upgrade	2,200,000	42,000	102,000	114,000
Biopower heavy upgrade	2,500,000	212,000	509,000	572,000
Western U.S.				
Current stand-alone production	67,000	17,000	32,000	43,000
50% Industry capacity increase	102,000	25,500	48,000	64,500
100% Industry capacity increase	136,000	34,000	64,000	86,000
Biopower light upgrade	3,600,000	69,000	165,000	185,000
Biopower heavy upgrade	4,100,000	343,000	824,000	927,000

3.4.3 Carbon credit demand potential

Carbon market experts describe biochar credits as high-quality, citing significant co-benefits, reliable carbon sequestration of 70-90% over 100 years, and effective environmental measures in production. Environmentally sound production practices will be crucial for industry growth. Carbon market trends currently favor credits with long-term durability and verified benefits, increasing demand for biochar carbon credits.

Biochar production generates a Carbon Dioxide Removal (CDR) credit, receiving between $90 to $600 per credit, with most prices between $95 to $145 (Nasdaq Carbon Removal Marketplace and Technologies, n.d.). Nasdaq's tracking of CDR and biochar carbon credit prices reflects biochar's unique place in the market. Increasing demand for secondary due diligence by buyers to ensure carbon credit rigor has also positioned biochar as a bridge to more certain carbon removal methods like direct air capture. Sales and contracts for biochar credits are already in the low hundreds of thousands. The $53 million deal for 112,000 credits at approximately $473 each by Frontier and Charm Industrial in 2023 underscores the high demand (Segal 2023).

However, biochar demand in the market is niche. Most of the carbon offset buyers still largely prioritize cost, often adopting a portfolio strategy to balance risk and diversify project type. If biochar carbon credit production scales, maintaining prices over $100 might be challenging, despite its quality. Pricing remains critical for most buyers, with the future market trajectory and price remaining uncertain.

3.4.4 Biochar production investment potential and market scenario analysis

This analysis utilizes the IRR to evaluate annual investment profitability and Net Present Value (NPV) to gauge return on investment (see Table 10). In our assumed market scenario, a light biopower upgrade on a 25 MW facility has a 29% IRR and $10.5 million NPV, while a heavy upgrade has a 9% IRR and $5.94 million NPV. Mobile biochar has a 2% IRR and negative NPV of $0.15 million, in contrast to centralized biochar with a negative 1% IRR and NPV of $8.7 million. Contingencies of 50% and 30% were added to the capital expenditures (CapEx) for light and heavy upgrades, respectively, to ensure conservative estimates.

Our financial analysis, which focuses on operational and capital expenditures, feedstock costs, biochar, and carbon credit prices, reveals varied investment potentials. Although some production systems may be less appealing to conventional investors, they may still represent valuable projects for private, state, or federal sponsorship. The analysis does not seek to identify the optimal biochar production system; instead, it explores the financial feasibility of four systems in different scenarios.

Table 10: Assumed baseline market scenario depicting the economic assumptions for costs, prices, operational and capital expenditures, and financial returns of each production system.

Cost and Price		
Feedstock cost	$50 USD	Per bone dry tonne
Biochar price	$200 USD	Per tonne biochar
Carbon price	$80 USD	Per tonne CO_2
Carbon benefit	2.5	Tonnes CO_2 benefit per tonne biochar
Capital Expenditure		
Biopower (25MW) light upgrade	$4,000,000 USD	One time cost
Biopower (25MW) heavy upgrade	$15,000,000 USD	One time cost
Biochar mobile	$750,000 USD	One time cost
Biochar centralized	$20,000,000 USD	One time cost
Operational Expenditures (not including feedstock costs)		
Biopower (25MW) light upgrade	$10 USD	Per tonne biochar*
Biopower (25MW) heavy upgrade	$22 USD	Per tonne biochar **
Biochar mobile	$225 USD	Per tonne biochar
Biochar centralized	$33 USD	Per tonne biochar
	*Assumes ½ FTE (full time equivalent employee) needed for light upgrade	
	**Assumes 3 FTE needed for heavy upgrade	
Biochar Production		
Biopower (25MW) light upgrade	6,160	Tonnes per year
Biopower (25MW) heavy upgrade	18,144	Tonnes per year
Biochar mobile	1,350	Tonnes per year
Biochar centralized	18,144	Tonnes per year
Net Present Value		
Biopower (25MW) light upgrade	$10.50 USD	Million over 20 years
Biopower (25MW) heavy upgrade	$5.94 USD	Million over 20 years
Biochar mobile	-$(0.15) USD	Million over 20 years
Biochar centralized	-$(8.70) USD	Million over 20 years
Internal Rate of Return		
Biopower (25MW) light upgrade	29% USD	Over 20 years
Biopower (25MW) heavy upgrade	9% USD	Over 20 years

Biochar mobile	2% USD	Over 20 years
Biochar centralized	-1% USD	Over 20 years

3.4.4.1 Market Analysis 1: Impact of biochar and carbon credit pricing on IRR

The impact of biochar and carbon price on profitability is assessed across production systems, with biochar priced between \$100 to \$250 per tonne and carbon between \$0 to \$100 per tonne CO_2. These ranges alter IRR significantly (Figure 7). We determine the breakeven carbon price for each system to achieve target IRRs, holding feedstock costs at \$50 per tonne (Table 11). This breakeven price reflects the necessary carbon credit sale price to achieve specific IRRs and assumes carbon price is the final realized by the producer after accounting for all transaction costs, commission, etc.

Figure 7: Depiction of the absolute Internal Rate of Return (IRR) of four biochar production types with biochar prices between \$100 and 250 and carbon prices between \$0 and 100 per tonne CO_2. Feedstock costs are fixed at \$50 per bone dry tonne. IRR values below negative 10% are excluded.

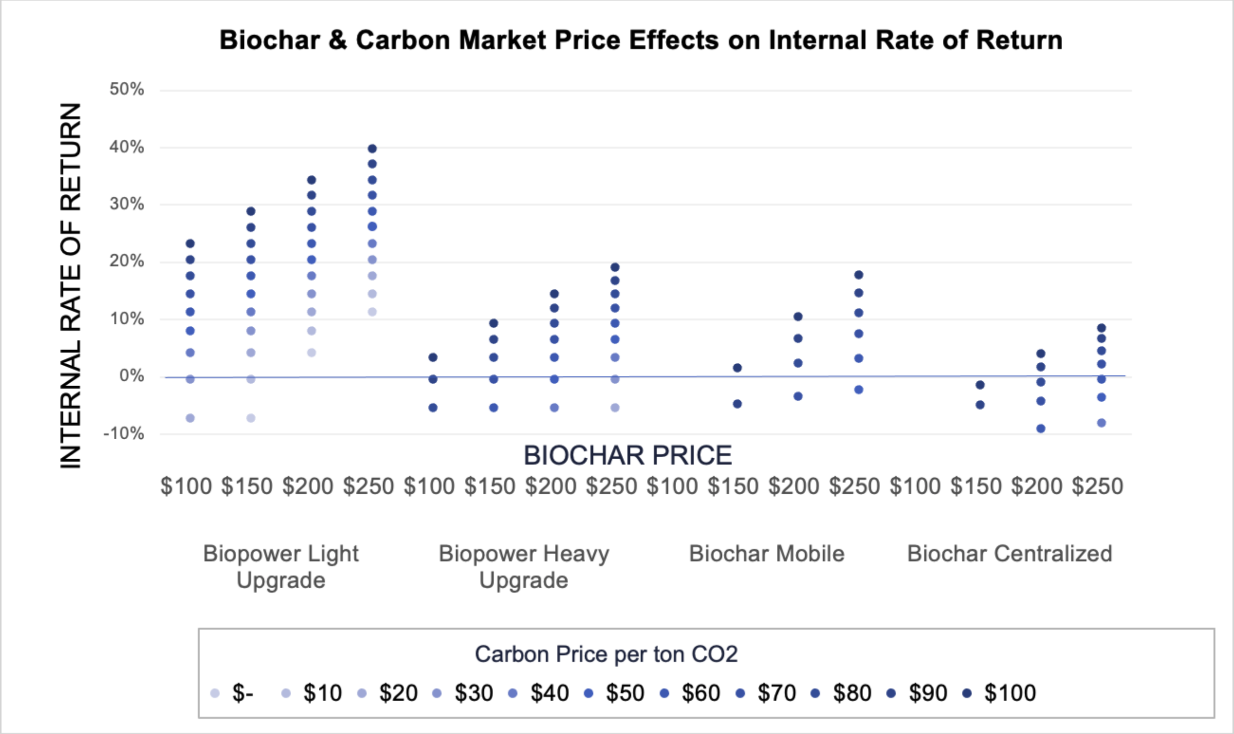


Table 11: Breakeven carbon credit prices (USD) of four biochar production types with biochar prices between $100 and $250 per tonne and Internal Rates of Return (IRR) of 5%, 10%, and 15%. Feedstock costs are fixed at $50 per bone dry tonne.

	Biochar Price (USD/ tonne biochar)	**IRR**		
		5%	**10%**	**15%**
Biopower light upgrade				
	$100	45	60	70
	$150	20	35	50
	$200	0	15	30
	$250	0	0	10
Biopower heavy upgrade				
	$100	105	120	140
	$150	85	105	120
	$200	65	85	100
	$250	45	65	85
Mobile biochar				
	$100	130	140	155
	$150	105	120	135
	$200	85	100	115
	$250	65	75	90
Centralized biochar				
	$100	145	175	200
	$150	125	150	180
	$200	105	130	160
	$250	80	105	135

3.4.4.2 Market Analysis 2: Biochar price and feedstock cost influence on IRR

The impact of biochar and feedstock costs on profitability is assessed across production systems, with biochar prices between $100 to $250 and feedstock costs between $0 to $120 per tonne and carbon price fixed at $80 per ton (Figure 8). The breakeven feedstock cost for achieving specific IRRs is presented in Table 12, with negative IRR scenarios essentially indicating the need for producers to be paid to accept feedstock.

Figure 8: Depiction of the absolute Internal Rate of Return (IRR) of four biochar production types with biochar prices between $100 and 250 and feedstock costs between $0 and 120 per bone dry ton. Carbon price is fixed at $80 per ton. IRR values below negative 10% are excluded.

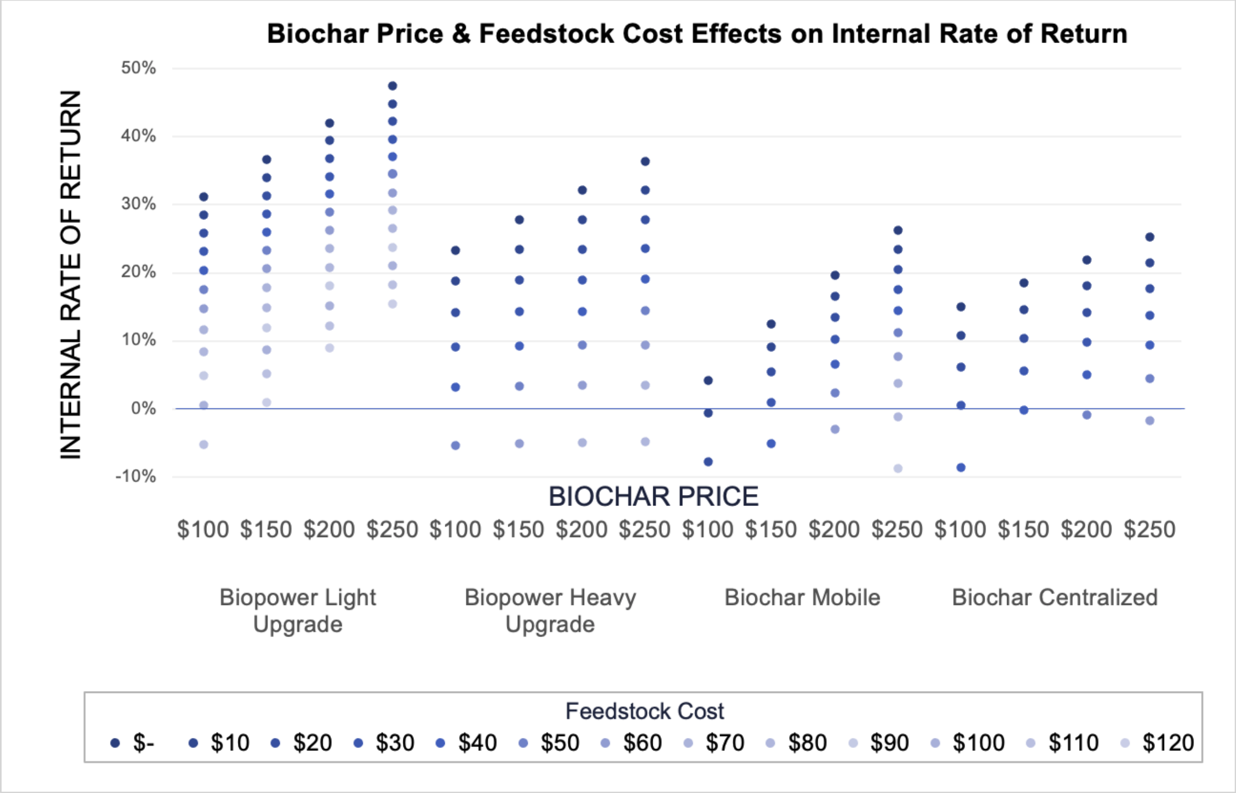


Table 12: Breakeven feedstock costs (USD/ bone dry tonne) of four biochar production types with biochar prices between $100-250 per tonne and Internal Rates of Return (IRR) of 5%, 10%, and 15%. Carbon credit pricing is fixed at \$80 per tonne CO_2.

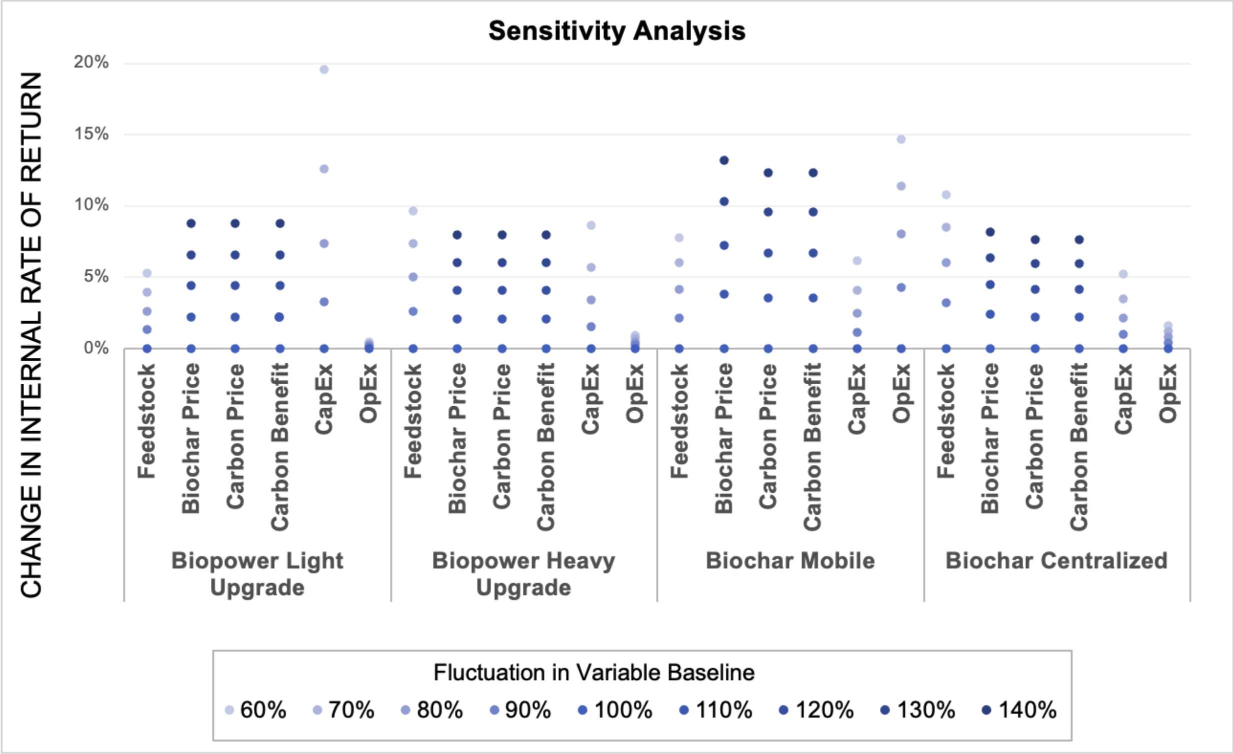
	Biochar Price (USD/ tonne biochar)	**IRR**		
		5%	**10%**	**15%**
Biopower light upgrade				
	$100	90	75	60
	$150	110	95	80
	$200	130	115	100
	$250	150	135	120
Biopower heavy upgrade				
	$100	40	30	20
	$150	50	40	30
	$200	60	50	40
	$250	70	60	50
Mobile biochar				
	$100	0	-15	-30
	$150	20	10	0
	$200	45	30	15
	$250	70	50	35

Centralized biochar				
	$100	20	10	0
	$150	30	20	10
	$200	40	30	20
	$250	50	40	30

3.4.4.3 Sensitivity analysis

The sensitivity analysis illustrates the IRR's responsiveness to changes in variables (Figure 9). Biopower upgrades are most affected by CapEx changes, while biochar mobile is most responsive to operational expense changes. Centralized biochar's IRR is primarily sensitive to feedstock cost variations. This analysis highlights how each system's profitability can shift with market and cost fluctuations.

Figure 9: Depiction of the absolute change of the Internal Rate of Return (IRR) from the baseline scenario with a stepwise change in the independent variables for each of the four technologies. Negative values are excluded.



3.4.5 Level of investment needed

There is substantial opportunity for both private and public investment into coupled biochar and carbon credit production from low-value forest biomass feedstocks. The potential would be considerably higher when including feedstock from agricultural or municipal waste. With a $100 million investment, nearly two million tonnes of biochar and four million carbon credits could be generated within a decade from low-value woody biomass (Table 13). However, the total investment potential is much higher – up to $50 billion (Table 14).

Table 13: Depiction of the amount of biochar and number of credits which could be generated by $100 million in investments in four technologies over one, five, and 10 years.

	$100 Million					
Years	**1**		**5**		**10**	
	Biochar (tonnes)	**Credits (tonnes CO_2)**	**Biochar (tonnes)**	**Credits (tonnes CO_2)**	**Biochar (tonnes)**	**Credits (tonnes CO_2)**
Light upgrade	154,000	385,000	770,000	1,925,000	1,540,000	3,850,000
Heavy upgrade	66,000	165,000	329,000	822,500	657,000	1,642,500
Mobile production	181,000	416,300	907,000	2,086,100	1,813,000	4,169,900
Centralized production	-	-	576,000	1,324,800	1,152,000	2,649,600

Table 14: Total investment needed to utilize all low-value forest biomass from Western U.S.

Technology	Billions (USD)
Light upgrade	$40
Heavy upgrade	$20
Mobile production	$50
Centralized production	$30

3.5 Discussion conclusion

The level of potential investment into biochar production linked with forest restoration throughout the Western U.S. is projected at over $20 billion in this analysis. The total feasible investment will ultimately be determined by production technology and access to economical feedstock. Our models suggest that light upgrades to 25 MW biopower facilities yield attractive IRRs of 10% to 35%, standing out as the system most profitable on revenue streams from either carbon credits or biochar alone.

Baseline feedstock costs are modeled at $50, reflecting typical biomass removal and transport costs – although costs will vary greatly. Mobile biochar processing, with its ability to operate in-situ, may be able to operate directly at or near a forest restoration site, effectively reducing the cost of feedstock close to $0 per tonne. At negligible feedstock costs, mobile biochar systems become financially viable with biochar priced at $100 per tonne and carbon at $80 per tonne (Figure 8), offering forest managers a cost-effective method to deal with low-value biomass.

Currently, the disposal of non-merchantable biomass through piling and burning costs roughly $300-600 per acre (Foster, 2022, pers. comm.). By producing roughly two tonnes of biochar per acre from the same amount of biomass, land management could effectively subsidize biochar production up to $150-300 per tonne biochar produced and still save costs as compared to pile and burn. This approach not only reduces treatment costs per acre but also generates carbon credits, providing an additional revenue stream from the carbon market.

Although current standalone biochar production in the Western U.S. is limited to a few thousand tonnes annually, far from the technical potential of 26 million tonnes, a growing demand for biochar carbon credits is igniting increased investment in biochar production. Despite previous limitations due to capital access and market fluctuations, the biochar market is poised for significant growth, with some projections at an annual compounding rate of 17% ("U.S. Biochar Market Size & Share Report" 2021) and roughly in line with a doubling of industry capacity in five years (Table 9).

Production costs have declined significantly from $200-$1000 per tonne in 2015 (W. Li et al. 2017; Sahoo et al. 2019) to numbers which can sustain bulk purchase prices close to $200 or less (Hunt, 2022, pers. comm). With biochar production often generating approximately 2.5 carbon credits per tonne, revenue from carbon markets is poised to become the primary revenue source for producers, turning biochar into a secondary product. Revenue from biochar and carbon markets are roughly equivalent when biochar prices are $250 and carbon credits are $100. Recent market prices between $95 to $145 per ton carbon credit are well aligned with the U.S. Department of Energy's Carbon Negative Shot initiative, which aims to achieve atmospheric CO_2 removal and long-term sequestration at costs below $100 per tonne (U.S. Department of Energy, n.d.) leading to potential public investment into biochar production. Coupling the increasing demand for biochar carbon credits with robust wholesale or high value specialized market options for biochar will be critical to sustained industry growth.

The potential to leverage low-value biomass from forest restoration to create biochar and carbon credits is substantial. Annually, forest restoration in the Western U.S. yields 5-20 million tonnes of such biomass, which could increase to 25-100 million tonnes with current restoration targets. This could translate into production of up to 4 million tonnes of biochar and 11 million carbon credits today, and as much as 26 million tonnes of biochar and nearly 70 million carbon credits in the future – roughly equivalent to the global carbon credit production from forestry and agriculture (Ivy So, Barbara Haya, and Micah Elias 2023).

Moving forward, there are three potential pathways for the biochar industry to scale and utilize biomass from forest management and fuel thinning projects. Either 1) the carbon market will need to sustain high carbon prices, 2) a subsidy or other mechanism will need to decrease the cost of feedstock biomass, or 3) production will need to take advantage of economies of scale to bring down biochar prices while increasing production. The most important barrier to scale is the lack of transparent biomass supply chains which enable long-term contracting for feedstock, production schedules, and investment. Clear timing, cost, quantity, and location of low-value biomass generation is critical to link forest restoration with biochar and carbon credit production.

There are other barriers to scale despite the enormous potential of biochar as a product and source of offsets, as well as ample supply of low-value biomass. From a technical standpoint, the lack of current production infrastructure limits scale. But more fundamentally, uncertain demand for biochar, volatile markets, and the variable characteristics of biochar produced through different processes must be overcome. Working with biochar end users to demonstrate the applicability of biochar in various use cases, and the specific characteristics of biochar needed for each use case, is necessary to establish sustained demand.

To continue growing the biochar industry, biochar producers will likely need to follow the example of the others who have already begun to leverage the niche characteristics of the carbon credits they produce to enhance their own growth. Given the growing interest in co-produced biochar and carbon credits, and the need to massively expand the pace and scale of forest restoration through the Western U.S., increased attention, investment, and collaboration is already happening in this space. While there are other products which can be made from low-value biomass, such as transportation fuels, biochar production requires relatively low capital expenditures compared to other innovative wood products, can be produced in modular ways, and can utilize feedstock in a much more ad hoc manner which can help to develop more formal biomass supply chains. With any luck, these forces will combine to overcome the historical barriers to the development of the biochar industry.

4 CHAPTER 3: Carbon finance for forest resilience in the Central Sierra Nevada

In preparation for *Frontiers in Forests and Global Change* 2024

4.1 Preface

Chapter 3 is an exploration of the carbon impacts of restoring resilience to high-risk forest areas in the American River watershed and the potential to leverage increases in aboveground carbon in living biomass as well as the carbon benefits of low-value biomass utilization to increase funding for forest restoration. The analysis begins by identifying a treatment area, a reference region from which to extract forest fire statistics, and then models thinning to a residual stand density index of 175 and prescribed burning on high-risk forest in a range of fire scenarios. It then explores the predicted changes in forest carbon levels using a range of potential fire extents informed by observed fires, a cumulative weighting approach to scaling carbon levels in treatment and no treatment scenarios over time, and a Monte Carlo simulation to explore the effects of annual fire extent on carbon levels. Once carbon dynamics are established, it explores potential use cases for low-value biomass including fuels, biochar, biopower, and wood vaults alongside scenarios for monetizing increases in aboveground carbon compared to a no-treatment scenario. This chapter is motivated by the emerging approach of dynamic baselines for carbon markets aimed to increase the quality and certainty of carbon markets and proposes methods to predict the carbon sequestration rates and storage levels, which will be critical to the successfully scaling dynamic baselines. This work is being prepared for submission to a special issue in *Frontiers in Forests and Global Change*. It is included with the permission of my co-authors Ethan Yackulic, Katharyn Duffy, Daniel L. Sanchez, Phil Saksa, and Nicholas Pevzner. This work was completed in research partnership with Blue Forest and Vibrant Planet as part of an exploration of how to predict and monitor the carbon benefits of treatment on public and private land and how those benefits can be leveraged to increase funding either through carbon markets or other avenues. It was funded by a CalFire Forest Heath Grant.

4.2 Introduction

Forests are vital for carbon storage (Pan et al. 2011; Harris et al. 2021), yet disturbances from fire, drought, climate change, and human activities such as logging and deforestation complicate carbon dynamics (Duffy et al. 2021; Hurteau, Koch, and Hungate 2008). In California, continued forest carbon storage plays a critical role in the development of pathways to achieve the state's goal of carbon neutrality by 2045 ("Carbon Neutrality by 2045 - Office of Planning and Research," n.d.). However, California's forests are overstocked due to past logging practices and ongoing fire suppression policies which have significantly decreased average tree size while increasing fuel load and continuity, stand density, and canopy cover (Scholl and Taylor 2010; Collins, Everett, and Stephens 2011; Knapp et al. 2013). These trends are exacerbated by global warming and increased aridity which has led to an eightfold increase in summer fire extent since 1972 (Williams et al. 2019). These fires pose a significant threat to the durability of forest carbon storage (Tyukavina et al. 2022) and has led to average annual emissions of 19 million tonnes CO_2 annually between 2000 and 2020 ("Public Comment Draft," n.d.).

California’s forest ecosystems co-evolved with periodic fires, which helped to maintain ecosystem integrity (DellaSala et al. 2017; Perry et al. 2011; Hessburg et al. 2016). Currently these fire adapted forests are out of equilibrium with climate and experiencing high mortality from severe drought and wildfire (Hill et al. 2023) which threatens the forests carbon carrying capacity (Goodwin et al. 2020; Hurteau et al. 2019). Accomplishing the State’s goal of treating one million acres a year via forest thinning and prescribed burning can mitigate the risk of severe wildfires (D. E. Foster et al. 2020) and increase the resiliency of forests to wildfire and other disturbance (Kennedy and Johnson 2014; Stephens, Westerling, et al. 2020). Nonetheless, forest management aimed at enhancing carbon stability initially lowers carbon stocks via biomass removal, which presents a challenge to achieve near-term objectives (M. North, Collins, and Stephens 2012; Liang, Hurteau, and Westerling 2018).

Historically, low and mixed-severity fires have played a crucial role in stabilizing carbon stocks in forests by maintaining carbon in fewer, larger trees, which accumulate carbon at higher rates (Hurteau et al. 2016; Stephenson et al. 2014). North et al. (2022) provides a historical benchmark for a resilient forest structure – those able to withstand disturbances such as fire while maintaining their core functions and structure. However, forest management involves balancing multiple objectives, including carbon storage, timber production, watershed protection, recreation, wildlife habitat, and cultural values alongside resilience (Clawson 1977). Navigating these goals, particularly when wildfire resilience and carbon benefits may not immediately align, presents a complex challenge characterized by social, political, financial, and logistical dynamics (Bowes and Krutilla 1985).

Forest management in the U.S. has traditionally been funded by federal appropriations and timber sales revenue (Quesnel Seipp et al. 2023). To successfully treat one million acres a year in California, over two billion dollars would be needed annually, assuming per acre costs between $2000 - 2500 per acre once preparation and planning, thinning, and pile burning is accounted for (Chang 2021; Hartsough et al. 2008). At these rates, California alone would exceed the total, non-recurring allocations for national forest treatments in under three years (“Visualizing Federal Funding for Wildfire Management and Response,” n.d.), highlighting the need for novel sources of revenue (Quesnel Seipp et al. 2023). Conservation finance leveraging voluntary or compliance carbon markets offer a potential additional funding source. But carbon market credibility has increasingly come under scrutiny due to lack of transparency (Delacote 2024), critiques of over crediting due to scientifically inaccurate protocols (Badgley, Freeman, et al. 2022), unfounded assumptions for leakage rates (Haya et al. 2020), and over-simplified carbon accounting practices (Haya et al. 2023).

These critiques of carbon markets often focus on issues associated with baseline scenarios - the theoretical "business as usual" conditions used to assess the impact of carbon finance projects on carbon removal or emission reductions, which then determine the generation of carbon credits. The critiques of forestry offsets in California’s Cap and Trade highlight both inaccurate fixed assumptions and static baselines (Badgley, Freeman, et al. 2022) as well as fundamental issues with design of the policy. The majority of California's Cap and Trade offsets are traditional Improved Forest Management (IFM) projects (Ivy So, Barbara Haya, and Micah Elias 2023) which incentivize lengthened harvest rotations to increase forest biomass and carbon levels relative to a standard harvest rotation baseline. These projects largely increase competition stress among trees and elevate fire risks in already overstocked forests, putting California's compliance carbon markets in direct conflict with state wildfire prevention goals (Herbert et al. 2022). These critiques of carbon market forestry projects in California and elsewhere have highlighted that 1) accurate baselines are critical for effective forest carbon offsets 2) traditional static baseline assumptions about ecological and economic factors tend to be inaccurate and overly simplistic, leading to overgeneration of carbon credits and 3) current carbon offset protocols increase the risk of high severity wildfires.

The movement of carbon accounting protocols away from static baselines and towards dynamic baselines offer a potential way to enhance the accuracy of carbon baseline estimates, increase carbon credit quality, and adapt to fire-prone ecosystems (Fick et al. 2021; Haya et al. 2023). Dynamic baselines are calculated by comparing observed changes in a project area to changes in a similar reference region over time, allowing for the generation of carbon credits ex-post, based on actual observed outcomes. In contrast, traditional static baselines are typically established using fixed assumptions about ecological and economic factors, often leading to the generation of carbon credits ex-ante, based on predicted outcomes (Michaelowa et al. 2021). This mismatch between projected and actual carbon loss is at the heart of current market criticisms. Although dynamic baselines show promise to increase the quality of carbon markets, projects will only be viable with accurate predictions of the timing and quantity of carbon benefits. Funders and investors need assurance that the risk associated with the future carbon credit repayment is manageable and predictive models will be necessary to ensure the growth of dynamic baseline methodologies. This paper uses methods grounded in dynamic baseline principles to predict the timing and quantity of carbon benefits from forest treatment in fire-prone forests. Predictive analyses will be critical to the development of ex-post and dynamic baseline crediting.

While dynamic baselines can increase certainty and validity of carbon benefits, they introduce a financing challenge - forest restoration projects require large amounts of upfront capital to meet initial management such as forest thinning and prescribed fire. Static, predictive baselines make funding available at the beginning of a project. Dynamic baselines generate revenue once impact has been observed and measured, sometimes not until years after the work has been completed. This shift may further increase uncertainty in the timing and quantity of carbon revenue due to uncertainties outside of forest management such as climate and drought as well as a lack of project history with dynamic baselines. Environmental impact bonds and other financial tools tailored to generate social and environmental outcomes alongside financial returns can help address project funding challenges and attract funding that is project aligned (Brand et al. 2021). But attracting impact-oriented finance to ex-post dynamic baseline projects will require accurate projections of timing and quantity of ex-post carbon credits for this approach to be successful.

This analysis couples forest growth models with the cumulative probability of fire to explore the carbon impacts of thinning and prescribed fire treatments to restore a fire-resilient forest structure. We use predictive tools aligned with the framework of a dynamic baseline protocol to explore the timing and quantity of future carbon credits that could be generated. It examines the potential and temporal dynamics of stacking carbon income from ex-post avoided wildfire emissions and biomass utilization to increase funding for forest resilience treatments. The American River watershed is at high risk for wildfire and critical for municipal and irrigation water, hydropower production, carbon storage, wildlife, recreation and thus proves as a useful case study. Ultimately, we assess whether integrating carbon finance with other novel funding sources could contribute to closing the multi-billion-dollar funding gap for forest restoration in California.

In this manuscript we aim to answer the following key questions:

1. What are the carbon dynamics associated with restoring resilience to the American River watershed?

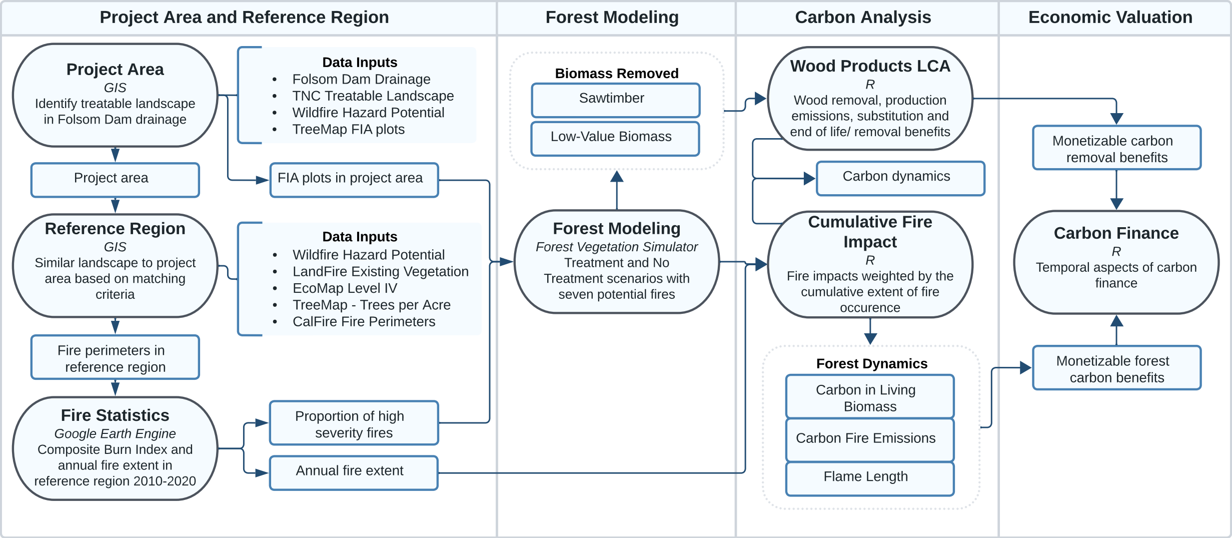
What is the value and certainty of different sources of carbon benefits?

4.3 Methods

4.3.1 Methodological Overview

We aim to quantify the dynamic carbon implications of restoring resilience to high fire risk forests in the American River watershed using the Forest Vegetation Simulator and statistical modeling to capture the cumulative probability of fire. To ground this analysis in ex-post observations, we apply remote sensing techniques to determine the annual rates of fire extent and severity from 2010 to 2020 within a reference region ecologically similar to the treatment area. Using these fire statistics, we simulate various fire scenarios, each weighted by the cumulative probability of fire, to quantify carbon dynamics under both treatment and no-treatment conditions. The same stands are used to model the treatment and no-treatment scenarios. Over 25 years, we calculate annual the carbon balance of the treatment scenario, focusing on aboveground live carbon, and compare carbon outcomes to the no-treatment scenario and pre-treatment carbon levels. When carbon benefits are quantified, we estimate potential revenues by monetizing carbon benefits from reduced wildfire emissions – evidenced by improved aboveground live carbon stocks – and various biomass utilization strategies.

Figure 10: The methodological workflow used to explore carbon dynamics and potential revenue generated from carbon.



4.3.2 Treatment Area, Reference Region, and Fire Statistics

For our study, we determined the treatment area by identifying high-risk forest stands suitable for treatment within the American River watershed's Folsom Dam drainage. Selection was based on the dam's drainage area, a Wildfire Hazard Potential (WHP) score of 'high' or 'very high' (4 or 5) in 2020 (Dillon and Gilbertson-Day, n.d.), vegetation cover over 10% in 2020 ("LANDFIRE Program: Data Products - Vegetation - Existing Vegetation Cover," n.d.), accessibility for mechanical treatment (Kelsey et al. 2017; M. North et al. 2015), and all Ecomap level 4 divisions, excluding oak woodlands ("EcoMap Provinces," n.d.). Ecomap is a map of the ecological regions of the conterminous U.S. with level 4 divisions representing the finest scale units (Omernik and Griffith 2014).

The treatment area consists of 115 Forest Inventory and Analysis (FIA) stands, covering 287,021 acres within the 1,189,689-acre watershed between the American River's North and South Fork.

It's largely composed of mixed conifer and softwoods (69%), with sections of white fir (14%), lodgepole pine (8%), and ponderosa pine (4%), plus some juniper woodland and western white pine. This area includes several Ecomap Level 4 divisions: northern Sierra subalpine, upper montane, mid-montane forests, central Sierra lower and mid-montane forests, and Sierra alpine forests.

Table 15: The initial spatial characteristics of the treatment area per acre captured at the start of the simulation before any fire events of treatment interventions (Riley et al. 2021).

Statistic	Stand Density Index (SDI)	Trees per Acre	Aboveground Live Carbon (tC)
Mean	198	267	34
Standard Deviation	66	228	19
Minimum	131	66	6
Maximum	492	1710	121

To increase the robustness of fire extent and severity used in the model, we created a reference region similar to the treatment area based on ecology and vulnerability criteria. The reference region included the Ecomap level 4 divisions which encompassed more than 5% of the treatment area, had Wildfire Hazard Potential score of 4 or 5 in 2012, and vegetation cover greater than 10% in 2012. Fire severity was analyzed annually between 2010 – 2020 following the methods of Parks et al. (Parks, Dillon, and Miller 2014) to construct a pixel level Composite Burn Index (CBI) for fire perimeters (CalFire 2024) within the reference region. High-severity burns had a CBI over 2.25 (J. D. Miller et al. 2009).

The reference region, covering 2,860,418 acres across northern and southern Sierra Nevada landmarks, recorded 174 fires from 2010 to 2020. Annually, a mean of 5.12% of the landscape burned, with a range between 0.05% and 14.86% which was used to parametrize the Monte Carlo simulations. 32% of burned acres were high-severity, which was the percent high severity used to parametrize the no-treatment fire scenarios modeled in Forest Vegetation Simulator (FVS) using the PotFPAB function which predetermines the portion of each stand that FVS burned with high or moderate-severity.

4.3.3 Forest Modeling - Forest Vegetation Simulator (FVS)

We employ the Forest Vegetation Simulator (FVS) to assess the impacts of forest management and fire on carbon stocks and flows within the treatment area. FVS is an individual-tree forest growth model widely used in the U.S. to support decision making (Crookston and Dixon 2005) which includes region specific model variants developed on local data, allows for incorporation of specific management scenarios including thinning and fuel treatments, and includes the Fire and Fuels Extension which was developed to asses risk, behaviors, and impact of fire in forest ecosystems (Rebain et al. 2022). Extensive forest thinning is modeled for the treatment scenario in the fifth of the simulation year on 287,021 acres within a 1,189,689-acre footprint, followed by prescribed fire in the ninth year to estimate model carbon dynamics over time. Treatments target a resilient Stand Density Index (SDI) of 175. A no-treatment scenario is also modeled which includes forest growth but no management intervention. We simulate both treatment and no-treatment scenarios across seven different fire scenarios: no fire, and fire in years 1, 5, 10, 15, 20, or 25, culminating in a total of 14 FVS runs which assume thinning and prescribed fire with no re-treatment in the treatment scenario and no management in the no-treatment scenario. In the no-treatment scenario the proportion of high severity is fixed at 32% using the PotPFAB function in FVS based on observed fire history in the reference region. In the treatment scenario, we allow FVS to predict fire severity given that forest treatment is fundamentally altering forest structure, which is a key factor in determining fire severity.

Utilizing data from Treemap, clipped to the polygon representing the treatment area, we identify the Forest Inventory and Analysis (FIA) plots for FVS modeling. We simulate the identified forest stands in both treatment and no-treatment scenarios starting for 25 years initialized with 2016 stand structure which is the most recently available year for Treemap data. In the treatment scenario, we perform forest thinning in the fifth year aiming to achieve a Stand Density Index (SDI) of 175 without removing trees exceeding 30” DBH. This SDI corresponds to 30% of the maximum SDI of the Western Sierra variant in FVS and is indicative of a resilient forest structure (M. P. North et al. 2022). We also implement prescribed fire in the ninth year, covering all treated stands, and use FlamAdj to limit the flame length of the prescribed fire to two feet which assumes that no prescribed fires escalate to crown fires. In the no-treatment scenario, we utilize FireSim to constrain the model by setting the proportion of the fire considered high severity to 32%, reflecting the observed fire severity in the reference region between 2010 and 2020. Each fire scenario run in FVS assumes 100% of each stand burns, allowing for secondary outputs to be calculated in R which weight the relative impact of fire on forest carbon based on the occurrence of fire (see *Predicting Carbon Dynamics and Fire Impact* section). Scaling from stand level to watershed scale involves counting unique stand identifiers in TreeMap on the treatment landscape and replicating FVS outputs based on the observed frequency.

4.3.4 Predicting Carbon Dynamics and Fire Impact

Once FVS simulations are complete, outputs were exported to R for reorganization and weighting. We use observations from 2010 – 2020 for annual wildfire extent and severity to create a cumulative probability density function (CDF) demonstrating the cumulative likelihood of fire over a 20-year stewardship contract period and aligns with recent developments in ex-post baselines. This approach helps us statistically propagate the cumulative impact of fire over time by considering both the annual extent of the fire and its frequency in the simulation (J. Agee 1996; Moritz et al. 2009). Each year, we calculate a cumulative sum that represents the predicted cumulative extent of fire, based on the annual fire extent and a multiplier representing the fire year. This cumulative sum, capped at 1, indicates the proportion of the landscape predicted to have experienced fire up to that year.

For years when the simulation year is greater than or equal to the fire year, the cumulative extent is calculated as:
CumulativeExtent = AnnualFireExtent x FireYear

Using this cumulative extent of fire, we integrate the FVS outputs from the fire and no fire scenarios based on the year of assumed fire for both the treatment and no-treatment scenario. This results in 12 integrated and weighted model outputs for both treatment and no-treatment scenarios (no fire, fire year 1, 5, 10, 15, and 20). For instance, if the mean 5-year cumulative extent of fire in the reference region is 25%, we calculate the aboveground live carbon (AGLC) for the treatment scenario in year t >= 5, when t >= FireYear, as:

$$AGLC_{Scenario=t,\ FireYear=1,\ t=5} = (AGLC_{Scenario=t,\ FireYear=1,\ t=5,\ Fire=yes} * CumulativeExtent) + (AGLC_{Scenario=t,\ FireYear=1,\ t=5,\ Fire=no} * (1-CumulativeExtent))$$

For years when the simulation year t is less than the fire year, we apply the NoFire scenario value, and no weighting occurs. In simple terms, we use values from the no-fire scenario up until the year of the modeled fire. Once the fire occurs, the outputs are weighted to reflect the cumulative extent of the landscape that would have burned.

To address uncertainty in fire extent, we conduct a Monte Carlo simulation with 100 iterations. For each iteration, we sample a random value for the annual fire extent from a truncated normal distribution reflecting the observed values in the reference region. The minimum annual fire extent used is 0.05%, the maximum 14.86%, and the mean 5.12% which represents the observed fire extent statistics in the reference region between 2010 – 2020. We use this random fire extent in the cumulative weighting model to calculate adjusted aboveground live carbon and wildfire emissions. When the predicted cumulative extent of the fire is 100%, only outputs from the fire FVS run are included. No stands are assumed to burn more than once. The Monte Carlo simulation generates a distribution of outcomes, providing a broad understanding of potential variability in carbon dynamics based on variations in annual fire extent.

4.3.1 Sawtimber, Low-Value Biomass, and Carbon Benefits of Biomass Utilization

To understand the carbon benefits of different biomass utilization options in the treatment scenario, we categorize biomass by size (DBH) and species. In the treatment scenario, we differentiate between merchantable saw-timber and low-value biomass based on the species and DBH of the trees removed. We consider species like true fir, douglas fir, ponderosa pine, and other softwoods accepted by the Sierra Pacific Industries sawmill in Lincoln, CA, as merchantable wood. Trees not exceeding 12” DBH and belonging to one of these merchantable species are classified as low-value, along with logging slash and bushes. We subtract the total carbon in merchantable saw logs from the total removed carbon, treating the remaining carbon as low-value.

We derive the carbon benefits of utilizing low-value biomass for fuels with carbon capture and sequestration (CCS), biochar, and traditional wood products in California from existing literature (Cabiyo et al. 2021). For each product, we consider emissions from processing, and benefits associated with substitution and storage. For storing low-value material in wood vaults, a methodology for carbon removal that stores wood to prevent decomposition and thus sequesters carbon, we base benefits on the lower end of carbon benefits from wood vault purchasing applications to Frontier (Github, n.d.). We assume that all carbon benefits for each biomass utilization scenario accrue in the year the biomass is removed from the landscape, except for traditional wood products, which we assume have an economic half-life of 38 years. After this period, we assume 58% of the carbon becomes inert in a landfill, with the remainder released to the atmosphere (Skog 2008). We largely base our selection of products for analysis on profitability, as outlined in Elias et al (2023) baseline scenario for various innovative wood products, breaking down carbon benefits by substitution, process, and removal. We consider several product types and average carbon benefits of each product type for carbon dynamic and carbon finance calculations: three fuel products with CCS, two fuel products without CCS, two biochar production technologies, two wood vault designs, traditional building materials, biopower, and pile burning.

4.3.2 Carbon Finance

We incorporate potential revenue from the voluntary carbon market from modeled increases in forest carbon stocks in the treatment scenario measured against the no-treatment counterfactual. We also include several pathways for monetizing the carbon benefits of biomass utilization via voluntary carbon markets for products like biochar and wood as well as policy incentives such as the Low Carbon Fuel Standard (LCFS), the Renewable Fuel Standard (RFS), and 45Q tax incentives for Carbon Capture and Sequestration (CCS). Prices used in the analysis are aligned with current market prices. Fuels produced with low-value biomass that incorporate CCS are assumed to generate \$100 (low) or \$150 (high) per tonne of CO_2 benefit, while fuels without CCS are estimated to generate \$50 (low) or \$100 (high) per tonne of CO_2 benefit, based on California's LCFS prices and 45Q tax incentives. We estimate wood vaults and biochar to generate \$100 (low) or \$150 (high) per tonne of CO_2 benefit, reflecting current prices in the voluntary market ("Nasdaq Carbon Removal Marketplace and Technologies," n.d.). We assume that increases in aboveground live biomass in the treatment scenario, compared to the no-treatment scenario, will generate carbon credits at \$35 (low) or \$75 (high) per tonne of CO_2. These carbon prices are used to generate the value of avoided wildfire emissions over the lifetime of the project.

4.4 Results

4.4.1 *Forest Modeling*

Forest thinning to restore resilience in year five and prescribed fire in year nine lead to a significant reduction of carbon in the aboveground live carbon pool in the treatment scenario. However, the thinning does not restore 15% of the stands to a resilient SDI of 175 because the treatment is limited to trees with a DBH of less than 30 inches and many trees in these stands are larger than the threshold, highlighting the challenges of restoring forest resilience with this treatment. On average, the thinning in year five removes 4.1 thousand board feet (MBF) per acre of merchantable timber containing 0.2 per acre tonnes of carbon and 5.8 per acre bone dry tonnes of low-value biomass containing 2.9 per acre tonnes of carbon.

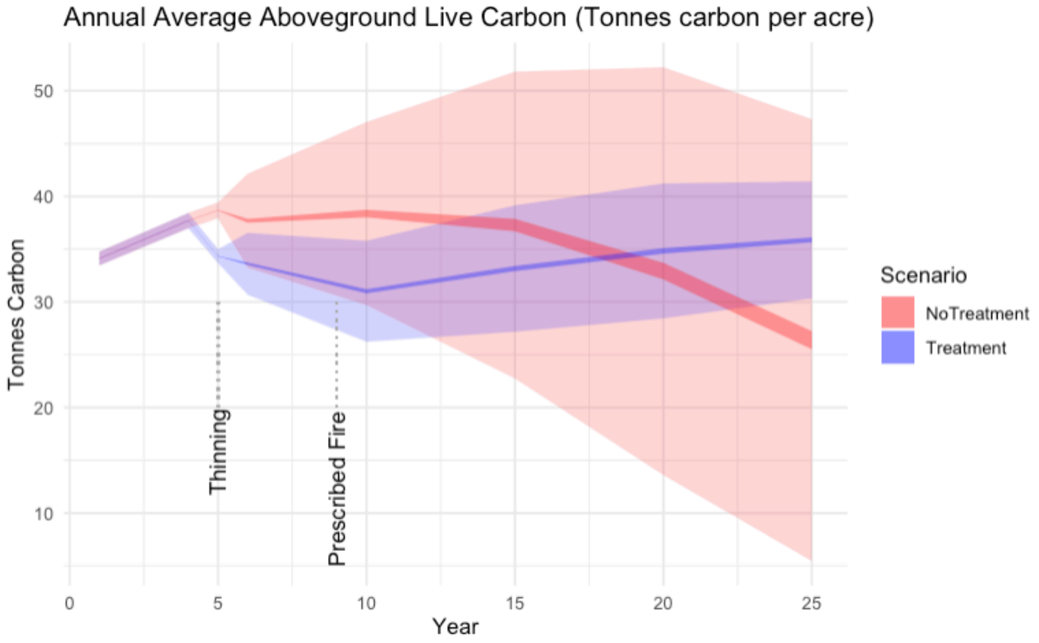
Table 16: Summary of the biomass removed, including statistics on low-value biomass tons, thousand board feet (MBF) of merchantable timber, and carbon contained in each biomass category. These acres represent average per-acre values over 287,021 treated acres within the larger 1,189,689-acre study area.

Statistic	**Carbon Removed (Low-Value Biomass)**	**Carbon Removed (Merchantable Biomass)**	**Tonnes Removed (BDT, Low-Value Biomass)**	**MBF Removed (Thousand Board Feet Merchantable)**
Mean	7.2	0.6	14.3	10.2
Standard Deviation	12.7	1.3	25.4	23.5
Minimum	0	0	0.1	0
Maximum	80.3	8.9	160.7	161

4.4.2 *Predicted Carbon Dynamics and Fire Impact*

After completing the thinning and prescribed fire treatments, the treatment scenario begins to accumulate carbon and demonstrates greater resilience to wildfire effects than the no-treatment scenario, measured by the gradual increase in carbon in the presence of fire. Initially, the no-treatment scenario continues to accumulate carbon, but its average per-acre carbon starts to decrease significantly within 10 years of the simulation due to the increased cumulative probability of fire. Nine years after the treatments are complete, the carbon levels in the treatment scenario have rebounded and begin accumulating 0.8 - 1.6 tonnes of carbon per acre per year (3 - 6 tonnes of CO_2e per acre per year) compared to the no-treatment scenario. In an avoided wildfire emission dynamic baseline crediting scenario, these carbon benefits could be monetized. Other greenhouse gasses are not accounted for.

Figure 11: Illustrates the estimated changes in per acre aboveground live carbon (tonnes) over time for both treated and untreated scenarios, derived from Monte Carlo simulations using the observed annual fire extents from 2010 to 2020 in the reference region. The simulations consider an annual fire extent range minimum of 0.05%, a maximum of 14.86%, and an average of 5.12%. The figure marks the years when thinning and prescribed burns are simulated in the treatment scenario. The figure uses color gradients to illustrate simulation results: lighter shades represent the variability in carbon levels across individual acres (one standard deviation from the mean), and darker shades convey the reliability of the average carbon benefit per acre over the entire treated area (standard error).



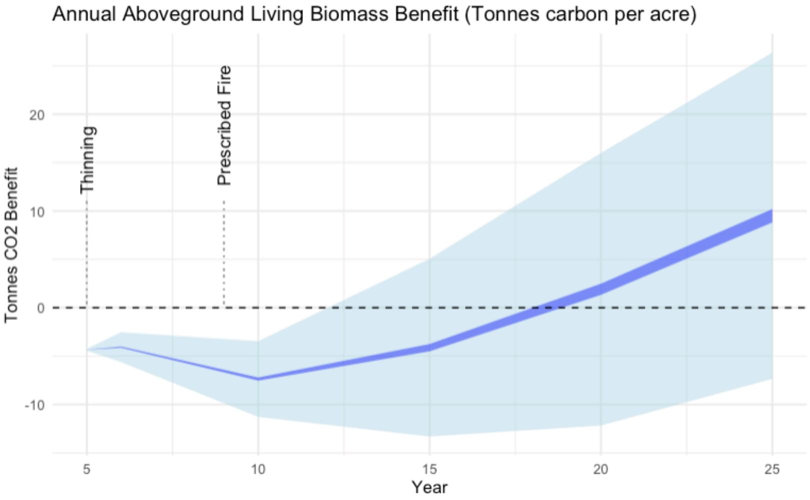
Notably, at the end of the simulation, mean aboveground live carbon levels per acre in the treatment scenario are 6% higher than levels at the beginning of the simulation, despite a decrease of 74% in the number of trees per acre. While treatment initially removes 7.8 tonnes of carbon (28.6 tCO_2e) on average per acre, the resilience provided by the new forest structure results in carbon benefits at the end of the simulation compared to the no-treatment counterfactual (see Table 17).

Table 17: Comparison of the Year 1 and Year 25 metrics for aboveground live carbon (tonnes), Stand Density Index, and Trees per Acre in both treatment and no-treatment scenarios.

Statistic	Year 1 Mean	Year 25 Mean (No Treatment)	Year 25 mean (Treatment)
AGLC	34	26	36
SDI	198	176	163
TpA	267	176	70

While the benefit of treatment varies on a per-acre basis, this variability notably decreases at scale. Figure 12 illustrates the standard error and standard deviation around the mean of per-acre benefits for aboveground live carbon, wildfire emissions, and flame length, indicating that while individual acre benefits are uncertain, the average benefits of landscape-scale treatment are relatively certain. The assumed fire extent has a significant impact on the number of years before the treatment scenario achieves net carbon benefits. Using unique simulations of discrete fire extents, a 7% annual fire extent yields carbon benefits seven years post-treatment, while a 3% extent results in benefits after 14 years. Using 100 Monte Carlo simulations and assuming future annual fire extent represent observations from 2010-2020 (minimum of 0.05%, maximum of 14.86% and mean of 5.12%), the treatment scenario is projected to exceed the no-treatment scenario in terms of average per-acre aboveground live carbon roughly 10 years after completing the treatment. However, this assumption – that fire extent and severity will not increase over the 25 years modeled – is highly conservative and arguably unrealistic. We chose conservativeness (assuming historical observation-based fire extent for both the treatment and no-treatment scenarios and proportion of high severity fire for the no-treatment scenario) given the importance of not overestimating the potential impacts of a carbon offset project. By 2040, the number of fires in the Sierra is projected to increase by over 50% (+- 32) with the extent increasing over 55% (+- 33) (Gutierrez et al. 2021). In our simulation, an increase in annual fire extent of roughly 40% (from 5% to 7%) lead to aboveground live carbon levels in the treatment scenario surpassing the no-treatment scenario in seven as opposed to nine years, highlighting the importance of assumed fire extent in the modeling.

Figure 12: Illustration of the annual carbon benefit per acre from treatment measured in carbon stored in aboveground live biomass, derived from Monte Carlo simulations. The light blue shade indicates the range within one standard deviation from the average of all simulations, reflecting the carbon benefit variability per individual acre. The dark blue shade represents the standard error, signifying the average per acre benefit of treatment when completed at landscape scale.



Benefits from wildfire emission reduction and flame length reduction are immediate after thinning in year five and are bolstered by prescribed fire treatments in year nine. Flame length decreases by 38% after thinning and prescribed fire compared to the no-treatment scenario, with the benefits increasing to 84% flame length reductions by the end of the simulation.

Figure 13: Illustration of the annual per-acre carbon benefits from reduced wildfire emissions from treatment, derived from 100 Monte Carlo simulations. Carbon transitioned from the live to the dead pool due to wildfire is not included in this figure.

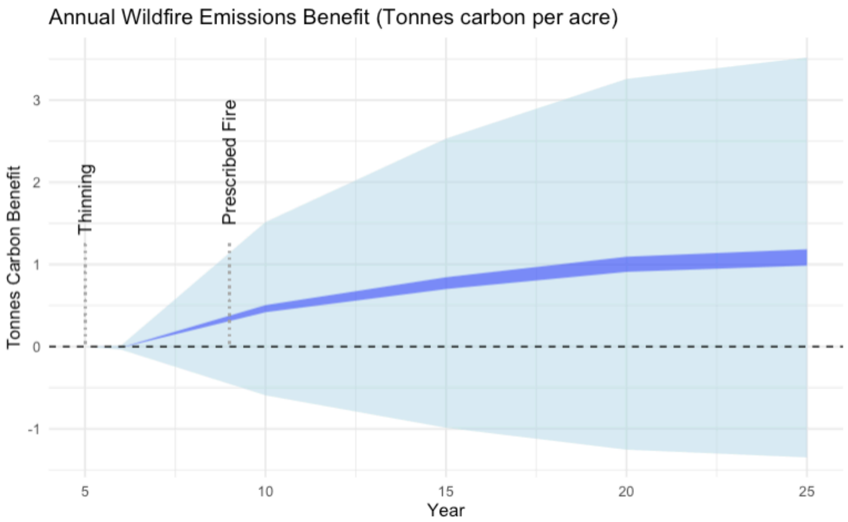
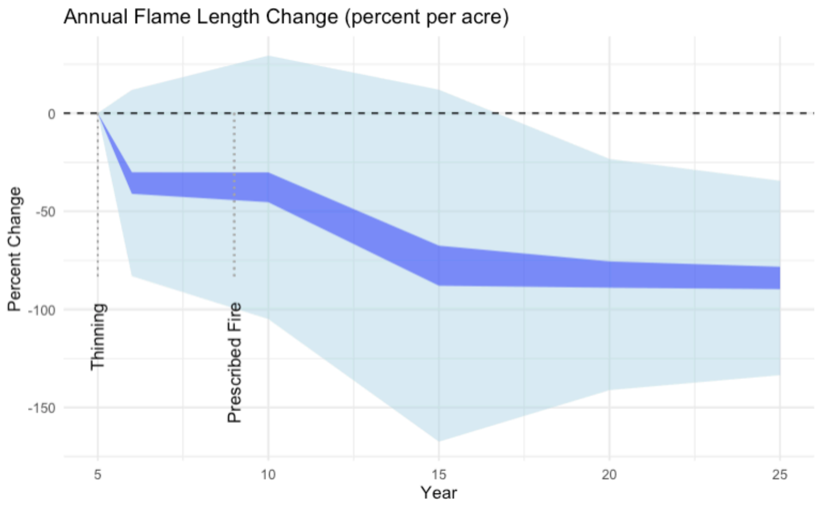


Table 18 and Figure 14: Depiction of the percent change in flame length over time resulting from treatment, which is used as a proxy for fire severity. Captures the percent change in flame length (ft) over time resulting from restoring resilience to forests. Flame length is used as a proxy for wildfire severity.

Fire year	**Percent Flame Length Change**	**Standard Deviation**	**Standard Error**
2021	-36	47	6
2025	-38	67	8
2030	-78	90	10
2035	-82	59	7
2040	-84	49	6



4.4.3 Sawtimber, Low-Value Biomass, and Carbon Benefits of Biomass Utilization

Biomass pile burning, which is assumed to release all of the carbon the biomass contains to the atmosphere in this model, has the worst carbon outcomes. Although there is a range of carbon benefits from the products modeled here, all have carbon benefits compared to pile burning. In terms of carbon benefits per tonne of carbon in feedstock, fuels with Carbon Capture and

Sequestration (CCS) exhibit the greatest benefits, whereas biopower presents the lowest benefits. Wood vaults offer the second-highest benefits, primarily due to low process emissions. Traditional building materials sequester approximately 59% of their carbon content once removed from the economy and deposited in landfills, but their benefits are minimal over the lifespan of this analysis, given that the economic half-life of these materials is 38 years (Skog 2008). Thus, building materials slowly accumulate carbon benefits over time after initially releasing carbon during production. Although biochar provides lower carbon benefits compared to fuels, it offers clear and immediate pathways for monetization given the market ready nature of the technology, which is advantageous for project developers seeking to enhance short-term revenue from biomass utilization, or simply avoid costs associated with biomass disposal (Elias et al. 2024).

Figure 15: Depiction of the carbon benefits per tonne of carbon in feedstock used to produce various products, accounting for storage benefits, process emissions, and substitution benefits. The dotted lines represent the assumed carbon benefits applied in the modeling.

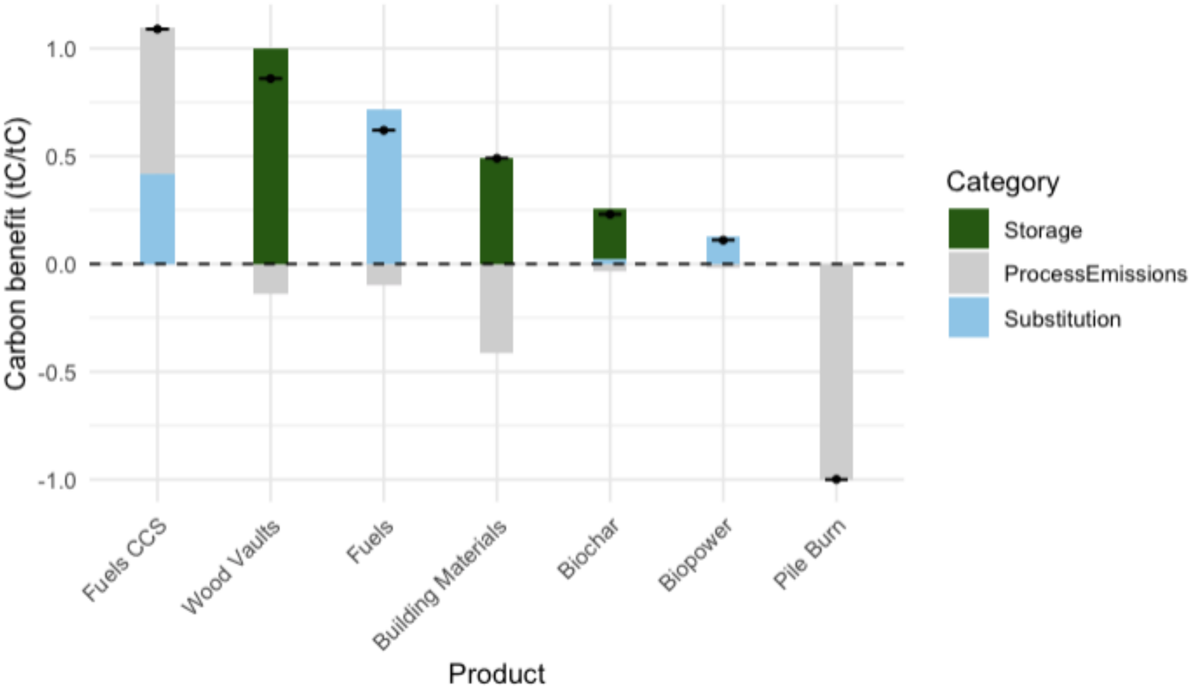


Table 19: The carbon benefits derived from using biomass as a feedstock in the production of various products, including storage benefits, processing emissions, and substitution benefits.

Product	Substitution	Process Emissions	Storage	Total
Fuels CCS	0.42	0.68	0.00	1.09
Wood Vaults	0.00	-0.14	1.00	0.86
Fuels	0.72	-0.10	0.00	0.62
Building Materials	0.00	-0.41	0.49	0.49
Biochar	0.02	-0.03	0.24	0.23
Biopower	0.13	-0.02	0.00	0.11
Pile Burn	0.00	-1.00	0.00	-1.00

4.4.4 Carbon Finance

The potential to generate revenue from the carbon benefits of restoring resilience to forests is significant. Results are conveyed in terms of CO_2e given market norms. This analysis assumes that through voluntary and compliance markets the carbon benefits observed and able to be monetized using recent market prices. In the first five years after the project, low-value biomass can generate revenue between $1310-1970 per acre in a fuels with CCS scenario while providing 13 tonnes CO_2 per acre, between $240-480 per acre in the fuels scenario, and between $250-370 in the biochar scenario. Interestingly, the wood vault scenario can generate between $910-1,370 per acre while providing nine tonnes per acre. Although fuels with CCS provide more carbon benefits, wood vaults provide a technologically feasible and highly carbon beneficial use case for low-value material in the short term.

The amount of revenue from carbon markets for avoided wildfire emissions and biomass utilization is roughly equivalent, although the timing of revenue generation is different. The 35 tonnes per acre from increased levels of forest carbon in the treatment scenario can provide between $1,220-2,620 per acre assuming carbon prices between $35 and $75 per ton CO_2.

Finally, the two most technologically mature pathways for biomass utilization are biochar and wood vaults. If the biochar scenario is coupled with the avoided wildfire emissions scenario, between $1,470-2,990 per acre could be generated. If the wood vaults and avoided wildfire emissions scenario are coupled, that amount increases to between $2,130 - $3,990 per acre.

Importantly, the timing for the potential revenue via carbon markets from biomass utilization and from avoided wildfire emissions is drastically different. Biomass utilization can generate income starting essentially the same year the work is completed. Using a dynamic baseline, avoided wildfire emissions will only start to generate income approximately 10 years after prescribed burning happens, which is 14 years after the initial thinning is completed.

Figure 16: Illustration of the revenue per acre from carbon revenue and timber after treatment to restore resilience. The revenue calculations are based on current market high and low estimates, as well as mean carbon data from Monte Carlo. The figure highlights the temporal differences in carbon revenue streams from biomass utilization and avoided wildfire emissions.

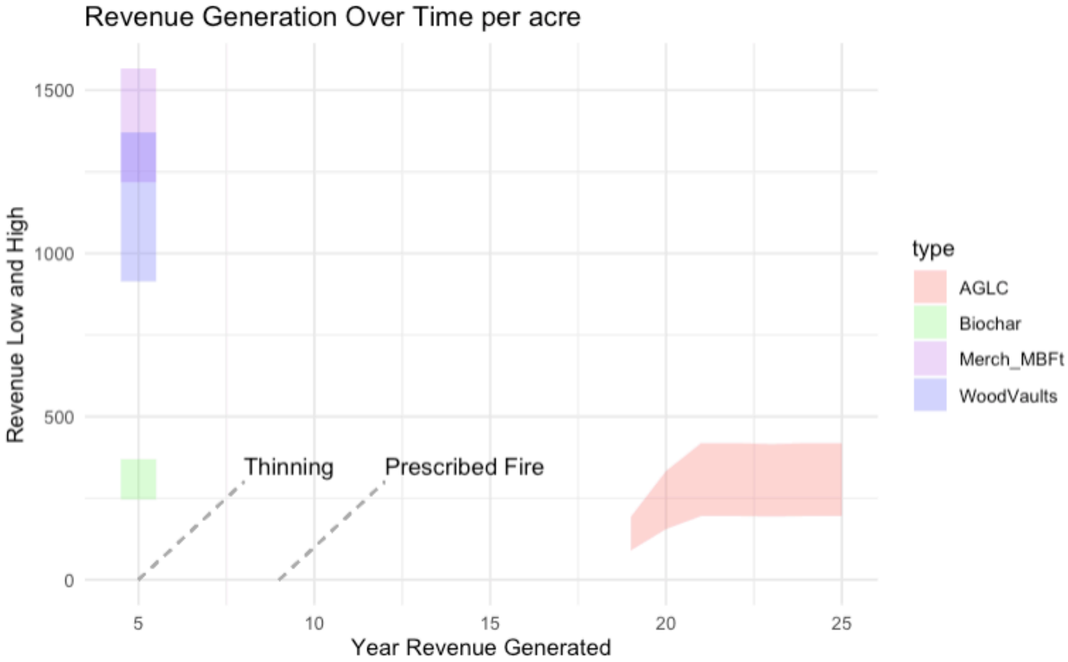


Table 20: Summary of the carbon benefits (in CO_2e), revenue sources, and projected timings for revenue from avoided wildfire emissions, biomass utilization, and sawtimber sales post-forest resilience restoration over the project lifetime. Per-acre average revenue estimates are based on the carbon outputs from Monte Carlo simulations.

Scenario	Total CO_2 Benefit	Revenue Source	Total Revenue Low (USD)	Total Revenue High (USD)	Revenue Year (Post Treatment)
Avoided Wildfire Emissions	35	Forest Carbon	1220	2620	10 onward
Fuels CCS	13	Biomass Carbon	1310	1970	1 – 4
Wood Vaults	9	Biomass Carbon	910	1370	1 – 4
Fuels	5	Biomass Carbon	240	480	1 – 4
Biochar	2	Biomass Carbon	250	370	1 – 4
Building Products	0.22	Sawtimber	1220	1570	1 – 4
Pile Burn	-11	NA	-300	-500	NA

4.5 Discussion and Conclusion

Restoring resilience to fire-adapted forests in the central Sierra Nevada mountains increases the durability of carbon storage and provides monetizable carbon benefits over a 25-year project lifetime. This analysis shows that carbon finance can generate up to \$3390 per hectare (\$1370 per acre) from CDR credits by using low-value biomass in wood vaults and up to \$6460 per hectare (\$2620 per acre) by monetizing avoided wildfire emission benefits from thinning and prescribed fire. With current management costs of roughly \$4942 - 6177 per hectare (\$2,000 - \$2,500 per acre), the state needs to generate approximately \$2 - \$2.5 billion annually to treat one million acres per year (404,686 hectares) - up to half of the current total and non-recurring federal allocations (FAS). Carbon revenues between \$5280 - 9850 per hectare (\$2,130 - \$3,990 per acre) from wood vaults and avoided wildfire emissions can reduce treatments costs associated with biomass disposal while generating carbon revenue from increased carbon stocks in treated stands and the carbon benefits of biomass utilization. This is one of the few analyses to examine the potential revenue generated from fuel treatments in fire prone ecosystems (Alcasena et al. 2021; Huang and Sorensen 2011). To our knowledge, we are the first to simultaneously examine the carbon dynamics of restored forest resilience (M. P. North et al. 2022), the potential to generate carbon revenue from increases in forest carbon from restored resilience, and the revenue from carbon benefits of biomass utilization.

Restoring resilience is crucial for maintaining carbon storage and the broad benefits of healthy forests. It provides a clear benchmark for assessing forest health and ensuring carbon durability. Restoring resilience yields on average 86 tonnes of CO_2e per hectare (35 tonnes per acre) in live biomass carbon compared to no treatment, while reducing average fire severity by 78% five years post-treatment, corroborated by others who have found decreases in severity up to 89% (Piqué and Domènech 2018). These findings are complementary to other studies, in particular those exploring the effects of coupling thinning with prescribed fire, which find treatment can reduce flame length, overall fire intensity, and contribute to less sever fire behavior (Butler et al. 2012; J. Agee and Lolley 2006; J. K. Agee and Skinner 2005), but this is the first study to explore treatments designed to restore empirically grounded forest resilience (M. P. North et al. 2022). Utilizing all low-value biomass for wood vaults or biochar, the most market-ready products in this analysis, would yield another nine or two tonnes of CO_2 benefits per acre, respectively.

Interestingly, the treatment scenario exhibited a slight increase in carbon levels at the end of the simulation compared to the beginning. This increase primarily resulted from the redistribution of carbon from dense, small trees to dispersed, large trees. The restoration of resilience to the landscape, which led to an 87% reduction in trees per acre at year 25, not only enhanced fire resilience but also marginally increased carbon stores relative to current levels. Previous analyses have indicated that current carbon stocks are disproportionately concentrated in small trees within homogenous forests, elevating the risk of losses due to wildfire, drought, and other disturbances (D. E. Foster et al. 2020; Hurteau, Stoddard, and Fulé 2011). These findings underscore the importance of aligning treatment prescriptions with resilience to maximize magnitude and durability of carbon storage.

This analysis deliberately employs historical observations of fire extent and severity from 2010 to 2020, thereby minimizing the potential impacts of climate change, the anticipated annual increase in fire extent, and the trend of escalating fire severity. These estimates are conservative when assessing the impacts of treatment relative to the no-treatment scenario - Gutierrez et al. (2021) forecasted an increase in the number of fires in the Sierra by over 50% and an increase in fire extent by over 55% by 2040 which is in line with both historical observations and predictions of future fire extent and severity (Kane et al. 2015; Schwartz et al. 2015; Jay D. Miller and Safford 2012; J. D. Miller et al. 2009; Yue et al. 2013). However, the implications of utilizing historical estimates for predicting carbon stocking relative to contemporary levels remain uncertain, underscoring the significance of establishing accurate baselines. Put simply, conservative assumptions regarding the escalation of fire extent and severity likely understate the benefits of treatment compared to the no-treatment scenario. Conversely, maintaining constant the effects of climate change, such as drought and temperature rises, may lead to an overestimation of the treatment's impact compared to current carbon levels. Nonetheless, the relative enhancement in carbon stability resulting from the restoration of resilience to forests is evident, as forest carbon shifts towards fewer, larger trees that are more capable of withstanding wildfires. The integration of forest carbon into policy decisions necessitates clear baseline assumptions for carbon stocks (be it current levels or future levels in the absence of management) and refined projections for forest carbon stocking amidst climate change.

While the carbon benefits of avoided wildfire emissions require nuanced assumptions about baselines, the carbon benefits of biomass utilization for wood vaults, biochar, and fuels are clear. While using biomass for fuels like hydrogen combined with carbon capture and sequestration offers significant carbon benefits, the required capital is enormous (Elias et al. 2023), and consistent, contracted feedstock supply is critical to attract investors (Clere). Given the current ad-hoc nature of supply chains for low-value biomass from forest restoration projects, less capital-intensive strategies like wood vaults and biochar are more promising in the near term. Moreover, wood vaults offer higher carbon removal efficiency compared to fuels - both cost per tonne carbon removed and tonnes of carbon removed per tonne carbon in feedstock. However, concerns about the durability and permanence of these CDR strategies persist, raising important questions about the environmental safeguards needed to prevent replicating widespread credibility problems in the voluntary carbon market.

Carbon finance in forest ecosystems has been fraught with challenges due to inaccurate methodologies and baselines, leading to carbon credits that do not represent actual emission reductions. Dynamic baselines and ex-post revenue offer a potential solution by shifting the carbon market towards an observable, results-based approach. However, this increased certainty introduces funding challenges, as revenue becomes more uncertain and is generated in the future under current carbon market structure. In this analysis, approximately half of the carbon income would be generated more than ten years after project completion, assuming benefits are monetized after they are observed.

Although this analysis primarily addresses traditional carbon markets, the methodologies employed are compatible with novel carbon attribution initiatives that do not necessarily aim for carbon neutrality or carbon credit generation. A carbon attribution model assigns carbon benefits to specific observed actions or projects and can be funded through voluntary contributions, corporate sponsorship, government grants and subsidies, impact investors, or public-private partnerships. This approach seeks to offer a more transparent and precise accounting of carbon benefits, concentrating on the tangible outcomes of conservation or restoration efforts rather than on predicted carbon stocks. Carbon attribution initiatives underscore the significance of stringent monitoring and verification to ensure the authenticity and verifiability of the attributed carbon benefits. By focusing on the benefits of management, these programs aim to foster more effective and accountable climate action, avoiding the complexities and potential issues associated with traditional carbon offset markets (Blanchard). Carbon attribution initiatives may be particularly well-suited to dynamic baselines methodologies, enabling accurate impact tracking of initial project contributions without the creation of conventional credits.

Large, landscape-scale projects decrease risk by increasing certainty in benefits, supporting the rationale for novel financing. The uncertainty of carbon benefits and revenue tied to incremental increases in carbon benefits is high for any individual acre but decreases as projects scale. The mean carbon benefits in aboveground live biomass when treatment is done at scale are 22 to 26 tonnes carbon per hectare (32 to 38 tonnes CO_2e per acre) - but between -18 to 65 tonnes carbon per hectare (-27 to 97 tonnes CO_2e per acre) for treatment of a single acre. This highlights the importance of landscape level restoration to increase carbon benefit certainty. However, this analysis is temporally limited and further research is needed to determine the longevity of single, landscape scale treatments which restore resilience. To ensure the permanence of carbon benefits from restoring resilience, reintroducing regular, low-severity fire at scale will be necessary (Odland et al. 2021; Molina et al. 2018; Rabin, Gérard, and Arneth 2022). This analysis shows that extensive forest treatments to restore a resilient forest structure has more durable carbon benefits than less extensive treatment. Extensive treatments are more expensive, but the increased initial expense extends the longevity of treatment impacts on wildfire resilience and carbon stocks (Collins et al. 2014). Cheaper, less extensive forest management practices will require more regular reentry and likely increased management costs over time. In essence, restoring resilience has a higher return on investment even though upfront treatment costs may be higher. From a project finance standpoint, coupling carbon revenue from avoided wildfire emissions with biomass utilization revenue can alleviate up-front project costs by generating revenue in the project's initial years and further enabling durable forest treatments.

To realize conservation finance via carbon finance for fire-prone forests, several areas need addressing, highlighting the need for a fundamental rethinking of carbon markets. First, the dynamic baseline approach requires validation and refinement to ensure high-quality credits representing durable carbon benefits are created, or methods are aligned with tracking for emerging carbon attribution programs. Second, durability of carbon benefits from fire resilience treatments needs to be ensured through recurring future treatments which is the consensus in the literature (Aponte, Tolhurst, and Bennett 2014; Stephens, Collins, and Roller 2012), although this study on examines the effects of one prescribed fire. Third, CDR credits like those from biochar and wood vaults need coupling with rigorous environmental safeguards to prevent reversals. Fourth, predictive carbon and financial models, such as the one used in this paper, need refining alongside investors to ensure confidence and maintain academic rigor. In essence, the successful harnessing of carbon markets for the restoration and resilience of fire-prone forests hinges on creating accurate baselines and reimagining carbon project finance.

5 Conclusion

This dissertation contributes to the discourse on viable biomass utilization strategies and restored forest resilience for meeting climate objectives. I find that investment in biomass utilization not only has the potential to be profitable but also offers substantial carbon benefits which can be monetized to further industry development. Monetizing carbon benefits from biomass utilization alongside carbon benefits from avoided wildfire emission can contribute substantially to forest restoration. This work helps fiscally reimagine forest restoration by connecting methodological advancements with innovative financial instruments by linking forest and carbon modeling with financial modeling. Specifically, I use statistically weighted forest stand modeling to incorporate probabilistic fire effects on carbon stocks, life-cycle assessments to account for biomass utilization benefits, and financial modeling to translate ecological findings to actionable financial metrics.

These methods meld principles from ecology, economics, and forest management, highlighting the importance of cross-sector collaboration in tackling intricate environmental management challenges. While understanding biogenic carbon dynamics begins in forests, understanding the carbon impacts of wood products require principles from engineering and economics. Applying these findings requires an understanding of policy and finance informed by a historical understanding of carbon markets to prevent repeating past mistakes and refine future systems. This research was motivated by my desire to understand and incentivize the societal benefits from resilient forests. Several themes have emerged from this work.

5.1 Biomass utilization has clear carbon benefits and is key to scale forest restoration and address funding gaps.

Biomass utilization emerges as a critical strategy within this dissertation, providing highly certain and highly durable carbon benefits which the current carbon markets value and pays a premium for. My findings demonstrate that environmentally sound utilization of low-value biomass can sequester significant quantities of carbon, help to reduce carbon emissions, and increase forest resilience. Biomass can be used as a feedstock to displace fossil fuels and in products which store carbon. The benefits are unlocked through investment and policy support for lower carbon intensity commodities like fuels while generating investor returns. Nonfuel products such as biochar have an average IRR of 13% while fuel products such as hydrogen and other transportation fuels have an average IRR of 19%. Generally, products eligible for government incentives such as LCFS and RFS are more profitable, highlighting the importance of sustained policy support to develop this industry. These findings further show that profitable, policy-supported investment in products utilizing biomass feedstocks can simultaneously help accomplish climate and forest management goals. As policy continues to develop, the insights from this research point to the need to continued support of market-based initiatives for lower carbon intensity fuels and carbon storage products. With continued support, climate policy has the potential to increase funding for forest restoration in California.

5.2 Technologically mature and low capex utilization can help build supply chains to unlock higher value biomass utilization options.

Although certain technologies that can utilize low-value biomass as a feedstock such as fuels with carbon capture and sequestration provide substantial carbon benefits, they also demand large quantities of consistent feedstock. They are enormously capital intensive, and investors prioritize investments with long term feedstock supply contracts, which are currently limited by regulatory and administrative frameworks for forest restoration. Adopting technologically mature and low-capital-expenditure biomass utilization strategies like biochar which can utilize biomass feedstock in a more ad-hoc manner is a cornerstone for developing robust supply chains for low-value biomass, which is a critical step towards unlocking more valuable biomass utilization strategies like fuels with CCS. Biochar made from low-value forest biomass is economically viable and provides high returns in many scenarios. Light upgrades to biopower facilities have the highest returns, generally with IRRs between 10-30%. Mobile biochar production often predicted to have the lowest return, but mobile biochar can help to decrease costs – landowners can pay up to \$150 to \$300 per ton biochar and still save money compared to pile burning low-value biomass. There is also enormous potential to generate high quality carbon credits from biochar production, which can reduce costs associated with disposing of waste biomass and even generate revenue for restoration projects in certain scenarios. Biochar can generate approximately one carbon credit for every two bone dry tonnes of low-value biomass turned to biochar. Public and private investments in biochar can help accelerate the transition to more advanced bio refineries capable of producing a wide array of bio-products, which can catalyze the forest restoration economy. Currently, the investment potential in the Western U.S. is over \$20 billion at current carbon prices. This investment could generate approximately 70 million carbon credits annually – roughly the same number of carbon credits currently generated by all forestry and agricultural projects. Moving forward, there are three potential pathways for the biochar industry to scale and utilize biomass from forest management and fuel thinning projects. Either 1) the carbon market will need to sustain high carbon prices, 2) a subsidy or other mechanism will need to decrease the cost of feedstock biomass, or 3) production will need to take advantage of economies of scale to bring down biochar prices while increasing production.

5.3 The carbon benefits of restoring resilience and biomass utilization can pay for forest management.

Restoring resilience in fire-prone forests and capitalizing on the carbon benefits of low-value biomass can often finance the restoration itself. Restoring resilience can generate a 35 tonne CO_2 benefit from avoided wildfire emissions, up to a 13 tonne CO_2 benefit from biomass utilization, and generate up to \$4000 per acre in carbon revenue from these benefits when compared to a no-treatment scenario. This dissertation finds that restoring resilient forest structure leads to more stable carbon storage compared to current levels as well, via gradual transitions from smaller trees in dense stands to larger trees in more diverse stands inherently more resilient to fire. Modeling treatments aimed at restoring resilience reduced the number of trees on the landscape by 78% while increasing carbon storage by 6% compared to year one by the end of the simulation. While the carbon benefits of treating acres are uncertain and variable, at a watershed scale these benefits become more predictable and substantial compared to scenarios without treatment. Resilience treatments also enable stands to rebound to pretreatment carbon levels, highlighting the potential to better align state wildfire and climate policy around resilience-oriented forest management. These findings underscore the potential for carbon markets or carbon contributions to fund restoration efforts. However, if rigor is increased in the carbon market via dynamic baselines, revenue is generated from avoided wildfire emission carbon benefits only after the carbon benefits are observed, often years after the initial treatment. Early-stage project finance is thus crucial and can be combined with carbon revenue from biomass utilization, with revenue from avoided wildfire emissions providing financial returns in later years. The need for innovative financial instruments is clear – investments that provide up-front financing, with clear predictions of amount and timing of revenue later, are essential. This approach could enable a shift toward financially sustainable and carbon positive forest restoration.

6 References

Agee, James. 1996. “Fire Ecology of Pacific Northwest Forests.” *The Bark Beetles, Fuels, and Fire Bibliography*, January.

Agee, James K., and Carl N. Skinner. 2005. “Basic Principles of Forest Fuel Reduction Treatments.” *Forest Ecology and Management*, Relative Risk Assessments for Decision – Making Related To Uncharacteristic Wildfire, 211 (1): 83–96. https://doi.org/10.1016/j.foreco.2005.01.034.

Agee, James, and M. Lolley. 2006. “Thinning and Prescribed Fire Effects on Fuels and Potential Fire Behavior in an Eastern Cascades Forest, Washington, USA.” *Fire Ecology* 2 (December): 3–19. https://doi.org/10.4996/fireecology.0202003.

Alcasena, Fermín J., M. Rodrigues, P. Gelabert, A. Ager, M. Salis, A. Améztegui, Teresa Cervera, and C. Vega-García. 2021. “Fostering Carbon Credits to Finance Wildfire Risk Reduction Forest Management in Mediterranean Landscapes.” *Land*. https://doi.org/10.3390/land10101104.

Aponte, Cristina, Kevin G. Tolhurst, and Lauren T. Bennett. 2014. “Repeated Prescribed Fires Decrease Stocks and Change Attributes of Coarse Woody Debris in a Temperate Eucalypt Forest.” *Ecological Applications* 24 (5): 976–89. https://doi.org/10.1890/13-1426.1.

Badgley, Grayson, Freya Chay, Oriana S. Chegwidden, Joseph J. Hamman, Jeremy Freeman, and Danny Cullenward. 2022. “California’s Forest Carbon Offsets Buffer Pool Is Severely Undercapitalized.” *Frontiers in Forests and Global Change* 5 (August). https://doi.org/10.3389/ffgc.2022.930426.

Badgley, Grayson, Jeremy Freeman, Joseph J. Hamman, Barbara Haya, Anna T. Trugman, William R. L. Anderegg, and Danny Cullenward. 2022. “Systematic Over-Crediting in California’s Forest Carbon Offsets Program.” *Global Change Biology* 28 (4): 1433–45. https://doi.org/10.1111/gcb.15943.

Baker, Sarah, Joshuah Stolaroff, George Peridas, Simon Pang, Hannah Goldstein, Felicia Lucci, Wenquin Li, et al. 2020. “Getting to Neutral: Options for Negative Carbon Emissions in California.” Lawrence Livermore National Labratory.

Barros, Ana M. G., Alan A. Ager, Michelle A. Day, Meg A. Krawchuk, and Thomas A. Spies. 2018. “Wildfires Managed for Restoration Enhance Ecological Resilience.” *Ecosphere* 9 (3): e02161. https://doi.org/10.1002/ecs2.2161.

Bergman, Richard, Maureen Puettmann, Adam Taylor, and Kenneth E. Skog. 2014. “The Carbon Impacts of Wood Products.” *Forest Products Journal* 64 (7–8): 220–31. https://doi.org/10.13073/FPJ-D-14-00047.

Bhave, Amit, Richard H.S. Taylor, Paul Fennell, William R. Livingston, Nilay Shah, Niall Mac Dowell, John Dennis, et al. 2017. “Screening and Techno-Economic Assessment of Biomass-Based Power Generation with CCS Technologies to Meet 2050 CO2 Targets.” *Applied Energy* 190 (March): 481–89. https://doi.org/10.1016/j.apenergy.2016.12.120.

“Bioenergy Market Adjusting Tariff (Senate Bill 1122).” n.d. PG&E. Accessed October 27, 2022. https://www.pge.com/en_US/for-our-business-partners/floating-pages/biomat/biomat.page?WT.mc_id=Vanity_rfo-biomat&ctx=large-business.

Blanchard, Libby, William R.L. Anderegg, and Barbara Haya. 2024. “Instead of Carbon Offsets, We Need ‘Contributions’ to Forests (SSIR).” 2024. https://ssir.org/articles/entry/forest-contributions-carbon-offsets.

Bowes, Michael D., and John V. Krutilla. 1985. “Chapter 12 Multiple Use Management of Public Forestlands.” In *Handbook of Natural Resource and Energy Economics*, 2:531–69. Handbook of Natural Resource and Energy Economics. Elsevier. https://doi.org/10.1016/S1573-4439(85)80019-1.

Brand, M. W., K. Quesnel Seipp, P. Saksa, N. Ulibarri, A. Bomblies, L. Mandle, M. Allaire, et al. 2021. “Environmental Impact Bonds: A Common Framework and Looking Ahead.” *Environmental Research: Infrastructure and Sustainability* 1 (2): 023001. https://doi.org/10.1088/2634-4505/ac0b2c.

Brown, Tristan R., Mark M. Wright, and Robert C. Brown. 2011. “Estimating Profitability of Two Biochar Production Scenarios: Slow Pyrolysis vs Fast Pyrolysis.” *Biofuels, Bioproducts and Biorefining* 5 (1): 54–68. https://doi.org/10.1002/bbb.254.

Butler, Bret, RD Ottmar, T. Rupp, Randi Jandt, Erza Miller, K Howard, R Schmoll, S Theisen, RE Vihnanek, and Daniel Jimenez. 2012. “Quantifying the Effect of Fuel Reduction Treatments on Fire Behavior in Boreal Forests.” *Canadian Journal of Forest Research* 43 (January): 97–102.

Cabiyo, Bodie, Jeremy S. Fried, Brandon M. Collins, William Stewart, Jun Wong, and Daniel L. Sanchez. 2021. “Innovative Wood Use Can Enable Carbon-Beneficial Forest Management in California.” *Proceedings of the National Academy of Sciences* 118 (49): e2019073118. https://doi.org/10.1073/pnas.2019073118.

CalFire. 2024. “Fire Perimeters | CAL FIRE.” 2024. https://www.fire.ca.gov/what-we-do/fire-resource-assessment-program/fire-perimeters.

“California Assessment of Wood Business Innovation Opportunities and Markets (CAWBIOM). Phase II Report: Feasibility of Potential Business Opportunities.” 2015. The Beck Group. https://www.nationalforests.org/assets/pdfs/Phase-II-Report-MASTER-1-4-16.pdf.

“California Biomass Utilization Facility Feedstock Supply Report.” 2018. The Beck Group. https://www.hcd.ca.gov/community-development/disaster-recovery-programs/ndrc/docs/biomassfeedstocksupplyreport.pdf.

California Council on Science and Technology and Blue Forest. 2023. “The Human Health Benefits of Improving Forest Health in California.” https://ccst.us/reports/ the-human-health-benefits-of-improving-forest-health-in-california/.

Carbon Direct. 2023. “Sustainable Biomass Dourcing for Carbon Dioxide Removal: Mitigating the Risks of Biomass-Based Carbon Dioxide Removal Contracting.” 2023. https://insights.carbon-direct.com/hubfs/Gated%20assets/Report_Sustainable-Biomass-Sourcing.pdf.

Carbon Market Watch. 2023. “Poor Framing: The Role of Negative Emissions Technologies in Existing Climate Policy Frameworks.” https://carbonmarketwatch.org/wp-content/uploads/2023/09/Poor-framing_-The-role-of-negative-emissions-technologies-in-climate-policy-frameworks-1.pdf.

“Carbon Neutrality by 2045 - Office of Planning and Research.” n.d. Accessed March 17, 2024. https://opr.ca.gov/climate/carbon-neutrality.html.

“Carbon Removal Price Indexes.” n.d. NASDAQ. Accessed October 27, 2022. https://www.nasdaq.com/solutions/carbon-removal-marketplace.

Carton, Wim, Jens Friis Lund, and Kate Dooley. 2021. “Undoing Equivalence: Rethinking Carbon Accounting for Just Carbon Removal.” *Frontiers in Climate* 3 (April). https://doi.org/10.3389/fclim.2021.664130.

Chang, Heesol. 2021. "The Cost of Forest Thinning Operations in the United States West: A Systematic Literature Review and Model Development." Northern Arizona University.

Clawson, Marion. 1977. "The Concept of Multiple Use Forestry." *Environmental Law* 8: 281.

Collins, Brandon M., Adrian J. Das, John J. Battles, Danny L. Fry, Kevin D. Krasnow, and Scott L. Stephens. 2014. "Beyond Reducing Fire Hazard: Fuel Treatment Impacts on Overstory Tree Survival." *Ecological Applications* 24 (8): 1879–86. https://doi.org/10.1890/14-0971.1.

Collins, Brandon M., Richard G. Everett, and Scott L. Stephens. 2011. "Impacts of Fire Exclusion and Recent Managed Fire on Forest Structure in Old Growth Sierra Nevada Mixed-Conifer Forests." *Ecosphere* 2 (4): art51. https://doi.org/10.1890/ES11-00026.1.

"Confronting the Wildfire Crisis." 2022. US Forest Service. January 14, 2022. http://www.fs.usda.gov/managing-land/wildfire-crisis.

Crookston, Nicholas L., and Gary E. Dixon. 2005. "The Forest Vegetation Simulator: A Review of Its Structure, Content, and Applications." *Computers and Electronics in Agriculture*, Decision Support Systems for Forest Management, 49 (1): 60–80. https://doi.org/10.1016/j.compag.2005.02.003.

Delacote, P. 2024. "Strong Transparency Required for Carbon Credit Mechanisms." *Nature Sustainability*. https://doi.org/10.1038/s41893-024-01310-0.

DellaSala, Dominick A., Richard L. Hutto, Chad T. Hanson, Monica L. Bond, Timothy Ingalsbee, Dennis Odion, and William L. Baker. 2017. "Accommodating Mixed-Severity Fire to Restore and Maintain Ecosystem Integrity with a Focus on the Sierra Nevada of California, USA." *Fire Ecology* 13 (2): 148–71. https://doi.org/10.4996/fireecology.130248173.

Dillon, Gregory K., and Julie W. Gilbertson-Day. n.d. "Wildfire Hazard Potential for the United States (270-m), Version 2020." Accessed February 9, 2023. https://doi.org/10.2737/RDS-2015-0047-3.

Duffy, Katharyn A., Christopher R. Schwalm, Vickery L. Arcus, George W. Koch, Liyin L. Liang, and Louis A. Schipper. 2021. "How Close Are We to the Temperature Tipping Point of the Terrestrial Biosphere?" *Science Advances* 7 (3): eaay1052. https://doi.org/10.1126/sciadv.aay1052.

"EcoMap Provinces." n.d. EcoMap Provinces. Accessed March 17, 2024. https://data.fs.usda.gov/geodata/edw/edw_resources/meta/S_USA.EcoMapProvinces.xml.

"Electricity Monthly Update." 2022. U.S. Energy Information Administration. 2022. https://www.eia.gov/electricity/monthly/update/wholesale-markets.php.

Elias, Micah, John Dees, Bodie Cabiyo, Phil Saksa, and Daniel L. Sanchez. 2023. "Financial Analysis of Innovative Wood Products and Carbon Finance to Support Forest Restoration in California." *Forest Products Journal* 73 (1): 31–42. https://doi.org/10.13073/FPJ-D-22-00049.

Elias, Micah, Daniel L. Sanchez, Phil Saksa, Josiah Hunt, and Jonathan Remucal. 2024. "Market Analysis of Coupled Biochar and Carbon Credit Production from Wildfire Fuel Reduction Projects in the Western USA." *Biofuels, Bioproducts and Biorefining*. https://doi.org/10.1002/bbb.2614.

Fick, Stephen E., Travis W. Nauman, Colby C. Brungard, and Michael C. Duniway. 2021. "Evaluating Natural Experiments in Ecology: Using Synthetic Controls in Assessments of Remotely Sensed Land Treatments." *Ecological Applications* 31 (3): e02264. https://doi.org/10.1002/eap.2264.

Forest Climate Action Team. 2018. “California Forest Carbon Plan: Managing Our Landscapes in a Changing Climate.”

Foster, Daniel E., John J. Battles, Brandon M. Collins, Robert A. York, and Scott L. Stephens. 2020. “Potential Wildfire and Carbon Stability in Frequent-Fire Forests in the Sierra Nevada: Trade-Offs from a Long-Term Study.” *Ecosphere* 11 (8): e03198. https://doi.org/10.1002/ecs2.3198.

Foster, Gabe. 2022. Personal Communication - Tahoe National Forest.

Friedenthal, Andrew. 2022. “Wood Waste to Biochar & Power Budget Pricing.” CharTech Solutions.

Galik, Christopher S., Justin S. Baker, Adam Daigneault, and Gregory Latta. 2022. “Crediting Temporary Forest Carbon: Retrospective and Empirical Perspectives on Accounting Options.” *Frontiers in Forests and Global Change* 5 (August). https://doi.org/10.3389/ffgc.2022.933020.

Galik, Christopher S., and Robert B. Jackson. 2009. “Risks to Forest Carbon Offset Projects in a Changing Climate.” *Forest Ecology and Management* 257 (11): 2209–16. https://doi.org/10.1016/j.foreco.2009.03.017.

“Gasoline and Diesel Fuel Update.” 2022. U.S. Energy Information Administration. 2022. https://www.eia.gov/petroleum/gasdiesel/index.php.

Github. n.d. “Carbon-Removal-Source-Materials/Project Applications at Main · Frontierclimate/Carbon-Removal-Source-Materials.” GitHub. Accessed March 17, 2024. https://github.com/frontierclimate/carbon-removal-source-materials/tree/main/Project%20Applications.

“Global Hydrogen Review 2021.” 2021. International Energy Agency. https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf.

Goodwin, Marissa J., Malcolm P. North, Harold S. J. Zald, and Matthew D. Hurteau. 2020. “Changing Climate Reallocates the Carbon Debt of Frequent-Fire Forests.” *Global Change Biology* 26 (11): 6180–89. https://doi.org/10.1111/gcb.15318.

Groot, Harry, Kathryn Fernholz, Chuck Henderson, and Jeff Howe. 2018. “Survey and Analysis of the U.S. Biochar Industry.” Dovetail Partners. https://dovetailinc.org/report_pdfs/2018/DovetailBiochar118.pdf.

Gutierrez, Aurora A., Stijn Hantson, Baird Langenbrunner, Bin Chen, Yufang Jin, Michael L. Goulden, and James T. Randerson. 2021. “Wildfire Response to Changing Daily Temperature Extremes in California’s Sierra Nevada.” *Science Advances* 7 (47): eabe6417. https://doi.org/10.1126/sciadv.abe6417.

Harris, Nancy, David Gibbs, A. Baccini, Richard Birdsey, Sytze de Bruin, Mary Farina, Lola Fatoyinbo, et al. 2021. “Global Maps of Twenty-First Century Forest Carbon Fluxes.” *Nature Climate Change* 11 (March): 1–7. https://doi.org/10.1038/s41558-020-00976-6.

Hartsough, Bruce R., Scott Abrams, R. James Barbour, Erik S. Drews, James D. McIver, Jason J. Moghaddas, Dylan W. Schwilk, and Scott L. Stephens. 2008. “The Economics of Alternative Fuel Reduction Treatments in Western United States Dry Forests: Financial and Policy Implications from the National Fire and Fire Surrogate Study.” *Forest Policy and Economics* 10 (6): 344–54. https://doi.org/10.1016/j.forpol.2008.02.001.

Haya, Barbara. 2019. “Policy Brief: The California Air Resources Board U.S. Forest Offset Protocol Underestimates Leakage.” Center for Environmental Public Policy, University of California, Berkeley.

https://gspp.berkeley.edu/assets/uploads/research/pdf/Policy_Brief-US_Forest_Projects-Leakage-Haya_2.pdf.

Haya, Barbara, Danny Cullenward, Aaron L. Strong, Emily Grubert, Robert Heilmayr, Deborah A. Sivas, and Michael Wara. 2020. “Managing Uncertainty in Carbon Offsets: Insights from California’s Standardized Approach.” *Climate Policy* 20 (9): 1112–26. https://doi.org/10.1080/14693062.2020.1781035.

Haya, Barbara, Samuel Evans, Letty Brown, Jacob Bukoski, Van Butsic, Bodie Cabiyo, Rory Jacobson, Amber Kerr, Matthew Potts, and Daniel L. Sanchez. 2023. “Comprehensive Review of Carbon Quantification by Improved Forest Management Offset Protocols.” *Frontiers in Forests and Global Change* 6 (March). https://doi.org/10.3389/ffgc.2023.958879.

Herbert, Claudia, Barbara K. Haya, Scott L. Stephens, and Van Butsic. 2022. “Managing Nature-Based Solutions in Fire-Prone Ecosystems: Competing Management Objectives in California Forests Evaluated at a Landscape Scale.” *Frontiers in Forests and Global Change* 5 (October). https://doi.org/10.3389/ffgc.2022.957189.

Hessburg, Paul F., Thomas A. Spies, David A. Perry, Carl N. Skinner, Alan H. Taylor, Peter M. Brown, Scott L. Stephens, et al. 2016. “Tamm Review: Management of Mixed-Severity Fire Regime Forests in Oregon, Washington, and Northern California.” *Forest Ecology and Management* 366 (April): 221–50. https://doi.org/10.1016/j.foreco.2016.01.034.

Hill, Avery P, Connor J Nolan, Kyle S Hemes, Trevor W Cambron, and Christopher B Field. 2023. “Low-Elevation Conifers in California’s Sierra Nevada Are out of Equilibrium with Climate.” *PNAS Nexus* 2 (2): pgad004. https://doi.org/10.1093/pnasnexus/pgad004.

Huang, Ching-Hsun, and Christopher Sorensen. 2011. “The Economic Value of Selling Carbon Credits from Restored Forests: A Case Study from the Navajo Nation’s Tribal Forests.” *Western Journal of Applied Forestry* 26 (1): 37–45. https://doi.org/10.1093/wjaf/26.1.37.

Hunt, Josiah. 2022. Personal Communication.

Hunt, Josiah, and Tom Miles. 2020. “Modification of Existing Biomass Power Plants for Biochar Production.” Pacific Biochar. https://pacificbiochar.com/how-we-produce-biochar/.

Hurteau, Matthew D, George W Koch, and Bruce A Hungate. 2008. “Carbon Protection and Fire Risk Reduction: Toward a Full Accounting of Forest Carbon Offsets.” *Frontiers in Ecology and the Environment* 6 (9): 493–98. https://doi.org/10.1890/070187.

Hurteau, Matthew D., Shuang Liang, Katherine L. Martin, Malcolm P. North, George W. Koch, and Bruce A. Hungate. 2016. “Restoring Forest Structure and Process Stabilizes Forest Carbon in Wildfire-Prone Southwestern Ponderosa Pine Forests.” *Ecological Applications* 26 (2): 382–91. https://doi.org/10.1890/15-0337.

Hurteau, Matthew D., Malcolm P. North, George W. Koch, and Bruce A. Hungate. 2019. “Managing for Disturbance Stabilizes Forest Carbon.” *Proceedings of the National Academy of Sciences* 116 (21): 10193–95. https://doi.org/10.1073/pnas.1905146116.

Hurteau, Matthew D., Michael T. Stoddard, and Peter Z. Fulé. 2011. “The Carbon Costs of Mitigating High-Severity Wildfire in Southwestern Ponderosa Pine.” *Global Change Biology* 17 (4): 1516–21. https://doi.org/10.1111/j.1365-2486.2010.02295.x.

Internal Revenue Service. 2021. “Credit for Carbon Oxide Sequestration.” Federal Register. 2021. https://www.federalregister.gov/documents/2021/01/15/2021-00302/credit-for-carbon-oxide-sequestration.

IPCC. 2019. "Appendix 4: Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments: Basis for Future Methodological Development." Intergovernmental Panel on Climate Change.

Ivy So, Barbara Haya, and Micah Elias. 2023. "Berkeley Carbon Trading Project Voluntary Registry Offset Database."

Jain, Theresa B, Jeremy S Fried, and Sara M Loreno. 2020. "Simulating the Effectiveness of Improvement Cuts and Commercial Thinning to Enhance Fire Resistance in West Coast Dry Mixed Conifer Forests." *Forest Science* 66 (2): 157–77. https://doi.org/10.1093/forsci/fxz071.

Jones, Angela C, and Molly F Sherlock. 2021. "The Tax Credit for Carbon Sequestration (Section 45Q)." Congressional Research Service.

Kaarakka, Lilli, Julia Rothey, and Laura E. Dee. 2023. "Managing Forests for Carbon–Status of the Forest Carbon Offset Markets in the United States." *PLOS Climate* 2 (7): e0000158. https://doi.org/10.1371/journal.pclm.0000158.

Kalies, Elizabeth L., and Larissa L. Yocom Kent. 2016. "Tamm Review: Are Fuel Treatments Effective at Achieving Ecological and Social Objectives? A Systematic Review." *Forest Ecology and Management* 375 (September): 84–95. https://doi.org/10.1016/j.foreco.2016.05.021.

Kane, Van R., C. Alina Cansler, Nicholas A. Povak, Jonathan T. Kane, Robert J. McGaughey, James A. Lutz, Derek J. Churchill, and Malcolm P. North. 2015. "Mixed Severity Fire Effects within the Rim Fire: Relative Importance of Local Climate, Fire Weather, Topography, and Forest Structure." *Forest Ecology and Management* 358 (December): 62–79. https://doi.org/10.1016/j.foreco.2015.09.001.

Kelsey, R., E. Smith, T. Biswas, C. McColl, K. Wilson, and D. Wilson. 2017. "Regional Prioritization of Forest Restoration across California's Sierra Nevada." https://www.scienceforconservation.org/assets/downloads/tnc_Prioritizing_Forest_Restoration_hr.pdf.

Kennedy, Maureen C., and Morris C. Johnson. 2014. "Fuel Treatment Prescriptions Alter Spatial Patterns of Fire Severity around the Wildland–Urban Interface during the Wallow Fire, Arizona, USA." *Forest Ecology and Management* 318 (April): 122–32. https://doi.org/10.1016/j.foreco.2014.01.014.

Knapp, Eric E., Carl N. Skinner, Malcolm P. North, and Becky L. Estes. 2013. "Long-Term Overstory and Understory Change Following Logging and Fire Exclusion in a Sierra Nevada Mixed-Conifer Forest." *Forest Ecology and Management* 310 (December): 903–14. https://doi.org/10.1016/j.foreco.2013.09.041.

Knight, Clarke A., Lysanna Anderson, M. Jane Bunting, Marie Champagne, Rosie M. Clayburn, Jeffrey N. Crawford, Anna Klimaszewski-Patterson, et al. 2022. "Land Management Explains Major Trends in Forest Structure and Composition over the Last Millennium in California's Klamath Mountains." *Proceedings of the National Academy of Sciences* 119 (12): e2116264119. https://doi.org/10.1073/pnas.2116264119.

"LANDFIRE Program: Data Products - Vegetation - Existing Vegetation Cover." n.d. Accessed March 12, 2024. https://www.landfire.gov/evc.php.

Lehmann, Johannes, and Stephen Joseph, eds. 2015. *Biochar for Environmental Management: Science, Technology and Implementation*. Second edition. London ; New York: Routledge, Taylor & Francis Group.

Li, Kaiyan. 2022. "Integrated Economic and Environmental Modeling of Forest Biomass-To-Electricity in California." M.S., United States -- California: University of California, Davis. https://www.proquest.com/docview/2665662984/abstract/749F7928B3284C0DPQ/1.

Li, Wenqin, Qi Dang, Ryan Smith, Robert C. Brown, and Mark M. Wright. 2017. "Techno-Economic Analysis of the Stabilization of Bio-Oil Fractions for Insertion into Petroleum Refineries." *ACS Sustainable Chemistry & Engineering* 5 (2): 1528–37. https://doi.org/10.1021/acssuschemeng.6b02222.

Liang, Shuang, Matthew D Hurteau, and Anthony L Westerling. 2018. "Large-Scale Restoration Increases Carbon Stability under Projected Climate and Wildfire Regimes." *Frontiers in Ecology and the Environment* 16 (4): 207–12. https://doi.org/10.1002/fee.1791.

Liu, Guangjian, Eric D. Larson, Robert H. Williams, Thomas G. Kreutz, and Xiangbo Guo. 2011. "Making Fischer−Tropsch Fuels and Electricity from Coal and Biomass: Performance and Cost Analysis." *Energy & Fuels* 25 (1): 415–37. https://doi.org/10.1021/ef101184e.

Lord, Carl Ehlen, David Stewart-Smith, John Martin, Loren Kellogg, Chad Davis, Melanie Stidham, Mike Penner, and James Bowyer. 2006. "Biomass Energy and Biofuel's From Oregon's Forests." Oregon Forest Resources Institute. https://oregonforests.org/sites/default/files/2017-08/Biomass_Full_Report_0.pdf.

"Low Carbon Fuel Standard." n.d. California Air and Resources Board. Accessed October 26, 2021. https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard.

"Low-Carbon Renewable Natural Gas (RNG) From Wood Waste." 2019. Gas Technology Institute (GTI). https://www.gti.energy/wp-content/uploads/2019/02/Low-Carbon-Renewable-Natural-Gas-RNG-from-Wood-Wastes-Final-Report-Feb2019.pdf.

Lydersen, Jamie M., and Brandon M. Collins. 2018. "Change in Vegetation Patterns Over a Large Forested Landscape Based on Historical and Contemporary Aerial Photography." *Ecosystems* 21 (7): 1348–63. https://doi.org/10.1007/s10021-018-0225-5.

McIntyre, Patrick J., James H. Thorne, Christopher R. Dolanc, Alan L. Flint, Lorraine E. Flint, Maggi Kelly, and David D. Ackerly. 2015. "Twentieth-Century Shifts in Forest Structure in California: Denser Forests, Smaller Trees, and Increased Dominance of Oaks." *Proceedings of the National Academy of Sciences* 112 (5): 1458–63. https://doi.org/10.1073/pnas.1410186112.

McIver, Chelsea P. 2015. "California's Forest Products Industry and Timber Harvest, 2012," 58.

Michaelowa, Axel, Katharina Michaelowa, Lukas Hermwille, and Aglaja Espelage. 2021. "Towards Net Zero: Dynamic Baselines for Internationalmarketmechanisms." *CIS Working Paper*, no. 107 (March). https://doi.org/10.5167/uzh-202215.

"Microsoft Carbon Removal - Lessons from an Early Corporate Purchase." 2021. Microsoft. https://query.prod.cms.rt.microsoft.com/cms/api/am/binary/RE4MDlc.

Miller, J. D., H. D. Safford, M. Crimmins, and A. E. Thode. 2009. "Quantitative Evidence for Increasing Forest Fire Severity in the Sierra Nevada and Southern Cascade Mountains, California and Nevada, USA." *Ecosystems* 12 (1): 16–32. https://doi.org/10.1007/s10021-008-9201-9.

Miller, Jay D., and Hugh Safford. 2012. "Trends in Wildfire Severity: 1984 to 2010 in the Sierra Nevada, Modoc Plateau, and Southern Cascades, California, USA." *Fire Ecology* 8 (3): 41–57. https://doi.org/10.4996/fireecology.0803041.

Molina, Juan Ramón, Juan Pedro García, Juan José Fernández, and Francisco Rodríguez y Silva. 2018. "Prescribed Fire Experiences on Crop Residue Removal for Biomass Exploitations.

Application to the Maritime Pine Forests in the Mediterranean Basin." *Science of The Total Environment* 612 (January): 63–70. https://doi.org/10.1016/j.scitotenv.2017.08.182.

Moritz, Max A., Tadashi J. Moody, Lori J. Miles, Matthew M. Smith, and Perry de Valpine. 2009. "The Fire Frequency Analysis Branch of the Pyrostatistics Tree: Sampling Decisions and Censoring in Fire Interval Data." *Environmental and Ecological Statistics* 16 (2): 271–89. https://doi.org/10.1007/s10651-007-0088-y.

"Nasdaq Carbon Removal Marketplace and Technologies." n.d. Accessed April 21, 2022. https://www.nasdaq.com/solutions/carbon-removal-marketplace.

"Natural Gas Monthly." 2022. Energy Information Administration. 2022. https://www.eia.gov/naturalgas/monthly/.

North, Malcolm, April Brough, Jonathan Long, Brandon Collins, Phil Bowden, Don Yasuda, Jay Miller, and Neil Sugihara. 2015. "Constraints on Mechanized Treatment Significantly Limit Mechanical Fuels Reduction Extent in the Sierra Nevada." *Journal of Forestry* 113 (1): 40–48. https://doi.org/10.5849/jof.14-058.

North, Malcolm, Brandon M. Collins, and Scott Stephens. 2012. "Using Fire to Increase the Scale, Benefits, and Future Maintenance of Fuels Treatments." *Journal of Forestry* 110 (7): 392–401. https://doi.org/10.5849/jof.12-021.

North, Malcolm P., Ryan E. Tompkins, Alexis A. Bernal, Brandon M. Collins, Scott L. Stephens, and Robert A. York. 2022. "Operational Resilience in Western US Frequent-Fire Forests." *Forest Ecology and Management* 507 (March): 120004. https://doi.org/10.1016/j.foreco.2021.120004.

Odland, M. C., M. J. Goodwin, B. V. Smithers, M. D. Hurteau, and M. P. North. 2021. "Plant Community Response to Thinning and Repeated Fire in Sierra Nevada Mixed-Conifer Forest Understories." *Forest Ecology and Management* 495 (September): 119361. https://doi.org/10.1016/j.foreco.2021.119361.

Omernik, James M., and Glenn E. Griffith. 2014. "Ecoregions of the Conterminous United States: Evolution of a Hierarchical Spatial Framework." *Environmental Management* 54 (6): 1249–66. https://doi.org/10.1007/s00267-014-0364-1.

Pan, Yude, Richard A. Birdsey, Jingyun Fang, Richard Houghton, Pekka E. Kauppi, Werner A. Kurz, Oliver L. Phillips, et al. 2011. "A Large and Persistent Carbon Sink in the World's Forests." *Science* 333 (6045): 988–93. https://doi.org/10.1126/science.1201609.

Parks, Sean A., Gregory K. Dillon, and Carol Miller. 2014. "A New Metric for Quantifying Burn Severity: The Relativized Burn Ratio." *Remote Sensing* 6 (3): 1827–44. https://doi.org/10.3390/rs6031827.

Perry, David A., Paul F. Hessburg, Carl N. Skinner, Thomas A. Spies, Scott L. Stephens, Alan Henry Taylor, Jerry F. Franklin, Brenda McComb, and Greg Riegel. 2011. "The Ecology of Mixed Severity Fire Regimes in Washington, Oregon, and Northern California." *Forest Ecology and Management* 262 (5): 703–17. https://doi.org/10.1016/j.foreco.2011.05.004.

Piqué, Míriam, and Rut Domènech. 2018. "Effectiveness of Mechanical Thinning and Prescribed Burning on Fire Behavior in *Pinus Nigra* Forests in NE Spain." *Science of The Total Environment* 618 (March): 1539–46. https://doi.org/10.1016/j.scitotenv.2017.09.316.

Puro.earth. n.d. "CORC Supplier Listing." Accessed October 27, 2022. https://puro.earth/CORC-co2-removal-certificate/.

"Puro.Earth Carbon Removal." n.d. Accessed December 21, 2023. https://www.nasdaq.com/solutions/carbon-removal-platform.

Quesnel Seipp, Kimberly, Tessa Maurer, Micah Elias, Phil Saksa, Catherine Keske, Kirsten Oleson, Benis Egoh, et al. 2023. “A Multi-Benefit Framework for Funding Forest Management in Fire-Driven Ecosystems across the Western U.S.” *Journal of Environmental Management* 344 (October): 118270. https://doi.org/10.1016/j.jenvman.2023.118270.

Rabin, S. S., F. N. Gérard, and A. Arneth. 2022. “The Influence of Thinning and Prescribed Burning on Future Forest Fires in Fire-Prone Regions of Europe.” *Environmental Research Letters* 17 (5): 055010. https://doi.org/10.1088/1748-9326/ac6312.

Rebain, Stephanie, Elizabeth Reinhardt, Nicholas Crookston, Sarah Beukema, Werner Kurz, Julee Greenough, Donald Robinson, and Duncan Lutes. 2022. “The Fire and Fuels Extension to the Forest Vegetation Simulator: Updated Model Documentation.”

“Renewable Fuel Standard Program.” 2015. United States Environmental Protection Agency. April 8, 2015. https://www.epa.gov/renewable-fuel-standard-program.

Riley, Karin L., Isaac C. Grenfell, Mark A. Finney, and Jason M. Wiener. 2021. “TreeMap, a Tree-Level Model of Conterminous US Forests circa 2014 Produced by Imputation of FIA Plot Data.” *Scientific Data* 8 (1): 11. https://doi.org/10.1038/s41597-020-00782-x.

Rummer, Bob, Jeff Prestemon, Dennis May, Pat Miles, John Vissage, Ron McRoberts, Greg Liknes, et al. 2005. “A Strategic Assessment of Forest Biomass and Fuel Reduction Treatments in Western States.” RMRS-GTR-149. Ft. Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://doi.org/10.2737/RMRS-GTR-149.

Sahoo, Kamalakanta, Edward Bilek, Richard Bergman, and Sudhagar Mani. 2019. “Techno-Economic Analysis of Producing Solid Biofuels and Biochar from Forest Residues Using Portable Systems.” *Applied Energy* 235 (February): 578–90. https://doi.org/10.1016/j.apenergy.2018.10.076.

Sanchez, Daniel, and Haris Gilani. 2022. “Advancing Collaborative Action on Forest Biofuels in California.” Joint Institute for Wood Products Innovation. https://bof.fire.ca.gov/media/mn5gzmxv/joint-institute-forest-biofuels_final_2022_ada.pdf.

Sanchez, Daniel L., James H. Nelson, Josiah Johnston, Ana Mileva, and Daniel M. Kammen. 2015. “Biomass Enables the Transition to a Carbon-Negative Power System across Western North America.” *Nature Climate Change* 5 (3): 230–34. https://doi.org/10.1038/nclimate2488.

Sarkar, S., and A. Kumar. 2009. “Techno-Economic Assessment of Biohydrogen Production from Forest Biomass in Western Canada.” *Transactions of the ASABE* 52 (2): 519–30. https://doi.org/10.13031/2013.26809.

Schimmelpfennig, Sonja, and Bruno Glaser. 2022. “One Step Forward toward Characterization: Some Important Material Properties to Distinguish Biochars.” *Journal of Environmental Quality* 41 (4): 1001–13. https://doi.org/10.2134/jeq2011.0146.

Schmidt, Hans-Peter, Claudia Kammann, and Nikolas Hagemann. 2021. “EBC-Guidelines for the Certification of Biochar Based Carbon Sinks Version 2.1 from 1st February 202,” 35.

Scholl, Andrew E., and Alan H. Taylor. 2010. “Fire Regimes, Forest Change, and Self-Organization in an Old-Growth Mixed-Conifer Forest, Yosemite National Park, USA.” *Ecological Applications* 20 (2): 362–80. https://doi.org/10.1890/08-2324.1.

Schwartz, M., N. Butt, Christopher R. Dolanc, A. Holguin, M. Moritz, M. North, H. Safford, N. Stephenson, J. Thorne, and P. J. Mantgem. 2015. “Increasing Elevation of Fire in the

Sierra Nevada and Implications for Forest Change." *Ecosphere* 6: 1–10. https://doi.org/10.1890/ES15-00003.1.

Segal, Mark. 2023. "Carbon Removal Buyers Group Frontier Announces First $53 Million Offtake Agreement." ESG Today. May 19, 2023. https://www.esgtoday.com/carbon-removal-buyers-group-frontier-announces-first-53-million-offtake-agreement/.

Shelley, J.R. 2007. "Woody Biomass Definitions and Conversion Factors." https://ucanr.edu/sites/WoodyBiomass/newsletters/IG003_-_Woody_Biomass_Definitions_and_Conversions_Factors31510.pdf.

Skog, Kenneth E. 2008. "Sequestration of Carbon in Harvested Wood Products for the United States." *FOREST PRODUCTS JOURNAL* 58 (6).

Springsteen, Bruce, Thomas Christofk, Robert A. York, Tad Mason, Stephen Baker, Emily Lincoln, Bruce Hartsough, and Takuyuki Yoshioka. 2015. "Forest Biomass Diversion in the Sierra Nevada: Energy, Economics and Emissions." *California Agriculture* 69 (3): 142–49. https://doi.org/10.3733/ca.v069n03p142.

Stephens, Scott L, Mike A Battaglia, Derek J Churchill, Brandon M Collins, Michelle Coppoletta, Chad M Hoffman, Jamie M Lydersen, et al. 2020. "Forest Restoration and Fuels Reduction: Convergent or Divergent?" *BioScience*, December, biaa134. https://doi.org/10.1093/biosci/biaa134.

Stephens, Scott L., Brandon M. Collins, and Gary Roller. 2012. "Fuel Treatment Longevity in a Sierra Nevada Mixed Conifer Forest." *Forest Ecology and Management* 285 (December): 204–12. https://doi.org/10.1016/j.foreco.2012.08.030.

Stephens, Scott L, A LeRoy Westerling, Matthew D Hurteau, M Zachariah Peery, Courtney A Schultz, and Sally Thompson. 2020. "Fire and Climate Change: Conserving Seasonally Dry Forests Is Still Possible." *Frontiers in Ecology and the Environment* 18 (6): 354–60. https://doi.org/10.1002/fee.2218.

Stephenson, N. L., A. J. Das, R. Condit, S. E. Russo, P. J. Baker, N. G. Beckman, D. A. Coomes, et al. 2014. "Rate of Tree Carbon Accumulation Increases Continuously with Tree Size." *Nature* 507 (7490): 90–93. https://doi.org/10.1038/nature12914.

Swain, Daniel L. 2021. "A Shorter, Sharper Rainy Season Amplifies California Wildfire Risk." *Geophysical Research Letters* 48 (5): e2021GL092843. https://doi.org/10.1029/2021GL092843.

Swezy, Camille, John Bailey, and Woodam Chung. 2021. "Linking Federal Forest Restoration with Wood Utilization: Modeling Biomass Prices and Analyzing Forest Restoration Costs in the Northern Sierra Nevada." *Energies* 14 (9): 2696. https://doi.org/10.3390/en14092696.

The Beck Group. 2015. "California Assessment of Wood Business Innovation Opportunities and Markets (CAWBIOM). Phase I: Initial Screening of Potential Business Opportunities."

The Nature Conservancy. 2022. "New Approach to Forest Carbon Accounting Aims to Enhance Accuracy and Transparency." The Nature Conservancy. 2022. https://www.nature.org/en-us/newsroom/verra-voluntary-carbon-market-accounting-methodology-dynamic-baseline/.

Thengane, Sonal K., Kevin Kung, Josiah Hunt, Haris R. Gilani, C. Jim Lim, Shahabaddine Sokhansanj, and Daniel L. Sanchez. 2021. "Market Prospects for Biochar Production and Application in California." *Biofuels, Bioproducts and Biorefining* 15 (6): 1802–19. https://doi.org/10.1002/bbb.2280.

Thengane, Sonal K., Kevin Kung, Robert York, Shahabaddine Sokhansanj, C. Jim Lim, and Daniel L. Sanchez. 2020. “Technoeconomic and Emissions Evaluation of Mobile In-Woods Biochar Production.” *Energy Conversion and Management* 223 (November): 113305. https://doi.org/10.1016/j.enconman.2020.113305.

Tyukavina, Alexandra, Peter Potapov, Matthew C. Hansen, Amy H. Pickens, Stephen V. Stehman, Svetlana Turubanova, Diana Parker, et al. 2022. “Global Trends of Forest Loss Due to Fire From 2001 to 2019.” *Frontiers in Remote Sensing* 3 (March). https://doi.org/10.3389/frsen.2022.825190.

University of Montana. 2016. “California’s Forest Products Industry and Timber Harvest.” Forest Industry Research Program, University of Montana.

“University of Montana Bureau of Business and Economic Research.” 2013. 2013. https://www.bber.umt.edu/FIR/H_Harvest.asp.

“U.S. Biochar Market Size & Share Report.” 2021. Grand View Research. 2021. https://www.grandviewresearch.com/industry-analysis/us-biochar-market.

U.S. Department of Energy. n.d. “Carbon Negative Shot.” Energy.Gov. Accessed February 11, 2022. https://www.energy.gov/fecm/carbon-negative-shot.

“U.S. Energy Information Administration.” 2023. U.S. Energy Atlas. 2023. https://eia.maps.arcgis.com/home/item.html?id=bf5c5110b1b944d299bb683cdbd02d2a.

U.S. Forest Service. 2016. “Fiscal Year 2017 Budget Overview.” Forest Service, United States Department of Agriculture. https://www.fs.usda.gov/sites/default/files/fy-2017-fs-budget-overview.pdf.

USFS. 2022. “Confronting the Wildfire Crisis: A Strategy for Protecting Communities and Improving Resilience in America’s Forests.” Forest Service, U.S. Department of Agriculture.

Verra. 2023. “VM0047 Afforestation, Reforestation, and Revegetation, v1.0.” *Verra* (blog). 2023. https://verra.org/methodologies/vm0047-afforestation-reforestation-and-revegetation-v1-0/.

———. 2024. “VM0045 Methodology for Improved Forest Management Using Dynamic Matched Baselines from National Forest Inventories, v1.1.” *Verra* (blog). 2024. https://verra.org/methodologies/methodology-for-improved-forest-management/.

“Visualizing Federal Funding for Wildfire Management and Response.” n.d. *Federation of American Scientists* (blog). Accessed December 21, 2023. https://fas.tghp.co.uk/publication/visualizing-federal-funding-for-wildfire-management-and-response/.

Wara, Michael. 2023. “Testimony to the Senate Budget Committee Hearing on ‘A Burning Issue: The Economic Costs of Wildfires.’” 2023. https://www.budget.senate.gov/imo/media/doc/Mr.%20Michael%20Wara,%20J.D.,%20Ph.D.%20-%20Testimony%20-%20Senate%20Budget%20Committee.pdf.

“Weekly LCFS Credit Transfer Activity Reports.” n.d. California Air and Resources Board. Accessed October 27, 2022. https://ww3.arb.ca.gov/fuels/lcfs/credit/lrtweeklycreditreports.htm.

Williams, A. Park, J. Abatzoglou, A. Gershunov, J. Guzman-Morales, Daniel A. Bishop, J. Balch, and D. Lettenmaier. 2019. “Observed Impacts of Anthropogenic Climate Change on Wildfire in California.” *Earth’s Future* 7: 892–910. https://doi.org/10.1029/2019EF001210.

Wiltsee, G. 2000. “Lessons Learned from Existing Biomass Power Plants.” NREL/SR-570-26946, 753767. https://doi.org/10.2172/753767.

Woolf, Dominic, James E. Amonette, F. Alayne Street-Perrott, Johannes Lehmann, and Stephen Joseph. 2010. “Sustainable Biochar to Mitigate Global Climate Change.” *Nature Communications* 1 (1): 56. https://doi.org/10.1038/ncomms1053.

Wu, Chao, Shane R. Coffield, Michael L. Goulden, James T. Randerson, Anna T. Trugman, and William R. L. Anderegg. 2023. “Uncertainty in US Forest Carbon Storage Potential Due to Climate Risks.” *Nature Geoscience* 16 (5): 422–29. https://doi.org/10.1038/s41561-023-01166-7.

Yue, Xu, Loretta J. Mickley, Jennifer A. Logan, and Jed O. Kaplan. 2013. “Ensemble Projections of Wildfire Activity and Carbonaceous Aerosol Concentrations over the Western United States in the Mid-21st Century.” *Atmospheric Environment* 77 (October): 767–80. https://doi.org/10.1016/j.atmosenv.2013.06.003.