Bren School
of Environmental Science & Management
UNIVERSITY OF CALIFORNIA, SANTA BARBARA

Functional Forests: The Role of California Forests in Achieving Statewide Carbon Neutrality

JOINT INSTITUTE FOR WOOD PRODUCTS INNOVATION

Authors: AnnaClaire Marley, Benjamin Edwards, Samantha Smith, Kyle Monper, and Max Russer

Advisors: Dr. Andrew Plantinga and Alice Lépissier

Signature Page

As authors of this Group Project report, we archive this report on the Bren School's website such that the results of our research are available for all to read. Our signatures on the document signify our joint responsibility to fulfill the archiving standards set by the Bren School of Environmental Science & Management.

Max Russer	Kyle Monper
AnnaClaire Marley	Samantha Smith
Benjamin Edwards	

The Bren School of Environmental Science & Management produces professionals with unrivaled training in environmental science and management who will devote their unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principal of the School is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technological decisions. The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue.

This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

Dr. Andrew Plantinga

Dr. Max Moritz

Alice Lépissier

Acknowledgements

We would like to gratefully acknowledge our advisors and our client for their support, guidance, and feedback on our project.

Advisors:
Dr. Andrew Plantinga
Dr. Max Moritz
Alice Lépissier

External Advisors:
Teal Zimring, Joint Institute of Wood Products Innovation

Client:
Dr. Daniel Sanchez, Joint Institute of Wood Products Innovation

Additional Thanks:
Jeremy Fried, USFS Pacific Northwest
Bodie Cabiyo, UC Berkeley Energy and Research Group
Dr. William Stewart, UC Berkeley
Dr. Allison Horst, Bren School
Dr. Kyle Meng, Bren School

Abstract

In 2018, California declared a goal of statewide carbon neutrality by 2045. To reach this goal, the State will need to both reduce emissions and remove carbon dioxide from the atmosphere across a variety of industries. Forest management is one option the State can implement to increase long-term carbon storage and support carbon neutrality. In this analysis, forest management broadly refers to a variety of different thinning regimes and clear-cutting, each of which has different costs and carbon implications. Our project focuses on determining the costs and carbon consequences of a host of forest management treatments across all forests in California, and how these treatments can contribute to the State's climate goals. To aid policymakers in designing cost-effective forest policies, we created marginal cost curves for forest management in the State. Our findings suggest that the degree to which forest management can play in increasing long-term forest carbon storage is highly dependent on the "baseline" level of forest carbon that is utilized. Additionally, we found that in general, forest management may not be very cost-effective in terms of increasing carbon storage. In light of this, and as the State continues to set forest management goals, we suggest that forest policy incorporate the co-benefits of management services to be more cost-effective. Although the abatement costs for other sectors of the economy are still undetermined, our results suggest that forest management may play a smaller role in achieving carbon neutrality as compared to other sectors.

Table of Contents

Figures

Tables

Key Terms

1. **Carbon Neutrality:** The "point at which the removal of carbon pollution meets or exceeds carbon emissions" according to EO B-55-18 for carbon neutrality.
2. **Carbon Sequestration**: Long-term, natural process of trees, plants, soil, and the ocean capturing and storing atmospheric carbon dioxide to mitigate the impacts of climate change.
3. **Carbon Storage:** The capture of carbon dioxide in trees, plants, soil, harvested wood products, and the ocean.
4. **Co-benefits:** Additional benefits beyond carbon sequestration as a result of forest management practices
5. **Clear-Cutting:** The harvest and removal of all trees from an area.

6. **Ecosystem Services:** Benefits provided by any kind of ecosystem for humans and wildlife. Generally, benefits are grouped into four categories: Provisioning, Regulating, Habitat, and Cultural services.
7. **Executive Order B-55-18:** Executive Order signed by former Governor Jerry Brown in 2018 that directs the state to become carbon neutral by 2045.
8. **Joint Institute of Wood Products Innovation**: Also referred to as the "Joint Institute." This is a working group under the California Department of Forestry and Fire Protection that researches wood products products and markets.
9. **Fire Return Interval:** The amount of time between wildfire events within a particular area.
10. **Forest Management:** Applying silviculture practices like thinning, prescribed fire, and fuels reduction to manage trees in the forest for a variety of reasons, including economic value, forest health, wildlife, or other ecosystem services.
11. **Forest Restoration:** Employing specific management practices for a healthier forest after disease or insect infestation, according to pre-industrial conditions, or for wildlife habitat.
12. **Paris Climate Change Accord:** Environmental agreement signed in 2015 as part of the United Nations Framework Convention on Climate Change, by nearly all countries in the world to limit global temperatures to a two-degree Celsius increase above pre-industrial levels.
13. **Prescribed Fire:** Forest management technique also known as a "planned burn" or "controlled burn." The goal of prescribed fires is to reduce hazardous fuel loads near urban areas or restore woodlands to historic conditions. This technique involves analyzing the existing fuel conditions, weather, climate, personnel, available land, and time before implementation.
14. **SB 32**: The Global Warming Solutions Act of 2006, that outlined statewide greenhouse gas emissions reductions targets between 2030-2050 and also established a state carbon trading program.
15. **Thinning:** The partial cutting of trees on forest lands as well as the removal of certain individual trees in order to achieve management priorities such as forest health or reduced wildfire risk.
16. **Wildland-Urban Interface:** Area of land in which developed areas with houses are located close but separate from nearby natural "wild" areas. Commonly referred to by its acronym "WUI" to describe areas prone to wildfire.
17. **Wildland-Urban Intermix:** Area of land in which developed areas with housing and natural areas are mixed and thus co-located.
18. **Woody Biomass**: Waste residue forest management practices. Often includes small-diameter or low value wood, damaged wood, diseased wood, or branches of trees.

Abbreviations

1. **CARB** - California Air Resources Board
2. **BLM** - Bureau of Land Management
3. **BioSum** - Bioregional Inventory Originated Simulation Under Management
4. **CalFire** - California Department of Forestry and Fire Protection
5. **CEC** - California Energy Commission
6. **CRP** - Conservation Reserve Program
7. **EQIP** - Environmental Quality Incentives Program
8. **FIA** - Forest Inventory and Analysis
9. **FCP**- Forest Carbon Plan
10. **FVS -** Forest Vegetation Simulator
11. **MCC**- Marginal Cost Curve
12. **NPS** - National Park Service
13. **NRCS** - Natural Resources Conservation Service
14. **PNW -** Pacific Northwest
15. **SPI** - Sierra Pacific Industries
16. **USDA** - United States Department of Agriculture
17. **USFS** - United States Forest Service

Executive Summary

In 2018, California officially pledged to achieve statewide carbon neutrality by 2045. This goal not only requires the State to reduce the rate of existing emissions, but also to increase negative carbon emissions (the removal of carbon from the atmosphere). Given that California is home to over 33 million acres of forest land, forests have been identified as a promising tool to increase negative emissions within the State. However, considering the increasing effects of climate change, such as exacerbated drought, disease, and wildfire, the role of forests in carbon sequestration has come into question. This report therefore aims to further explore the role of California's forests in helping to achieve carbon neutrality.

In this analysis, we worked to determine the costs and carbon consequences of a variety of forest management treatments across most forest lands in California. The analysis was based primarily on data from a 2016 California Energy Commission (CEC) Report that utilized Forest Vegetation Simulator (FVS) software and Forest Inventory and Analysis (FIA) data collected by the US Forest Service on forested plots throughout California between 2001 and 2010. In the CEC Report, researchers designed 28 treatments believed to be promising forest management treatments (Fried et al., 2016), along with two clear-cut scenarios, and a grow-only sequence. These 31 treatments were applied to the selected FIA plots. FVS then simulated forest growth and harvested merchantable and unmerchantable wood across these plots from these treatments. Following this, our group utilized the outputs from the 31 treatments and input them into Bioregional Inventory Originated Simulation Under Management (BioSum) software where we determined total harvest costs associated with treatment, harvest, and transportation.

Using data generated from this report, we selected the treatment that resulted in the most valuable carbon benefits for a particular plot (as defined by treatments that optimized for the ratio between cost of treatment and increase in carbon storage). For each plot, we took the output of the treatment that resulted in the most valuable carbon benefits and created marginal cost curves (MCC) for forest management and carbon storage in the State. These MCCs offer policymakers a tool to broadly understand what type of management treatment is most cost-effective for carbon storage in the state. These results were then analyzed further at a county scale to determine where each of these types of management treatments for cost-effective carbon would occur.

A key component of developing a MCC is establishing a baseline by which to measure any additional carbon storage from implementing a treatment. Because carbon implications may differ depending on different baselines, we modeled two baseline scenarios: 1) a business-as-usual baseline (BAU) based on an approximation of the current amount of management taking place within California forests, and 2) an assumed management baseline (CARB) modified to be similar to the California Air Resources Board methodology that assumes management on all forested plots in the State.

Our results indicate that grow-only management scenarios generally store the most carbon, and were most commonly chosen as the most cost-effective treatments for carbon storage in both baselines. However, in light of California's commitments to actively manage its forests for reasons besides carbon storage, we removed grow-only scenarios from our analysis and modeled the effects of excluding it under both baseline scenarios. Not surprisingly, the most commonly

chosen treatments excluding grow-only were still those that had relatively little management as compared to other thinning treatments. Additionally, between these two baselines, there were differences in which plots and treatments were chosen, as well as differences in total carbon storage and total costs. The CARB scenario had lower baseline levels of carbon storage, and thus resulted in more overall carbon storage compared to the BAU.

We also found that treatments within both baseline scenarios were dependent on geographic region. This is likely due to the fact that 1) forested plots throughout the State have different ecosystem types that will store varying amounts of carbon depending on the treatment type implemented; 2) forested plots are in different geographic regions where costs for treatment types can vary based on topography as well as the location of the nearest processing facility.

Although our analysis simulated cost-effective thinning treatments for carbon storage on the majority of forested plots in California, our results do not include any landscape-scale effects of these treatments- rather, they only include "project-level" carbon effects of thinning treatments. Our analysis also did not include a reduction in wildfire emissions from thinning treatments because of the difficulty in quantifying avoided wildfire emissions, both at the project-level and landscape scale. Finally, our model does not include carbon benefits of wood products substitution created from harvested wood. Together, these limitations suggest an incomplete model of forest carbon flow. If however these aspects were included, the carbon implications of forest management may look different by capturing a more thorough life-cycle of the carbon consequences of forest management.

Aware that forests play a critical role in the carbon cycle, policymakers are keen to understand their potential contribution among a variety of sectors to design cost-effective climate policy. As is, our analysis suggests that forest policy motivated by carbon goals alone may not be cost-effective as compared to other sectors, although the marginal cost curves for other sectors of the economy remain unknown. However, we suggest that if the co-benefits of management, including avoided fire emissions, were included in our model or in policy design, the carbon benefits of forest management could be greater and seemingly more cost-effective for the State. Therefore, in light of these limitations and also the considerable private and federal forest management goals outlined by the State, we propose that forest policy for private and federal forests be motivated by thinning co-benefits in addition to carbon sequestration to support policy cost-effectiveness.

Finally, to better understand and measure the additionality of how management affects these co-benefits, we also propose that California consider a statewide carbon inventory for forest carbon accounting. Compared to the current Forest Carbon Offset Program, a statewide carbon inventory could potentially support a more cost-effective and efficient way for the State to measure the forest's contribution to the statewide carbon neutrality goal.

Significance

California is currently experiencing the effects of climate change, including increased frequency and severity of wildfires and droughts. In the absence of strong federal climate policy, many states have begun to pursue their own climate initiatives. California, historically a leader in the environmental movement, in 2018 declared a goal of statewide carbon neutrality by 2045 (Brown, Jr, 2018). This pledge, Executive Order B-55-18, aligns with the 2015 Paris Agreement to restrict global mean temperature rise to two-degrees Celsius (Brown, Jr, 2018). To reach carbon neutrality, the State will need to both reduce emissions and remove carbon dioxide (CO_2) from the atmosphere. A recent State report estimated the amount of negative emissions necessary to reach this goal has been estimated to be on the order of 125 million tons of CO_2 per year (Baker et al., 2020).

California's forests play an important role in carbon sequestration in the state. In 2015 alone, California forests sequestered approximately 26 megatons (1 megaton=1 million tons) of CO_2 equivalent (CO_2e) carbon from the atmosphere (CalFire, 2018). This represented around five percent of California's carbon emissions released in that year (CARB, 2019). However, increasing drought severity and intensity of wildfires threatens the effectiveness of California's forests as a carbon sink. To ensure California's forests continue to help offset the state's emissions, state policymakers and land managers will need to prioritize carbon storage in forest management (Liang et al., 2018).

Our project focuses on determining the costs and carbon consequences of a host of forest management treatments across public and private forests in California, and how these treatments can contribute to the State's climate goals. To aid policymakers in designing cost-effective forest policies, we created marginal cost curves (MCC) for forest management in the State. These MCCs act as tools to determine the costs (dollars per ton of carbon) and carbon implications (tons of carbon stored) of a range of forest management treatments. They outline what type of management treatments are most cost-effective for carbon storage and in which areas of the State. These MCCs could also be useful to compare the costs of forest management to reach a target abatement level as compared to other mitigation and abatement strategies.

However, to determine additional carbon storage in the state as a result of different management practices, a baseline needs to be created to represent current state forest practices. Baseline conditions of carbon stored in California currently determines how much carbon any one management practice will additionally sequester. Therefore, an important part of this project includes comparing a more conservative baseline scenario that includes predominantly grow-only practices, with one modified from the California Air Resources Board which includes heavier baseline forest management.

This project therefore provides a key initial tool for policymakers to craft carbon-incentivized forest management policy. We estimate the costs and carbon consequences of managing California's forests for carbon storage under two different baseline scenarios. The state then has two distinct frameworks from which to compare future forest carbon projects. State agencies and working groups can also better understand which management practices to promote under the State's carbon neutrality goal and provide a mode of comparison to other carbon abatement strategies. This supports California's carbon-neutral future and provides a path to achieve cost-effective carbon storage on California's forest lands.

Project Objectives

Research Goal

Assess how forest management can cost-effectively contribute to Executive Order B-55-18, California's pledge to be carbon-neutral by 2045.

Objectives

1. Develop a tool to inform policymakers of cost-effective forest management practices that also prioritizes carbon sequestration.
2. Using this tool, identify potential policies to incentivize cost-effective forest management for carbon sequestration to support carbon neutrality.

Background

Carbon Neutrality in California

California has long been a leader in the U.S. environmental movement. In light of the climate crisis facing both residents and ecosystems today, California has begun to focus its environmental advocacy and legislative efforts on climate change mitigation. In 2018, Governor Jerry Brown signed Executive Order (EO) B-55-18, a statewide pledge to become carbon neutral by 2045 (Brown, Jr, 2018). The EO aligns with the pledge made by over 200 jurisdictions in the world to comply with the 2015 Paris Agreement under the UN Framework Convention on Climate Change, which aims to restrict the rise in global mean temperatures to 2-degrees Celsius (Brown, Jr, 2018).

The EO acknowledges that climate change inflicts considerable harm to California's natural resources (Brown, Jr, 2018). Carbon neutrality, "the point at which the removal of carbon pollution meets or exceeds [carbon] emissions," is identified as a policy goal to combat climate change (Brown, Jr, 2018). However, it should be noted that carbon neutrality does not mean that the state does not produce carbon emissions (a "zero-carbon economy") - rather, what is emitted is balanced by what is naturally or anthropogenically sequestered. Importantly, carbon neutrality can be achieved through a variety of mitigation measures across the many state industries that produce carbon emissions such as transportation, energy, and waste management (Brown, Jr, 2018).

The State has been working to reduce carbon emissions for years. The 2018 carbon neutrality pledge builds on the State's climate goals as mandated by SB-32 (2006 Global Warming Solutions Act) to reduce carbon emissions to 40% below 1990 levels by 2030 and 80% below 1990 levels by 2050 (CARB, 2019). California also has numerous, wide-ranging initiatives to support its climate goals in addition to the cap and trade program begun in 2013 as part of AB 32. Relevant programs include Low Carbon Fuel Standards and Renewable Portfolio Standards.

The EO directs the State's Air Resources Board (ARB) to develop a framework for expansion and implementation of programs to achieve this goal, with emphasis on those that support state economic growth, air quality, water quality, and biodiversity (Brown, Jr, 2018). The EO also specifically alludes to the role of natural and working lands in achieving statewide carbon neutrality. It directs four agencies, California Environmental Protection Agency, the California Air Resources Board, California Department of Food and Agriculture, and California Natural Resources Agency, to work together to implement programs and policies (Brown, Jr, 2018).

To understand how to achieve this goal, AB-74, the 2019 budget bill last amended in July 2019, allocates $1.5M dollars to "identify strategies to decrease demand and supply of fossil fuels in a way that is economically responsible and sustainable" (CalEPA, 2019).

One of the first reports studying carbon neutrality was released in January 2020. The report "Getting to Neutral: Options for Negative Carbon Emissions in California" outlines a three-pillared strategy for the state to achieve carbon neutrality by 2045. It highlights that carbon neutrality is more ambitious than the 2050 goal of 80 percent reduced emissions below 1990 levels (Baker et al., 2020). Based on its analysis, the report suggests that the State remove 125 million tons per year of CO_2 from the atmosphere (Baker et al., 2020). Of the 125 million tons of emissions to remove, the report estimated that forest management could potentially capture and store 15.5 million tons of carbon per year by 2045 (Baker et al., 2020).

Existing State Forest Policies and Plans

The 2030 California Natural and Working Lands Climate Change Implementation Plan (NWL CCIP) and the 2018 Forest Carbon Plan (FCP) are prime examples of statewide efforts to manage forests and other natural and working lands for a variety of goals, including carbon sequestration. The NWL CCIP suggests that significant effort is required on natural and working lands to protect carbon stocks, increase carbon sequestration, and reduce GHG emissions, all of which are critical to meeting carbon neutrality. The FCP is complementary to the NWL CCIP because it provides guidance on how to manage forests for increased carbon storage and reduced emissions. Both plans highlight that California's forests are at risk of becoming a carbon source rather than its largest land-based sink— a change that would hinder the state's largest natural sink as it works to meet carbon neutrality.

2030 Natural and Working Lands Climate Change Implementation Plan (NWL CCIP)

The 2017 NWL CCIP, created by the California Environmental Protection Agency, the Air Resources Board, Department of Food and Agriculture, California Natural Resources Agency, and the California Strategic Growth Council, outlines the State's vision for land management until 2030 (CalEPA et al., 2019). The Plan highlights that State forests and agricultural lands cover over 90% of land in California and provide myriad ecosystem services, including carbon sequestration. Thus, the role of natural and working lands to achieve carbon neutrality is key: the plan proposes "doubling the rate of state-funded forest and restoration management efforts" to support the State's goal of restoring 500,000 acres of private forest land per year. To increase forest carbon, the Plan calls for "a shift from even to uneven-aged management, extended harvest rotation lengths, and larger harvest buffers around riparian and habitat areas." Relatedly, the NWL CCIP aims to promote forest biomass projects that utilize woody biomass from forest management activities to meet the State's forest, wood products, and renewable energy mandates. Importantly, these types of biomass projects could replace the current practice of burning excess woody biomass in open piles, a process that produces carbon emissions and harmful air pollutants. Listed below are the major forest management practices proposed by the State, in terms of acres of forest treated.

Forestry	
Improved forest health and reduced wildfire severity	
Prescribed fire	23,800-73,300 acres/ year
Thinning	59,000-73,000 acres/ year
Understory treatment	23,500-25,300 acres/ year
Enhanced carbon in forested ecosystems *Less intensive forest management*	49,800-58,800 acres/ year
Biomass utilization	Additional 50% of slash diverted from pile burn/decay

Figure 1. Acreage goals for each specific forest management practice, as outlined in the 2030 NWL CCIP.

To support carbon neutrality, the 2030 NWL CCIP also highlights the opportunity to transform natural and working lands from carbon sources to carbon sinks between 2030 and 2045 following the implementation of numerous carbon-smart practices. These practices also work to enhance forest resilience against the impacts of worsening climate change. The plan recognizes that treatments such as fuels reduction and thinning result in an initial loss of carbon, but support long-term, stable forest carbon due to a decreased threat from wildfire and associated emissions.

Major implementing partners of the NWL CCIP include the Department of Forestry and Fire Protection ("CalFire") and regional conservancies across the State. Currently, CalFire has several cost-share and grant programs that directly support carbon sequestration goals. Programs include the Forest Health Grant Program, Forest Legacy Program, Forest Improvement Program, Vegetation Management Program, and the Fire Prevention Grant Program.

2018 California Forest Carbon Plan

The 2018 Forest Carbon Plan (FCP) outlines how climate change is altering the natural ability of forests to sequester carbon and act as carbon sinks (Forest Climate Action Team, 2018). The FCP importantly provides a blueprint for how the State can increase carbon sequestration, reduce carbon emissions, and increase forest resilience in light of climate change and increasing high-severity wildfires. It also describes the myriad of public and private benefits that forests provide, and outlines policies and practices that the State can take to support its long-term climate goals, of which carbon neutrality is paramount. Relatedly, the FCP sets forest carbon targets for 2030 to align with the State's 2017 Climate Change Scoping Plan. Specific goals are set for private land management, public land management, the prevention of forest land conversions, the wood products industry, forest research, and urban forest protection.

Although increased state resources, mainly through the California Climate Investment grant program funded by the State's cap and trade program, have been allocated in recent years to improve forest health and combat wildfire, the FCP describes the considerable work needed to reduce the likelihood of fire across the State. Additionally, significant barriers persist that limit forest management. These include an undeveloped bioenergy industry, limited infrastructure for wood products production, and a lack of trained forestry personnel. The FCP also notes that the current pace and scale of forest restoration in California is slower and smaller than what is needed to meet the State's longer-term climate goals. It should be noted that this plan was developed prior to the State's carbon neutrality pledge.

Similar to the NWL CCIP, the FCP highlights that many management practices to reduce the likelihood of fire and support forest health do in fact reduce forest carbon in the short-term. However, in the long-term, these actions support a more resilient forest that is less susceptible to fire, drought, and insect infestations that can result in carbon losses. Finally, the FCP emphasizes a regional approach to management: ecology and policies differ across the State such that effective solutions are those devised at the regional landscape or watershed level.

To ensure large-scale management for forest carbon, partnerships between the State, federal government, and non-profit organizations are recommended. Additionally, to finance forest management, the plan highlights the role of state investment and also sustainable timber harvests to incentivize treatments. Without financial support, these practices would otherwise not be performed due to high costs of removing small, non-merchantable trees.

The Role of Forests in Carbon Sequestration

Forests in California function as an integral part of the State's carbon cycle.[1] During photosynthesis, trees and other living plant matter take in atmospheric carbon dioxide (CO_2) and transform it into carbon that is stored in biomass. This process, also referred to as carbon sequestration, aids in the mitigation of effects of greenhouse gases in the atmosphere. In 2015, California forests sequestered approximately 0.79 metric tons (MT) of CO_2 equivalent (CO_2e) carbon from the atmosphere per acre, per year (CalFire, 2018). Because forests in California have such a high density of plant matter compared to other landscape types, they are able to sequester large amounts of atmospheric carbon. Some of this carbon stays within forests in the form of living plant and soil organic matter, and some of it gets transported out of forests as a result of timber harvesting or thinning operations. Although forests can sequester large amounts of carbon, they also emit carbon during various processes. When trees and other plants die in forests, their biomass decays and carbon is released back into the environment. Additionally, carbon is released from forests through the combustion of plant matter during wildfires and during plant respiration (Forest Climate Action Team, 2018).

Because of past and current forest management practices that have increased the fire return interval[2] within California forests, there is greater stand density and, therefore, carbon stored in current forests compared with historic forests. Between 2006 and 2015, the US Forest Service's Forest Inventory and Analysis (FIA) program estimated that there was an average of 2.04 billion metric tons (MT) of carbon stored in living and dead plant matter (both above ground and below) per year in California forests. Although estimates vary because of differing methodologies, it is estimated that California forests sequester approximately 32.8 million MT of CO_2e carbon from the atmosphere each year. This approximation, however, does not include carbon emissions from wildfires. Between 2001 and 2010, California forests lost approximately 120 million MT of carbon due to wildfires. Although California forests are currently a carbon sink, due to increased wildfire severity, decreased forest health and climate change, forests are at risk of becoming a carbon source (CalFire, 2018; Forest Climate Action Team, 2018).

Climate Change and Forest Carbon

The effects of climate change have negatively impacted forest health and have resulted in increased loss of forest carbon in recent years. Average ambient temperature in California has warmed one degree Fahrenheit compared to the first half of the 20th century, with some regions of California experiencing a two degree Fahrenheit increase. Global climate models project average temperatures in California to increase between 5.6 and 8.8 degrees Fahrenheit by the latter half of the 21st century. In addition to rising temperatures, California has also experienced shifting precipitation patterns. This was made evident to many residents during the 2012-2016 drought, which resulted in emergency water conservation measures being taken at the state and local level. Climate models project an overall increase in the year-to-year variability of precipitation patterns, an increase in the amount of dry versus wet years, an increase in the probability of extreme precipitation events such as atmospheric rivers, increased intensity of seasonal dryness, and decreased annual snowpack (California Governor's Office of Planning and Research, 2018).

1 Although the carbon cycle is global in nature, for this report we will be focusing on the carbon cycle within the State of California.

2 The amount of time between wildfire events within a particular area.

Changing climatic conditions have decreased the health of trees in California forests and made them more susceptible to drought, disease and pests, such as the bark beetle. It is estimated that between 2010 and 2017, stress from drought conditions in California's conifer forests led to a widespread bark beetle infestation, which resulted in the death of approximately 129 million trees (California Governor's Office of Planning and Research, 2018). Not only does forest carbon get released from these dead and dying trees, but the overall reduction in forest health has resulted in increased wildfire severity.

Wildfire is already the largest source of carbon emissions from California forests, and emissions from wildfires are expected to increase in the coming decades due to impacts associated with climate change. By 2100, emissions from wildfires are projected to increase by between approximately 20 and 100 percent when compared to a baseline of average wildfire emissions recorded between 1961 and 1990. Approximately 50 percent of the increase in dry fuels present in California forests between 1985 and 2015 have been attributed to the consequences of climate change. This increase in fuel has resulted in fires that burn hotter and emit more carbon. An additional impact resulting from more severe wildfires is that forests that experience these hotter fires have a lower probability of re-establishing themselves and, instead, regrow as shrub or grassland. A transition in land-cover from a forest ecosystem to shrubland or grassland may decrease long-term carbon storage within the State (Forest Climate Action Team, 2018).

The Effect of Thinning on Forest Carbon

Forest thinning broadly involves the partial cutting and removal of trees on forest lands (see adjacent text box). Land managers thin forests for a variety of ecosystem services and co-benefits, including timber production and decreased fire severity. Most land managers, however, do not perform thinning operations to maximize long-term forest carbon storage as it is typically not a management priority.

Historically, fires within forests have been suppressed, which has led to an increased fire return interval and an increase in forest stand carbon. However, this has also resulted in forest overcrowding, limiting the ability of large portions of California's forests to increase carbon storage in the long-term (CalFire, 2018).

There have been numerous studies on the effects of different thinning regimes on both above-ground forest carbon storage (carbon stored in the tree above the soil) and below-ground forest carbon storage (carbon stored in the tree below the soil). These effects depend on the thinning type (e.g.

What is forest thinning?

Forest thinning is a forest management practice that includes the partial cutting of trees in forested areas as well as the removal of certain individual trees in order to achieve management priorities such as increased tree growth and reduction in wildfire severity. Thinning regimens can range from heavy to light thinning and differ based on factors such as amount of trees and tree residue (biomass) removed, diameter of trees that are removed from a project area as well as the type of equipment used (e.g. mechanical versus hand thinning). Additionally, thinning is often followed by a range of post-treatments including prescribed burns, mastication and removal of biomass from a project area for use in wood products.

moderate versus heavy thinning) and forest ecosystem (e.g. mixed conifer forests versus redwood forests) in which the thinning practice is performed. Because thinning involves the removal of woody biomass from forests, initially thinning results in a reduction in above-ground carbon storage. However, in the years following a thinning operation, above-ground carbon has been shown in some instances to grow back at a faster rate than the forest was sequestering prior to thinning (Zhou et al., 2013). As can be seen in Figure 2 below, forest lands in California that are subject to a consistent biomass removal regime (whole tree harvest, thinning operations, etc.) have an increased positive flux in annual carbon storage (CalFire, 2018). Compared to the other forest landowners, USFS land is subject to the smallest biomass removal regime, and subsequently has the smallest positive flux in annual carbon storage.

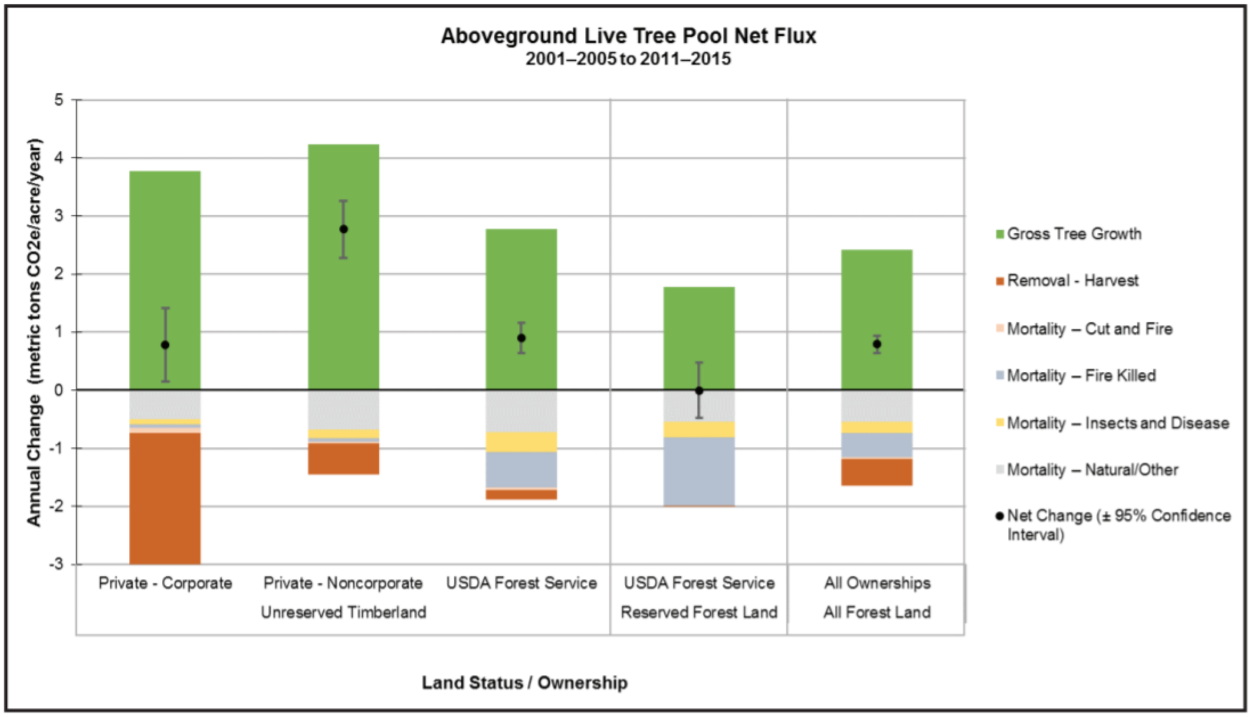

Figure 2. Diagram from CalFire Forests and Rangelands report that shows forest growth and harvesting intensities for forests owned by different entities. Source: CalFire, 2018.

Thinning of forest lands has also been shown to increase carbon stability in the long-term. As discussed above, the effects of climate change as well as decades of fire suppression have decreased the stability of long-term carbon storage in forests, in both the near and long term (CalFire, 2018). A recent study focusing on the Sierra Nevadas has shown, however, that landscape-scale restoration and thinning operations can result in increasing forest carbon stability under future climate change scenarios and resulting wildfire conditions (Liang et al., 2018). Another study conducted in the Sierra Nevadas concluded that thinning priority areas based on wildfire severity resulted in increased carbon storage stability and reduced severity and emissions from wildfires when they did occur (Krofcheck et al., 2018). Some studies have indicated that the fire return interval used in the analysis of the effects of thinning treatments on carbon storage and emissions strongly affects the carbon implications of thinning (Winford and

Gaither, 2012). These studies indicate, however, that both landscape-scale and priority thinning can have a positive effect on forest carbon stability today and into the future.

Although forest thinning has been shown to generally increase forest health, increase the rate of carbon sequestration and stability over the long-term, and reduce wildfire severity in California's forests, additional studies would be beneficial to determine the effects of thinning at the more granular level (such as specific forest ecosystems) (Winford et al., 2015). Additionally, whether forest thinning results in a net carbon increase is also dependent on what is done with the biomass that is generated as a result of thinning (Zhou et al., 2013). Biomass generated from forest thinning would need to be taken out of the forests and incorporated into long-lived wood products in order to prevent associated carbon releases.

Carbon Stored in Wood Products

Once carbon has been sequestered by forests, biomass can be harvested through management practices and manufactured into wood products. Manufactured wood products produced in California include both primary products (products that are able to be manufactured from timber such as lumber and plywood) as well as reconstituted primary products (products manufactured from primary product residue, such as biofuels). These products can be placed into four general categories: sawlogs, veneer logs, bioenergy and miscellaneous products. Of the approximately 360 million cubic feet (MMCF) of timber harvested in California in 2012, 83 percent was used to manufacture sawlogs, eight percent for veneer logs, eight percent for bioenergy and less than three percent for other miscellaneous products. Most of the timber used to manufacture these products came from Douglas-fir, True Fir, Pine and Redwood species (USDA, 2015).

Carbon can remain in wood products for decades; however, this depends on the type of product as well as the decay rate of carbon in a particular wood product (the rate at which carbon is released from the product and returns to the atmosphere). This decay rate depends on the species of wood used, how the product is stored, and various other factors. For example, lumber produced from softwoods (the majority of California tree species harvested are softwood species) would retain less than 25 percent of its original carbon content 100 years after harvest due to its decay rate. Wood products used for energy production such as biofuels, do not store any carbon as carbon stored in the wood used to make these fuels would be released upon combustion (Smith et al., 2006). Although use of fuels derived from biomass such as wood from forests displaces conventional fossil fuels, the consequence for carbon emissions is that fossil fuel extraction and consumption is delayed but not eliminated entirely.

However, despite the potential carbon benefits from forests in California, traditional wood product markets do not currently provide adequate incentives for forest management at the economies of scale needed to achieve state forest management and climate goals. In 2018, the state created the Joint Institute of Wood Products Innovation ("Joint Institute") to address this problem. As a research group, the Joint Institute works to determine which, if any, woody biomass product streams and markets could incentivize cost-effective carbon management practices, recognizing the potential of forest management and harvested wood products to support carbon storage (see Appendix Table A-2).

Additional Forest Ecosystem Services

Forests also provide many additional ecosystem services beyond carbon sequestration. Other important ecosystem services include clean water, regulated water supply, recreation and provisioning services, and clean air.

The natural watersheds encompassed by our forests can provide for more cost-effective water treatment than water filtration plants (Brauman, 2007). For example, New York City invested $1.5 billion dollars to protect the city's water source in upstate New York to capitalize on the ecosystem services provided by the forest for regular, clean water (Ecosystem Marketplace, 2006). This decision contrasted the alternative constructed option, a $6 billion filtration plant to clean the city's water supply (Ecosystem Marketplace, 2006).

In California, water is of particular importance as the population grows and recent droughts threaten the State's water supply. Notably, roughly 60% of California's developed water supply is located on forest land in the Sierra Nevadas (Sierra Nevada Conservancy, 2014). Preliminary estimates based on existing climate information suggest that forest management practices that would reduce forest cover by 40 percent of maximum levels across a watershed could increase water yields by about nine percent (Bales, 2011).

Recreation services and opportunities provided by forest ecosystems also support the outdoor recreation sector in California, which alone generates significant local and regional income and creates over 691,000 direct jobs throughout the State (Outdoor Industry Association, 2017). The outdoor recreation sector also contributes to the State's tourism industry, generating $92 billion in direct travel spending and $6.2 billion in state and local taxes (Visit California, 2016), with an additional $30.4 billion in wages and salaries (Outdoor Industry Association, 2017). There are an estimated 24 million visitors to National Forests annually, who spend approximately $2 billion during these visits, contributing over $700 million to local economies and over 18,000 local jobs (Rosenberger et al., 2017) Forests also provide raw materials that benefit society in the form of jobs in rural communities. In 2012, California's wood products industry employed approximately 52,200 workers (McIver et al, 2015).

Forests also support clean air by removing airborne pollutants through the interception of particulate matter on plant surfaces and the absorption of gaseous pollutants (Nowak, 2002). In 2012 alone, trees and forests were found to have removed 17.4 million tons of air pollution, generating $6.8 billion dollars in equivalent human health benefits for the conterminous United States (Nowak, 2014). These health benefits include the avoidance of more than 850 incidences of human mortality and 670,000 incidences of acute respiratory symptoms (Nowak, 2014). Forest management may also help reduce wildfire and its associated air quality issues such as smoke inhalation and particulate matter concentrations. In 2018, forest fires in California released 1,105 thousand short tons of particulate matter into the atmosphere (CARB, 2019). In Los Angeles, these fires resulted in levels of particulate matter more than twice the recommended levels for over 10 million residents (Washington Post, 2019).

Existing Forest Management in California

Public Forest Land Management

In California, the federal government is the largest landowner. Federal agencies including the USFS, National Park Service (NPS), and the Bureau of Land Management (BLM) own and manage roughly 57% of forest land, or 19 million acres (UC ANR, n.d). In contrast, the State of California owns and manages a relatively small amount (two percent, less than one million acres) and local governments own another one percent (500,000 acres) (LAO, 2018). State and local forest land falls primarily under CalFire or state water agency jurisdiction (UC ANR, n.d.) and is concentrated along the North Coast (LAO, 2018). CalFire works to both prevent wildfire on state and private land and also enforce timber harvesting regulations (LAO, 2018). In contrast, the Board of Forestry and Fire Protection designs and develops forest policy and regulations that CalFire then implements (LAO, 2018).

State forest management has followed a similar path to that of the federal government until recently. Under the Brown and Newsom administrations, forest management practices such as thinning and fuels reduction activities have increased and allocated greater funding. Recently, Governor Newsom waived state environmental laws to fast-track 35 fuels management projects across the State to treat roughly 90,000 acres of land and reduce the risk of wildfire (Luna, 2018). Relatedly, the Board of Forestry and Fire Protection in December 2019 approved a Vegetation Management Exemption for similar projects after a 10-year study (US News, 2019). This exemption is anticipated to reduce the multi-year timeline that land managers encountered for common forest management projects such as fuel breaks, prescribed burns, and thinning.

For most of the 1900s, USFS, the agency responsible for federal forest management under the Department of Agriculture, has been practicing a policy of wildfire suppression across the West (Schultz et al., 2019). As recently as 2015, nearly 98 percent of all fires continued to be suppressed (US Forest Service, 2015). This is in large part due to safety concerns for those living in the wildland-urban interface (WUI), areas in which housing and natural vegetation are mixed. Increasingly, more people are living in WUI areas in California: of the roughly 8 million homes in California, three million are found in WUI areas and 1.7 million of these are at highest risk to fire (Walsh, 2018). This is of particular concern because fires are becoming more severe. In 2018, the Camp Fire in Paradise, California killed 85 people (Associated Press, 2019).

In particular, the practice of fire suppression has altered California forests, where the federal government (including NPS and USFS) owns and manages over half of all forest lands (UC ANR, 2020). The Forest Service's annual budgets reflect the extent to which wildfire suppression was (and continues to be) a priority. As recently as 2017, roughly 60% of the Forest Service's federal allocation was spent on wildfire management (USFS, 2015). In California, USFS has previously spent up to "$200 million per year to suppress 98 percent of all fires and up to $1 billion to suppress the other two percent of fires" that became catastrophic in size (US Forest Service, n.d.). In contrast, little money was spent on forest management activities. In 2018, this funding imbalance was recognized by the government with the passage of the Consolidated Appropriations Act (Schultz et al., 2019). This law is designed to increase funds available for federal fire management and also decrease the portion of the overall USFS budget that goes to fighting fires (Schultz et al., 2019).

There are multiple challenges that USFS faces to change its management approaches. One major roadblock is that there is little financial incentive for USFS to conduct forest health practices and fuel reduction activities. This is because the majority of the wood harvested from these practices is not of sufficient size and quality for traditional lumber markets and other wood products (Zimring, 2019). USFS continues to offer contracted timber sales for logging companies to do the work to harvest valuable wood on federal land. However, there is similarly little to no financial incentive for logging companies to perform this type of management practice; thus, many of these contracts remain unbid or unperformed (Zimring, 2019).

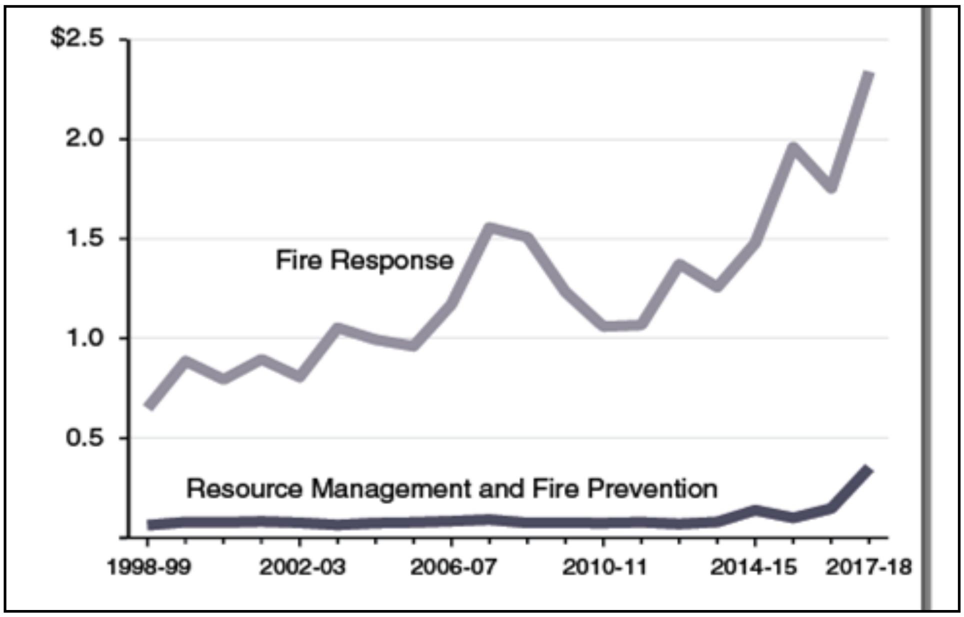

Figure 3. Significantly More CalFire Spending on Fire Response Than Proactive Management. Source: LAO, 2018.

However, there are some signs that the USFS is changing its policies toward wildfire. In 2003, Congress passed the Healthy Forests Restoration Act to prioritize hazardous fuels reduction projects on federal land (HFRA; 16 USC 6501 et seq). The 2009 Collaborative Forest Landscape Restoration Plan (CFLRP) also highlights a shift away from fire suppression: the program funds large-scale forest restoration and fuels reduction projects while also prioritizing engagement with stakeholders other than USFS (Schultz et al., 2019). Importantly, both laws recognize fire as a threat to communities, ecosystems, and water supplies – HFRA promotes practices like fuels reductions within National Forests while CFLRP further "characterizes fire as a risk to be managed and a natural process to be restored" (Schultz et al., 2019). In 2009, the National Cohesive Wildland Fire Strategy was also developed to guide forest and fire management within the USFS (Schultz et al, 2019). The strategy calls for using fire and other non-mechanical treatments like thinning to restore and maintain National Forest ecosystems, in addition to promoting resilient WUI communities and improving the response to fires (Wildland Fire Executive Council, 2014). These three laws highlight how the agency has evolved to recognize the importance of fire in Western forest ecosystems and begun to reverse the previous century of suppression.

In accordance with these policy changes, USFS in California aims to treat 500,000 acres of forest land per year (Forest Climate Action Team, 2018). However, the pace of treatment is estimated to take 35-45 years to "make a difference" against catastrophic wildfire on USFS lands (USFS, n.d). This effort may require investment of $300 million dollars per year, although it is estimated to save $800 million dollars per year in direct avoidance costs (US Forest Service, n.d.)

Private Forest Land Management

Any discussion regarding the history of land ownership in California begins with the acknowledgement that as recently as 1800 more than 200,000 Native Americans lived in California (Pritzker, 2000). However, by 1900 this population had been reduced to less than 15,000 due to diseases introduced by European settlers (Pritzker, 2000). Over this same time period, the vast majority of native tribes in California were dispossessed of their land, with the majority of it going to timber corporations, National Parks and National Forests (Huntsinger, 1995). By the time the USFS was formed in 1905, land management by Native Americans played almost no role in shaping California's forests.

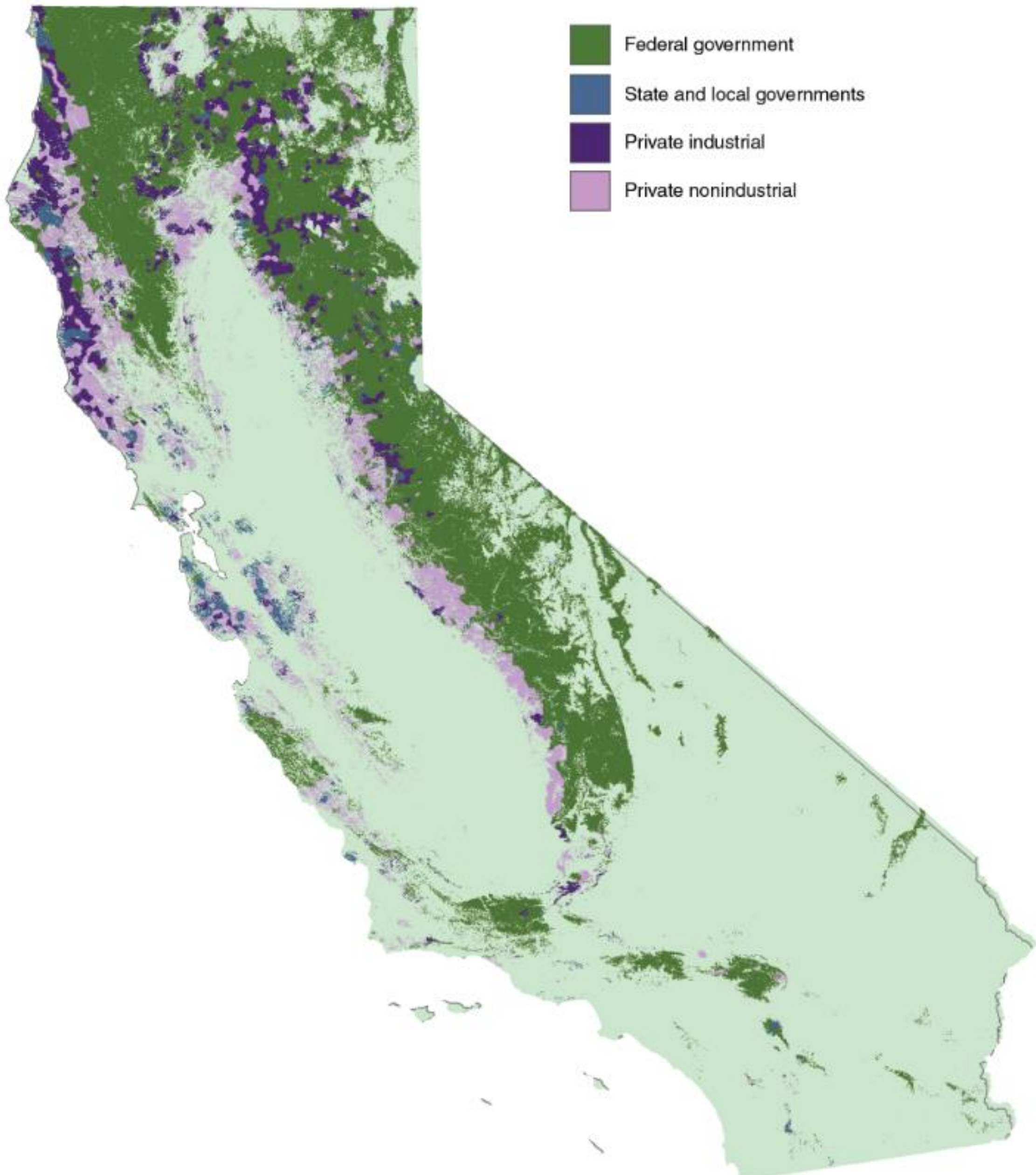

Figure 4. Forest land ownership in California, by landowner class. Source: LAO, 2018 with data and analysis by: Jaketon Hewes, Brett J. Butler, Greg C. 2017. Fort Collins, CO; Forest Service Research Data Archive. https:doi.org/10.2737/RDS-2017-0007.

Apart from federal lands, the private sector is the second-largest owner of forest lands in California. Individuals, companies and tribes account for 40%, or 14 million acres of forest land in California (UCANR, 2020). Of this 14 million acres, individuals own nine million acres with nearly 90% of these individuals having less than 50 acres of forest land (UCANR, 2020). Industrial timber companies account for five million acres, with tribes holding the remaining acres (UCANR, 2020 (Figure 4).

The great Montana & Idaho Fire of 1910, which burned over 3 million acres in under two days, greatly impacted early forest policy. This fire was the primary reason that USFS began its practice of fire suppression on federal lands, a policy that continued for nearly a century and directly contrasts with the intentional use of fire across forest lands employed by Native Americans. Fire enabled them to alter and improve wildlife habitats, manage for agriculture, and clear travel routes, among many other possible uses (National Forest Magazine, 2020). The loss of traditional Native American fire practices, coupled with the introduction of fire suppression policies in the early 1900s, has greatly reduced the role of fire in natural ecological processes.

For the majority of the past century, individuals owning less than 50 acres of forest land in California have not had the economic incentive to harvest timber, let alone carry out any meaningful forest management practices such as thinning or controlled burns (UCANR, 2015). For this reason, private forest land in California not owned by a commercial timber company or tribe is generally considered not to be managed in any form (UCANR, 2015). It has also been found that this lack of management on the majority of privately-owned forest land in California is not conducive for carbon sequestration: studies have shown that managed lands sequester more carbon (UCANR, 2015). It should be noted that while these unmanaged forest lands may technically store more carbon than their managed counterparts, this storage is not stable in the long-term as it is particularly vulnerable to fire, drought, disease and land use change (UCANR, 2020).

With regards to industrial timber operators, Sierra Pacific Industries (SPI) accounts for 1.5 million of the 5 million acres of commercially operated forest land in California (SPI, 2020). Although often portrayed as a profit-driven business that favors clear-cuts, SPI claims that in less than 100 years they will raise the average diameter of log harvested from SPI owned land from 18 inches to 30 inches, while tripling the overall volume of timber on company owned land (SPI, 2020). In addition, SPI regularly augments their harvest through the purchase of publicly available logging contracts from the State and Federal governments (SPI, 2020). A recent study also found that commercial logging is not currently a major threat to California's forests, however, the conversion of forests to non-forests due to wildfire and other deliberate land-use changes is a greater threat (UCANR, 2020). Overall, timber harvest trends in California, on both private and public lands, have shown a significant decline over time (LAO, 2018, see Figure 5). This decline is due to a number of factors, of which the most significant were changes in state and federal timber harvest policies (LAO, 2018). It is also worth mentioning that owners of forest land where timber was harvested were nearly twice as likely as those who did not harvest timber to undertake non-revenue-generating stewardship activities such as protection of water quality, improvement of fish and wildlife habitats, and removal of individual trees to promote forest health (Stewart et al., 2016).

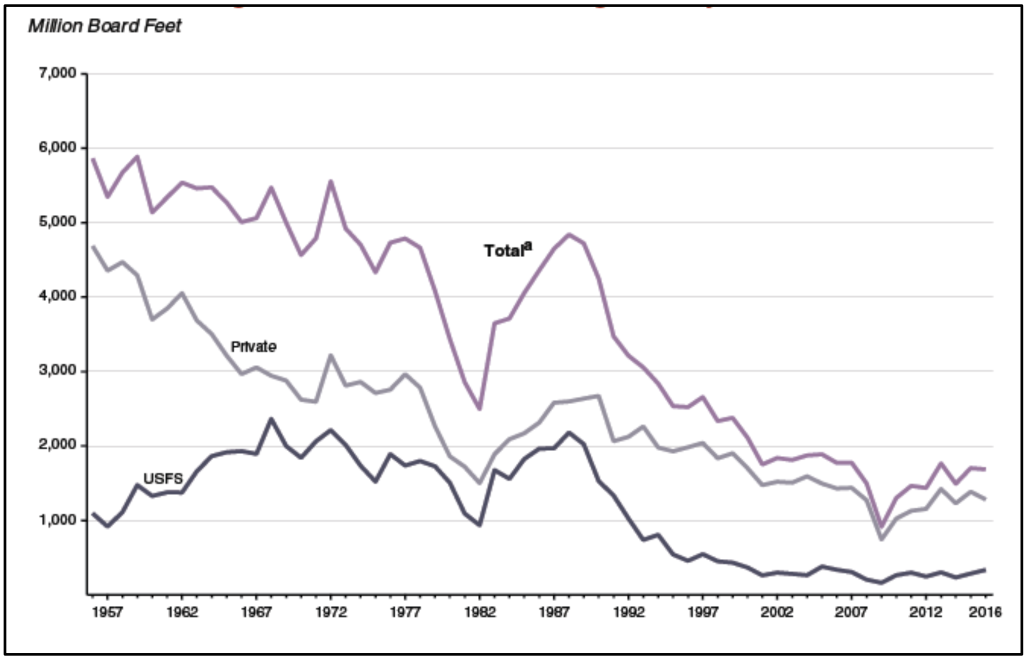

Figure 5. Timber harvesting volume (million board feet) in California from 1967-2016. Source: LAO, 2018

Regardless of ownership, all forest management practices on private land, from clear-cutting to reforestation or controlled burns, must first be approved by the State. In this sense, forest land management on private land closely resembles management on state-owned forest land. The State promulgates guidelines to be followed to harvest timber on private land. To harvest timber, private landowners must complete and submit either a Timber Harvest Plan (THP) or a Non-Industrial Timber Management Plan (NTMP) to CalFire for approval. THPs last for five years, have no size limit, and can be submitted by small private landowners or industrial timber operators (Forestry Challenge, n.d.). In comparison, NTMPs must be less than 2500 acres and have the goal of uneven-aged managed timber and sustained yield (Anonymous). With this ecological approach, if approved, NTMPs last in-perpetuity (Forestry Challenge, n.d.).

The cost of preparing THPs is high: estimates range between $40,000 and $120,000 depending on size and complexity (Anonymous, 2020). Thus, private land management in California faces considerable economic barriers and is seen as uneconomical to small-scale landowners. If landowners seek to engage in California's carbon market, this economic barrier becomes even more prohibitive: estimates for Integrated Forest Management plans to become certified forest offsets under CARB are 20-30% higher than THPs or NTMPs of the same size (Anonymous, 2020).

Forest Management and California's Negative Emissions Pathways

A recent 2020 report, "Getting to Neutral: Options for Negative Carbon Emissions in California", commissioned by the U.S. Department of Energy, highlights the important role that forest management practices can play to help California reach carbon neutrality by 2045. In particular, forest management has the potential to contribute to the State's most promising negative emissions pathways. Negative emissions are defined by the physical removal of carbon from the atmosphere and subsequent storage for a time period that is consistent with climate stabilization. This physical removal and storage of carbon is critical, since research has shown that California may not attain carbon neutrality through emissions reductions alone (Baker et al., 2020).

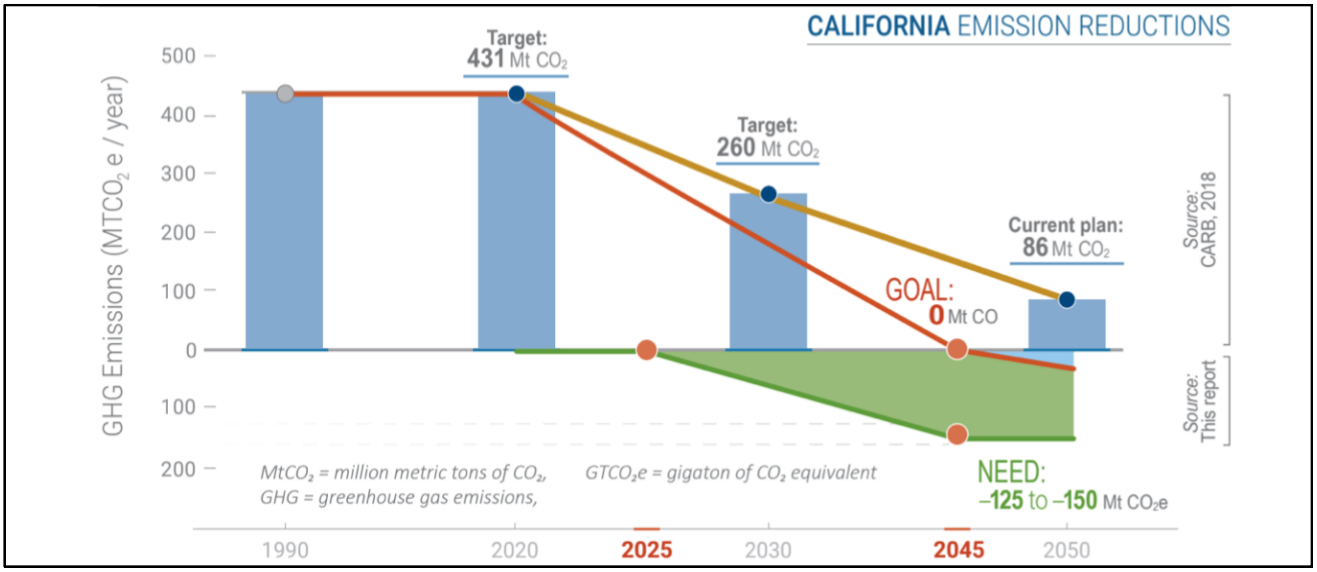

Figure 6. California's emissions goals, including negative emissions, extrapolated to 2045. Source: Baker et al, 2020.

These negative emissions pathways include three promising carbon-reduction pillars, which could in total remove and store approximately 125 million tons of carbon dioxide equivalent per year from the atmosphere. The first of these carbon-reduction pillars is defined as "Natural Solutions" and involves harnessing natural processes to remove and store carbon from the atmosphere. In particular, "changes to forest management to increase forest health and carbon uptake" are noted not only for their ability to increase the amount of carbon stored in trees and soils, but also for being among the least expensive of the three pillars (Baker et al., 2020).

The second carbon-reduction pillar involves the conversion of waste biomass to fuels in combination with carbon storage. Waste biomass is readily available across California (Baker, 2020) and partly consists of woody biomass residue generated by forest management practices such as logging and fire prevention. Currently, California's woody biomass residues enter one of three main carbon streams. They decay in the forest, burn in wildfires and prescribed burns or are used to produce energy. This biomass residue could instead be converted into fuels via a process that simultaneously captures the carbon generated in the process, which would be a necessary component of any zero emission or negative emission technology. This pillar also includes the conversion of woody biomass to liquid fuels and biochar through pyrolysis as well as the conversion of woody biomass to gaseous fuels through gasification. In particular, gasifying woody biomass to produce hydrogen fuel holds considerable promise for carbon removal and also aligns with California's specific goals on renewable hydrogen as identified in California's Renewables Portfolio Standard. It is also worth noting that renewable hydrogen production has risen dramatically in the United States in recent years, primarily based on policy support by the U.S. Renewable Fuel Standard and California's Low Carbon Fuel Standard (SoCalGas, 2019).

The third carbon-reduction pillar involves the development and deployment of machines that remove carbon directly from the air and store it underground. While more expensive than most negative emissions strategies, this method has the greatest overall capacity to remove and store carbon (Baker et al., 2020). This pillar identifies the use of geothermal heat for energy where possible but also relies on energy generated from renewable, low-carbon natural gas sourced from California's agricultural lands (Baker et al., 2020).

As well as removing and storing carbon, these negative emissions strategies provide important co-benefits to the state. Overall air quality would increase by the replacement of fossil-based transportation fuels and the reduction of biomass combustion and wildfires (Baker et al., 2020). The state's overall water quality and quantity would also be improved by restoring and improving natural ecosystems- such as the Sierra Nevada mountain range, which represents at least 60% of California's developed water (Sierra Nevada Conservancy, 2014). These strategies could also contribute to the economic development of rural areas such as the Central Valley and areas of the Sierra Nevada mountain range.

An additional co-benefit from these negative emissions pathways is reduced exposure to short-lived climate pollutants (SLCP). SLCP are powerful climate forcers and include methane (CH_4) and particulate matter (PM 10, PM 2.5) all of which come from prescribed burns and forest fires. These burns and fires also contribute to typical greenhouse gas (GHG) emissions through the release of carbon dioxide (CO_2) and nitrous oxide (N_2O). All of these emissions have negative impacts on human health and safety and in recent years, the frequency and severity of these types of emissions have increased substantially in California (CARB, 2019).

Methods

Data

The data used to generate our marginal cost curves come primarily from a 2016 report published by the USFS Pacific Northwest (PNW) Research Station. This report, funded by the California Energy Commission (CEC, referred to here as the "CEC Report"), assessed the feasibility of cost-effectively reducing fire risk within California's forests while supplying renewable building material and energy sources across the State (Fried et al., 2016**)**. The analysis for this report utilized the Bioregional Inventory Originated Simulation Under Management (BioSum) software developed by members of the PNW Research Station. BioSum is a workflow manager that, in short, provides users with a single interface to:

1. Select their forested study area based on Forest Inventory & Analysis (FIA) data
2. Model the effects of management treatments on forest growth within the study area using Forest Vegetation Software
3. Determine the cost of and potential revenue from those treatments
4. Select the optimal treatment for each plot based on desired outcomes (Figure 7). The specific data and workflows for each of these four steps are outlined in detail below.

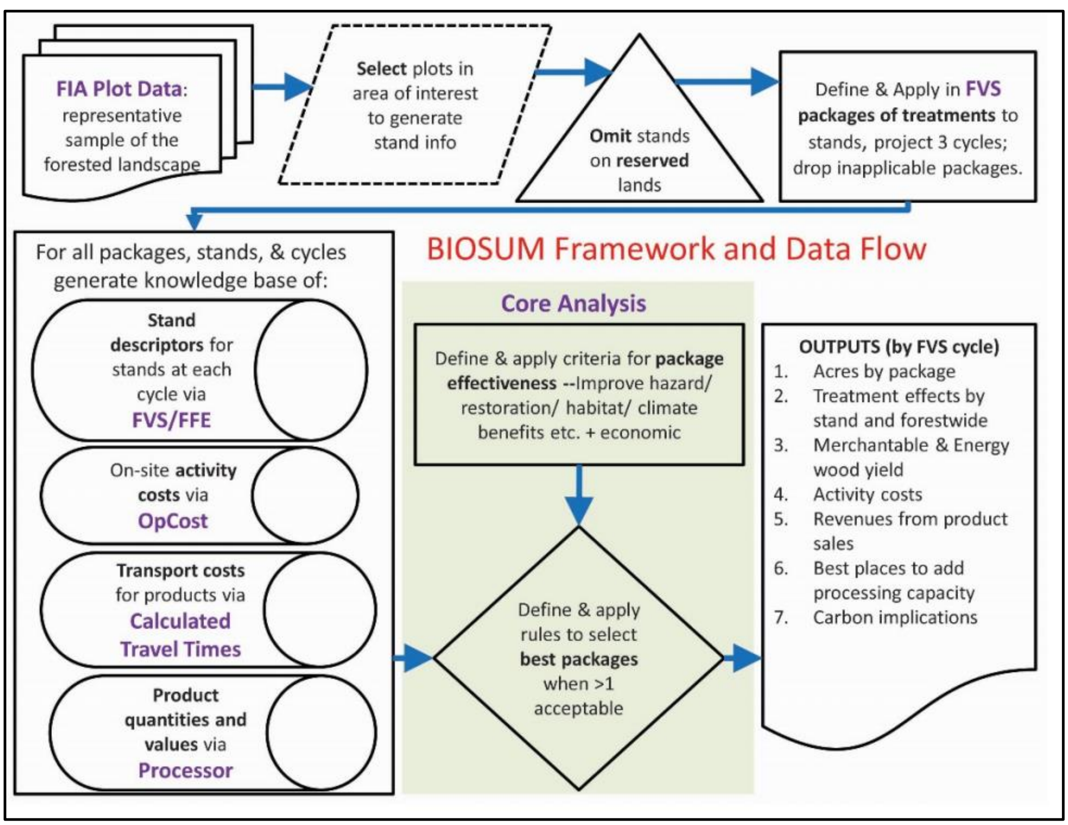

Figure 7. Generalized Biosum workflow (Potts et al., 2018).

Plot data

Biosum uses FIA data collected and published by the USFS from 2001-2010. The FIA program relies on a nationally standardized field sampling protocol to collect a wide range of data to define the condition of a given plot of land. Data include, but are not limited to, information on tree species, size, health, growth, mortality, harvest and wood production rates, as well as location[3] and forest land ownership (USFS, 2019). In California, there are approximately 5,000 FIA plots gridded across the State. For the CEC report, the research team selected approximately 2,289 plots, of the original 5,000, that were at least 25 percent forested. These plots are located on private and federal land but exclude protected areas like National Parks and Wilderness Areas (Figure **8**).

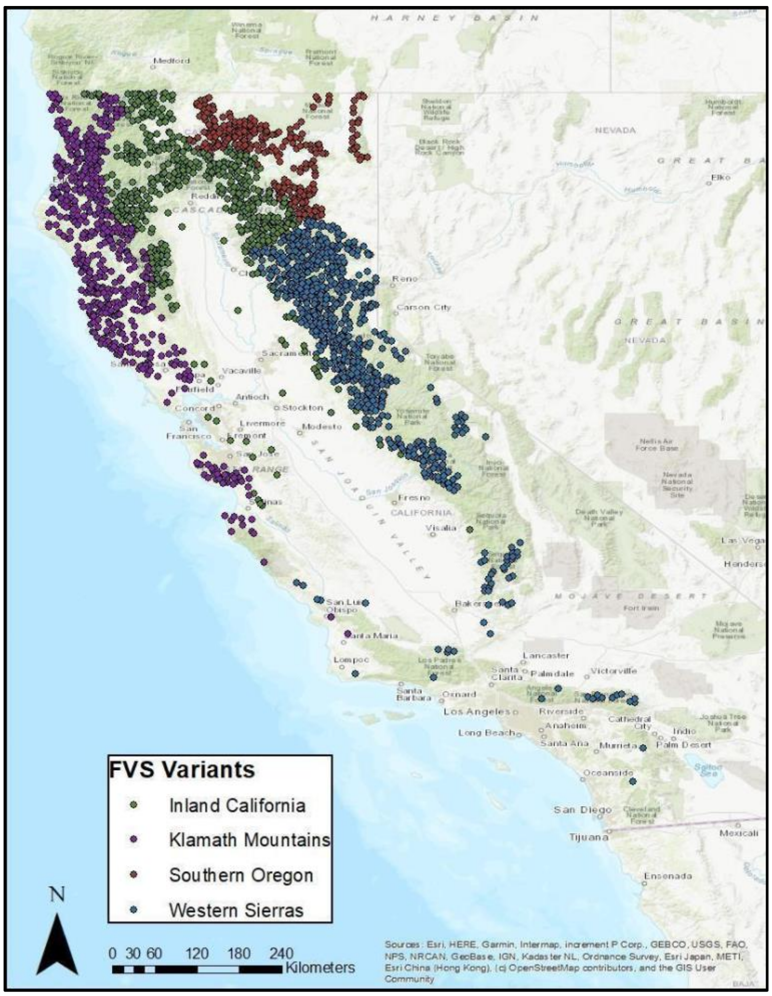

Figure 8. Selected FIA plots colored by their FVS Variant (ecological region within CA).

[3] To protect the privacy of landowners regarding the forested condition of their land and to prevent the temptation of owners to alter forest conditions around an FIA plot on their land, exact FIA plot locations are confidential. Instead, FIA developed a technique whereby the plot coordinate data are slightly altered (fuzzed) and some of the plot data are exchanged (swapped).

Model data
The USFS Forest Vegetation Simulator (FVS) was used to model forest growth in response to management treatments. FVS is specifically designed to use FIA plot data, which it uses to characterize approximately 5,500 acres of land surrounding each plot. For the CEC Report, researchers designed 28 treatments believed to be promising forest management treatments (Fried et al., 2016), along with two clear-cut scenarios, and a grow-only sequence, for a total of 31 treatments (Table **1**). These 31 treatments were each applied to the selected FIA plots. The model works by simulating ten year intervals (i.e., years 1, 11, 21, 31) and assessing if the basal area of the forest plot meets the minimal basal area criteria for the treatment, and if so, applying the treatment. If the minimum basal area requirement is not met, no treatment is applied and the criteria is reassessed during the next cycle 10 years later. Additionally, when a treatment is applied the model waits a full two cycles (or 20 years) before assessing the basal area criteria again -- this is done to mimic the typical rotation time for a thinning treatment. Biosum outputs a snapshot of the forest condition every ten years. If a harvest occurred during one of those years, it provides stand carbon data following the harvest, along with how much merchantable wood is harvested as a result of the treatment. Because we are interested in the change in forest carbon as a result of these treatments, we manually created a data point for the year before each harvest where the total stand carbon is the sum of the stand carbon in the following year and the amount of material that was harvested.

Economic Data
We took the FVS outputs from the 31 separate treatments on forest plots in California generated by the CEC report and input them into BioSum. Once the FVS outputs are in BioSum, there are two main components of the BioSum analysis: the processor and the optimizer. The BioSum processor allows the user to create scenarios where tree species can be grouped into specific categories (either Redwood, Sequoia, Pine, Conifer, True Fir or other). It also includes parameters related to harvest method; cost and wood value are determined using the integrated OpCost model (Connor et al., 2017). This OpCost model has been developed over the past decade by surveying commercial foresters across the western United States regarding the cost of harvesting and thinning treatments. These costs are based on a variety of metrics, including what harvest equipment, yarding technique, or post-treatment equipment is used as well as how different slopes and yarding distances affect these costs.

In addition to calculating the cost of performing treatments, Biosum calculates travel times for transporting harvested biomass from each site to the nearest wood processing facility. This travel time calculation, along with a per hour per ton cost of transportation, gives us the total cost of transporting biomass from each plot to a processing facility.

Treatment Selector
BioSum guides users through one final step that optimizes which treatment should be applied to each plot to best achieve the user’s desired outcome (maximize total stand carbon, minimize probability of fire ignition, maximize revenue, etc.). For our analysis, this step was skipped and was instead performed independently after calculating the relative value of carbon sequestered for each treatment, as outlined below.

Marginal Cost Curve

Total Cost (Treatment and Transportation)

Total cost of each treatment for each plot was calculated as the cost of the treatment, plus the cost of transporting the harvested biomass. This was done for each applicable harvest cycle, and was repeated twice, once with discounting of costs at a rate of five percent[4] to obtain the net present total cost, and once without discounting. The five percent discount rate was chosen as a conservative estimate for An important assumption is that the processing facility can process all of the biomass brought to it. We do not incorporate the cost of facility upgrades that may be necessary to meet an increased supply in feedstock. Additionally, when considering the various non-merchantable wood product pathways, we did not consider the cost of building facilities to process these innovative products.

Change in Carbon

Change in carbon was calculated as the change in total stand carbon plus the sum of all harvested biomass across the entire 32-year span. We assumed that all merchantable timber went into producing construction lumber. Then, to account for degradation of lumber over time, we used the annual carbon decay rates for softwood-derived lumber as calculated by Smith et al (2006). Equation 1 in the Appendix shows a mathematical representation of this formula.

It is important to note that, for each treatment, we only have 8 data points across the 32-year period (at years 1, 2, 11, 12, 21, 22, 31, and 32). When discounting carbon, we calculated the yearly change by assuming a linear relationship between year and stand carbon. Additionally, our calculations do not include emissions associated with the transportation of biomass, nor carbon intensity of producing lumber.

Baseline

When creating a marginal cost curve, it is important to establish a baseline level of carbon storage to determine how much *additional* storage will occur as a result of new management strategies. Selecting a baseline is therefore a critical decision that can affect the results of our interventions and also the shape of the resulting marginal cost curve. Because of the potentially strong differences in results that varying baselines can yield, we decided to apply two different baselines to our treatments: one business-as-usual baseline based on an approximation of the current amount of management taking place within California forests, and one baseline that reflects a simplified approach of how CARB determines additionality for improved forest management projects.

Baseline – Business-as-Usual (BAU)

To construct the business-as-usual baseline, we used a USDA timber harvest report that details how much timber was harvested within each county during 2012 (Mclver et al. 2015). This became the target baseline harvest value within each county. Then, for each county, we randomly selected a configuration of plots as well as acres from those plots which, when combined, came within an acceptable range of the target value. This was repeated for all four

[4] The 5% discount rate was chosen as a conservative estimate based on typical rates for evaluating the impacts of climate change (Nordhaus 2007).

harvest cycles within the county. We assumed that the target baseline for each county would remain constant at each 10-year interval.

Additionally, because treatments often differ between federal and private ownerships, the baseline calculation was performed separately for each owner type. In 2012, 84 percent of the total harvest came from private land and 14 percent from federal; the rest came from BLM or state land and was not included in this analysis. The target for each owner type was based on these statewide proportions of harvests -- because we do not know how much harvested material came from private and federal land for each county we applied these proportions (84% private, 14% federal) to each county. When calculating the baseline for private land, we used the clear-cut scenario, and for federal land we used a treatment that aligns with the most common thinning treatment used by USFS in California (Treatment #2).

Once the plots and their harvested acres were randomized and selected, the baseline was determined as the change in carbon from treatment (clear-cut for private land, Treatment #2 for federal land) on the randomly selected acres, plus the change in carbon that occurs from the grow-only scenario being applied to the remaining unchosen acres within each plot. If a plot was not selected, the baseline was the grow-only scenario for the entire plot. This baseline change in carbon was then subtracted from the change in carbon for each treatment on each plot to determine the amount of additional carbon that would be stored as a result of the modelled treatments.

<u>Baseline - Assumed Management (CARB)</u>

The business-as-usual approach for developing a baseline is not how CARB calculates forest carbon offsets for California's cap-and-trade program. CARB instead sets a baseline determined by the amount of carbon that is stored by region-specific forest types as a result of the Common Practice for that region/forest type. These Common Practice baseline carbon levels have been identified by CARB based on the most common forest management treatments within each area. The baseline carbon level thus represents the average aboveground carbon stocks for managed forest within each area. CARB uses the Common Practice baselines as a starting point for determining project-level baselines that depend on specific stand characteristics within the proposed offset boundary in relation to the forest characteristics of the entirety of a landowner's property. Because of the difficulties with estimating these project-level differences for our entire California landscape, we have simplified the CARB baseline calculations by assuming the Common Practice baseline for all plots in our analysis.

Treatment Selection

There are three main steps for selecting which plots and treatments are selected for our marginal cost curve:

1) To be considered, a treatment must result in a net present increase in carbon stored relative to its respective baseline.
2) Then, to select the best treatment for each plot, we calculate the *value* of the carbon stored -- as defined by the theoretical value of the carbon being stored (based on a $200/ton price of carbon -- deemed to be a prohibitively high cost) minus the cost of the treatment.

3) Calculate the total cost per ton of carbon ($/ton) for the selected treatment for each plot.

The marginal cost curve is created by arranging the selected plots by their $/ton value in ascending order and taking the cumulative sum of their respective total discounted carbon stored. This cumulative sum value for each plot becomes the x-axis with the $/ton on the y-axis.

Table 1. Forest management treatment descriptions used in analysis. Treatment packages used in this analysis and the 2016 CEC Report. These 28 treatments represent promising forest management treatments, along with two clear-cut scenarios, and a grow-only sequence, for a total of 31 treatments. BA= Basal area, pvt= max/min cut limit (inches) on private land, pub max/min cut limit (inches) on public lands, Rx Fire= Prescribed Fire (Fried et al., 2016).
* Thin to 20% of original BA, all other have 33.33% reduction

<table>
<tr><th>Treatment number</th><th>Treatment Type</th><th>Entry density</th><th>Max Cut Limit</th><th>Min Cut Limit</th><th>Fuels Treatment</th></tr>
<tr><td>1</td><td rowspan="24">Thinning</td><td rowspan="14">BA≥115</td><td rowspan="12">36 pvt/30 pub</td><td rowspan="10">4</td><td>Rx Fire</td></tr>
<tr><td>2</td><td>Pile/burn</td></tr>
<tr><td>3</td><td>Masticate</td></tr>
<tr><td>4</td><td>Lop/scatter</td></tr>
<tr><td>5</td><td>Rx Fire</td></tr>
<tr><td>6</td><td>Lop/scatter</td></tr>
<tr><td>12</td><td>Rx Fire</td></tr>
<tr><td>13</td><td>Pile/burn</td></tr>
<tr><td>19</td><td>Lop/scatter</td></tr>
<tr><td>20</td><td>Rx Fire</td></tr>
<tr><td>14</td><td rowspan="2">9</td><td>Lop/scatter</td></tr>
<tr><td>15</td><td>Rx Fire</td></tr>
<tr><td>17</td><td>36 pvt/21 pub</td><td rowspan="12">4</td><td>Lop/scatter</td></tr>
<tr><td>7</td><td>36 pvt/36 pub</td><td>Lop/scatter</td></tr>
<tr><td>8</td><td rowspan="2">BA≥135</td><td rowspan="12">36 pvt/30 pub</td><td>Lop/scatter</td></tr>
<tr><td>23</td><td>Lop/scatter</td></tr>
<tr><td>9</td><td rowspan="5">BA≥150</td><td>Lop/scatter</td></tr>
<tr><td>10</td><td>Rx Fire</td></tr>
<tr><td>24</td><td>Rx Fire</td></tr>
<tr><td>25</td><td>Lop/scatter</td></tr>
<tr><td>27</td><td>Lop/scatter</td></tr>
<tr><td>11</td><td rowspan="3">BA≥180</td><td>Lop/scatter</td></tr>
<tr><td>26</td><td>Lop/scatter</td></tr>
<tr><td>18*</td><td>Lop/scatter</td></tr>
<tr><td>32</td><td rowspan="2">Clearcut</td><td rowspan="2">BA≥150</td><td>NA</td><td>Pile/burn</td></tr>
<tr><td>33</td><td>NA</td><td>Lop/scatter</td></tr>
<tr><td>31</td><td>Grow Only</td><td>NA</td><td>NA</td><td>NA</td><td>NA</td></tr>
</table>

Starting in Year 1, treatments are implemented if the plot is at the entry criteria basal area (Fried et al., 2016). If this condition is not met during the first cycle, the criteria will be checked again during the next cycle (10 years later). When a treatment is implemented, FVS waits 20 years before checking the criteria again. Max cut limit defines the maximum size (diameter at breast height (dbh) in inches) of a tree that can be cut (for private and public lands respectively). Minimum cut size defines the minimum size that can be cut. Fuel treatment defines how the remaining fuels slash and debris will be treated after harvest/ thinning.

Results

Carbon storage distributions across all plots

Carbon storage implications of the 31 treatment options were analyzed on all 2,289 forested plots for both the simplified CARB and BAU baselines under a five percent discount rate. Treatments that had a CARB baseline stored significantly more carbon (tons per acre) than those that had a BAU baseline ($t = -182$, $p < 0.0001$) (Figure 9). Approximately 64 percent of clear-cutting scenarios and 82 percent of thinning scenarios within the BAU scenario stored less carbon than the baseline (carbon storage (tons/acre) was less than zero). In comparison, 64.7 percent of clear-cutting scenarios and 52.2 percent of thinning scenarios within the CARB scenario stored less carbon than the baseline. However, 65.5 percent of grow-only treatment scenarios that had a CARB baseline stored more carbon per acre relative to the baseline while only 34.6 percent of grow-only treatments with a BAU baseline did.

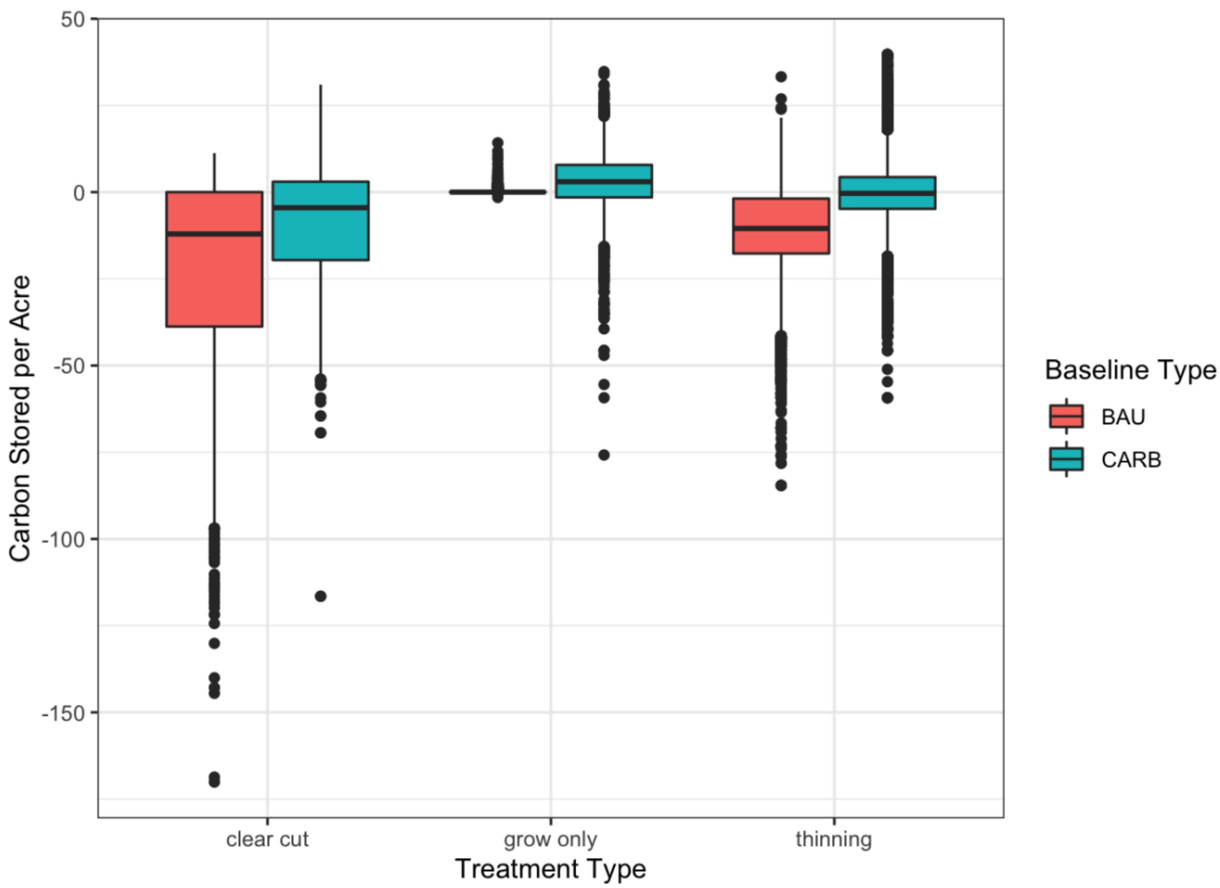

Figure 9. Carbon stored (tons/acre) for each treatment type compared between CARB and BAU baselines. Boxes indicate interquartile range (IQR); solid horizontal line is median carbon storage; whiskers extend to last observation within 1.5 times the IQR.

Treatments

Including grow-only

One treatment was then chosen for each plot that had positive carbon storage using the treatment selection methodology. Treatments primarily differ in regards to four key components: 1) their entry criteria (i.e the basal area at which a treatment is applied), 2) the treatment type (thinning, clear-cut, grow-only), 3) the maximum and minimum tree size to be cut, and 4) the post management fuels treatment type (prescribed burn, mastication, lop-and-scatter, and pile burn) (Table 1).

Based on our treatment selection, 701 plots matched our criteria (see Methods "Treatment Selection" for criteria specification) for the simplified CARB baseline and 466 plots matched our criteria for the BAU baseline. Using the BAU baseline, the grow-only scenario (Treatment #31) was most frequently selected for the highest cost to carbon ratio (Figure 11). Most of the other treatments selected were thinning treatments with the exception of a clear-cut with lop-and-scatter scenario (Treatment #33) occurring 5th most frequently of over 30 treatment types. Similarly, when a CARB baseline was used, a grow-only scenario (Treatment #31) was also most frequently selected. However, a clear-cut treatment with pile burns (Treatment #32) was the fourth most chosen and was selected more frequently than clear-cutting under the BAU baseline scenario.

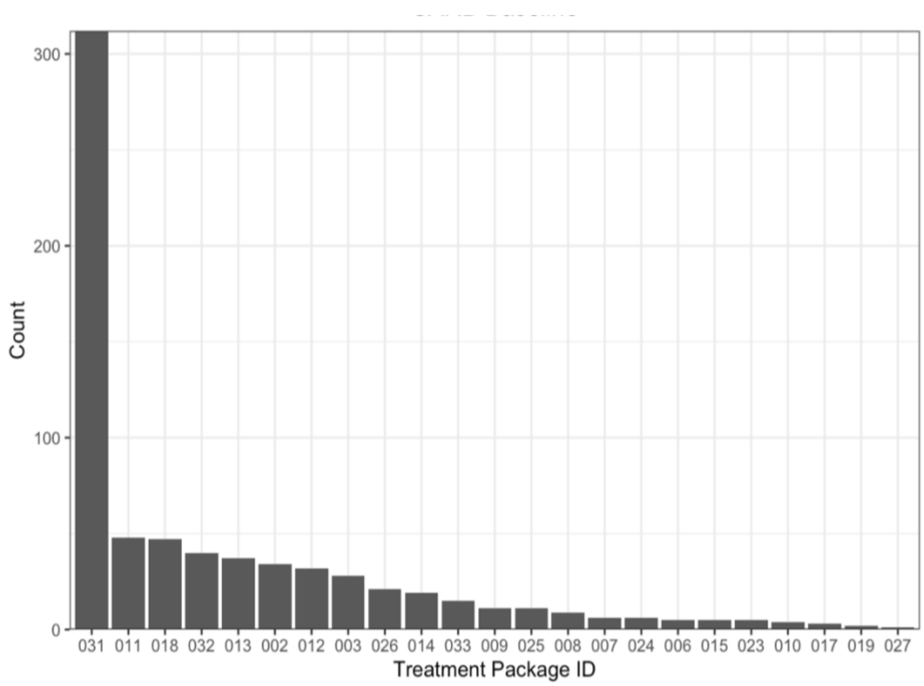

Figure 10. Frequency of treatments chosen as having the highest cost to carbon ratio ($/ton) relative to the CARB baseline.

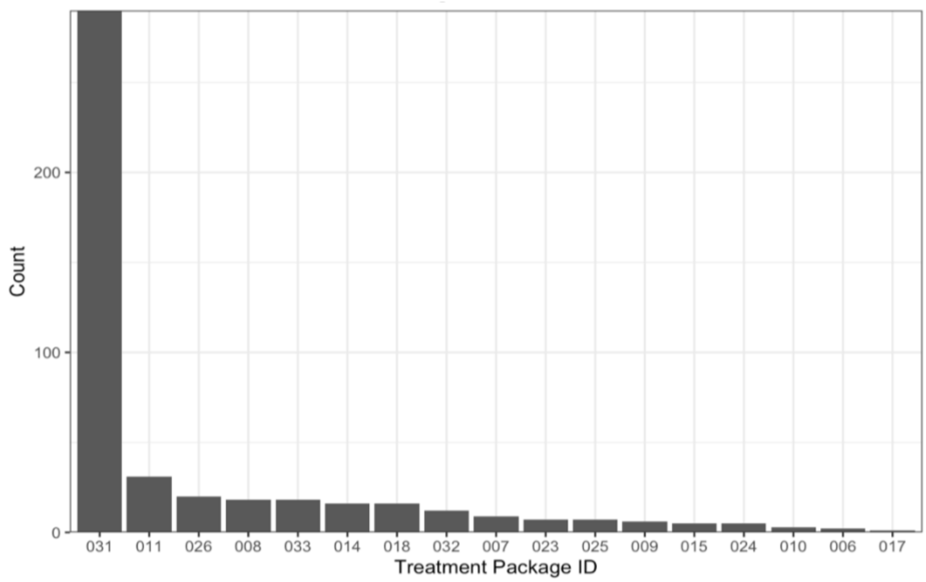

Figure 11. Frequency of treatments chosen as having the highest cost to carbon ratio ($/ton) under the BAU baseline.

Excluding grow-only

However, because of the State's interest in actively managing much of its forested lands, we are interested in which treatments are selected when grow-only scenarios are excluded. When the plots were optimized without grow-only, 108 plots were chosen under the BAU baseline scenario and 446 plots matched our criteria under a simplified CARB baseline scenario.

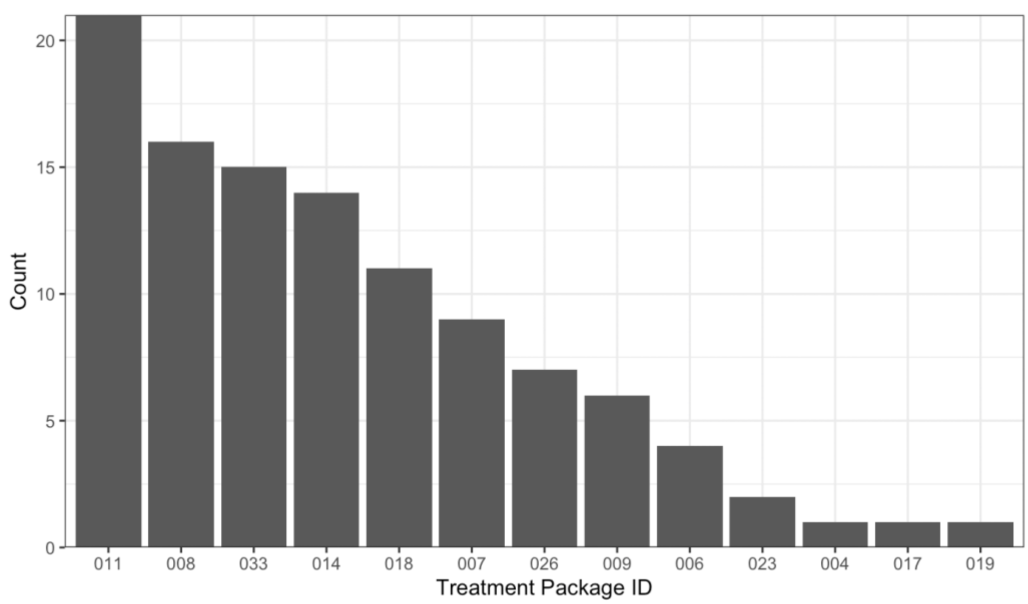

Figure 12. Frequency of treatment packages chosen as having the highest cost to carbon ratio under a BAU baseline, excluding grow-only as a treatment option.

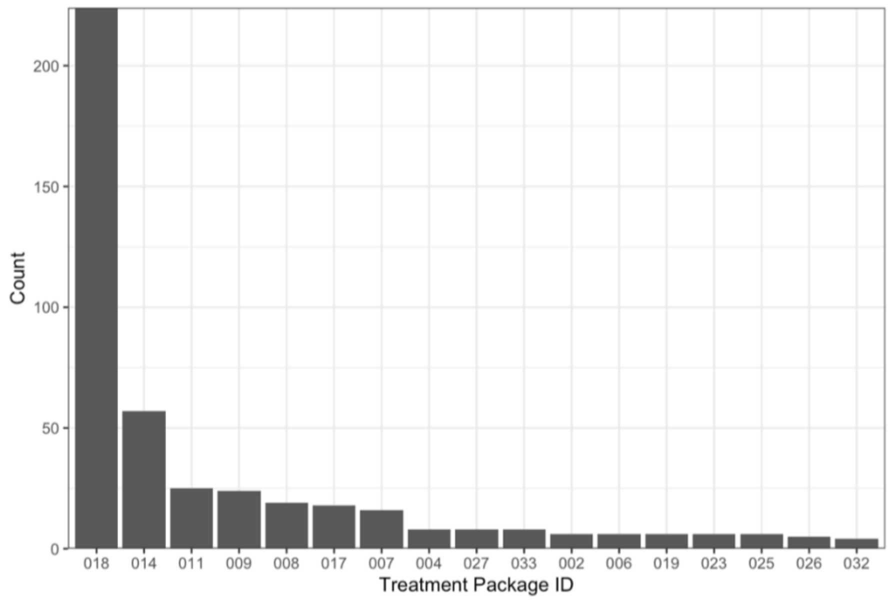

Figure 13. Frequency of treatment packages chosen as having the highest cost to carbon ratio relative to a CARB baseline, excluding grow-only as a treatment option.

The most commonly chosen treatment under a BAU baseline excluding grow-only scenarios was Treatment #11 followed by #8 and Treatment #18 followed by #14 under a simplified CARB baseline (Figures 12 and 13). Interestingly, Treatments #11 and #18 comprise the treatments that fall into the most conservative entry criteria class for all thinning treatments (basal area ≥180). This is perhaps not surprising as these treatments are the closest that our treatments come to "grow-only" and have the highest basal area entry criteria of all treatments. Treatment #14, however, has the lowest basal area entry criteria (basal area >115). Additionally, clear-cut scenarios (Treatments #32 and 33) were chosen third most frequently for the BAU baseline.

A majority of the plots selected with positive carbon storage but not grow-only scenarios are federally owned (Figure 14). In the BAU baseline scenario, six plots were privately owned and no plots selected under the CARB baseline were privately owned.

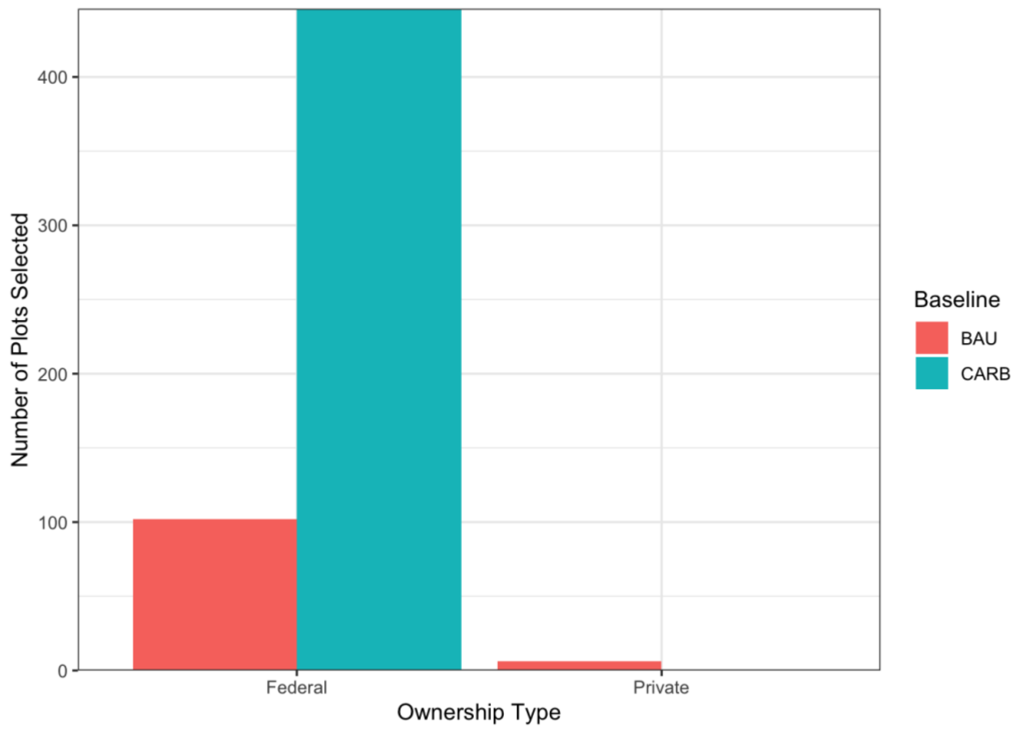

Figure 14. Number of plots in each ownership category under the BAU and CARB baselines.

Costs distribution

Costs per ton of carbon were sometimes $100 per ton less than under a BAU baseline when only plots that had positive carbon storage and were not treated with grow-only were selected (108 plots) (Figure 15). As the cost of treatment was not relative to a CARB baseline cost, all costs per ton of carbon are not relative to the baseline and thus were all positive. Most of the plots selected were located in the Northern Interior, Modoc Plateau, and Sierra Regions, while no plots were selected along the coast (Figure 15). There was no clear trend in the distribution of costs across the State.

a) BAU baseline **b)** CARB baseline

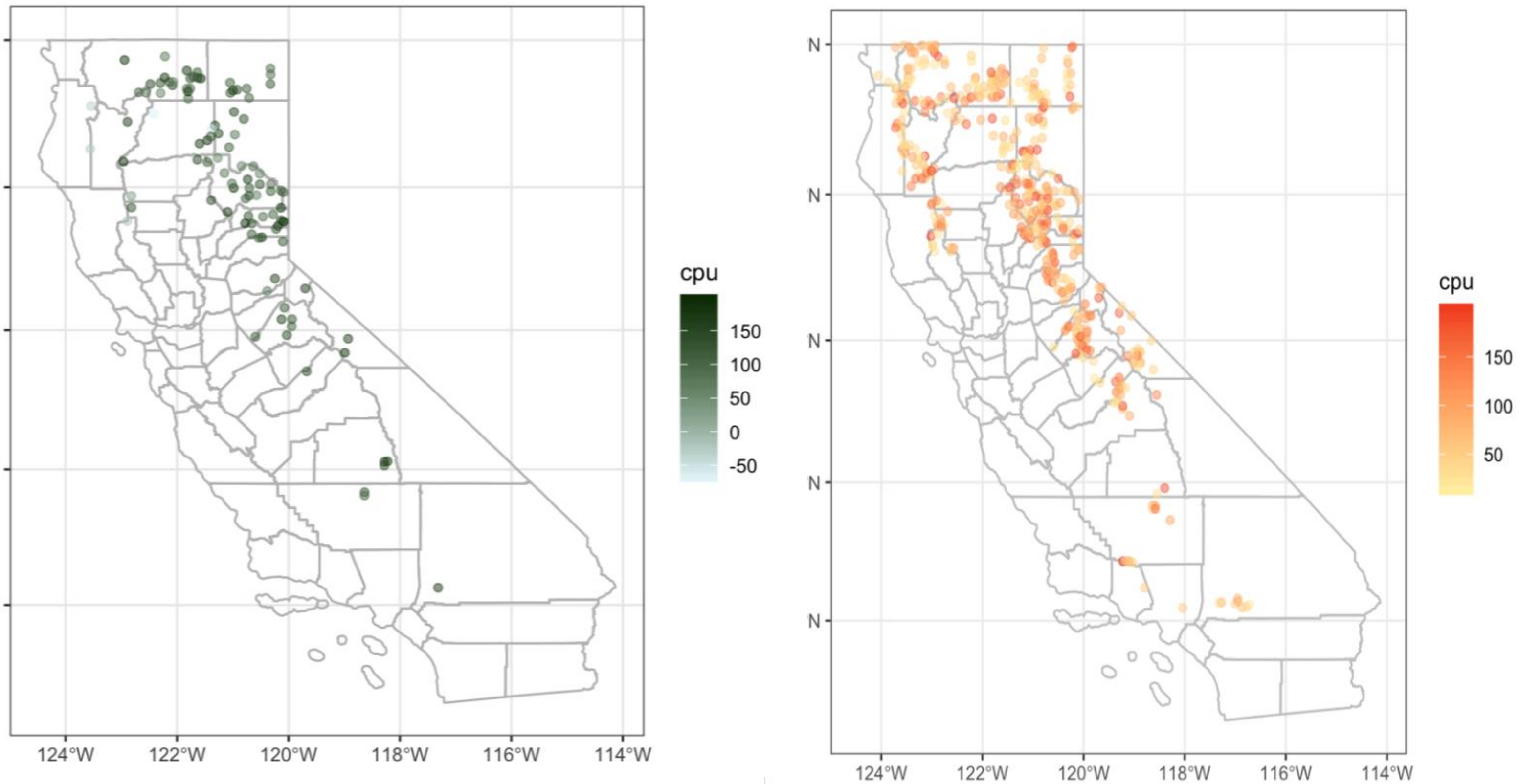

Figure 15. Average cost per ton of carbon (cpu) for each plot under the BAU (a) and CARB (b) baselines. CPU for the BAU baseline scenario includes costs that are relative to a baseline cost while the CPU for CARB baseline includes absolute costs.

Carbon distribution

On average, in every county and for both the CARB and BAU baseline, most carbon per acre is stored in the remaining biomass in the forest after treatment (Figure 16). However, when treatments had a CARB baseline, relatively more carbon on average was stored in chips and merchantable wood than when treatments had a BAU baseline.

a) BAU baseline **b)** CARB baseline

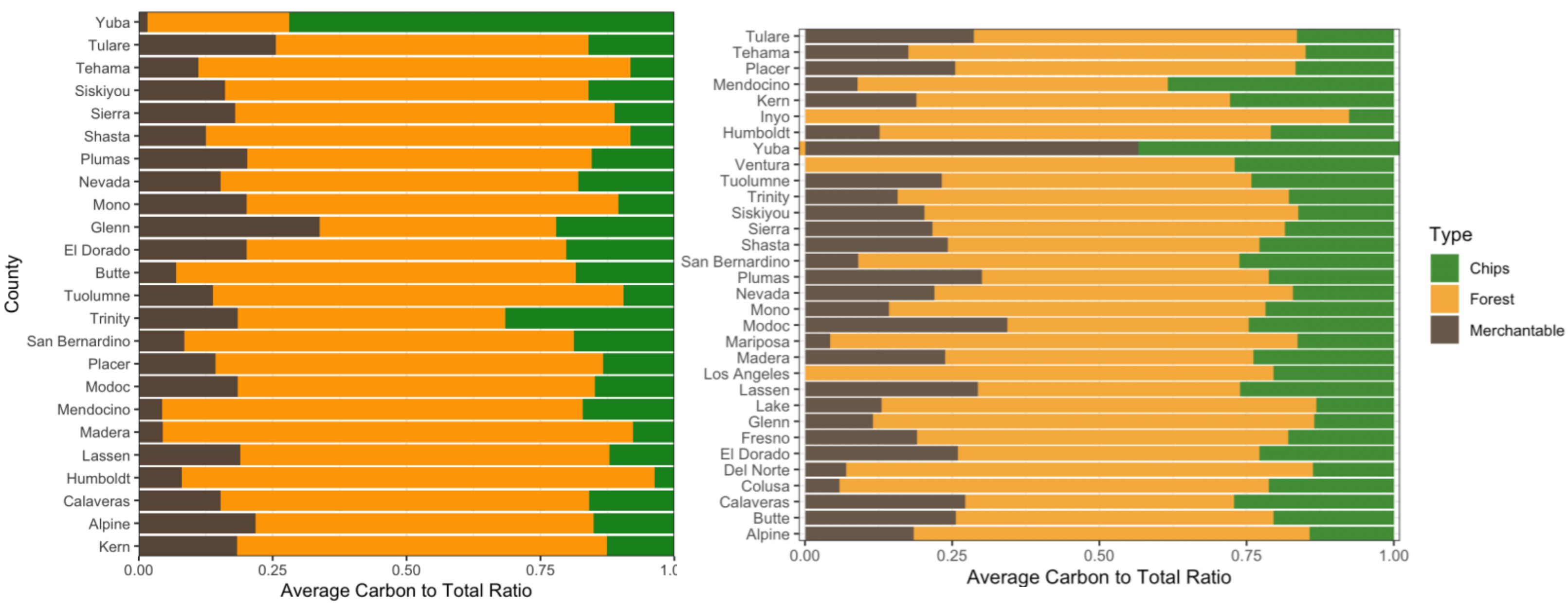

Figure 16. Average ratio of each type of carbon storage (carbon stored in chips, in merchantable wood and in the forest stand) for each county in California that contained optimized forest plots without grow-only treatments relative to the BAU (a) and CARB (b) baselines.

Marginal Cost Curve

The marginal cost curve was very sensitive to the type of baseline method used (Figure 17). A BAU baseline yields much more expensive forest carbon storage than under a CARB baseline. Under a CARB baseline, California's forests can sequester up to nearly 17.5 million tons of carbon for under $200/ton of carbon. In contrast, using a BAU baseline, it is only possible to sequester up to one million tons of carbon for under $200/ton. At the current price of $15/ton of carbon under the California cap-and-trade program, relative to the BAU baseline the modeled treatment scenarios can abate approximately 0.42 million tons of carbon at a cost of approximately five million dollars.

The marginal cost curve is also very sensitive to whether we include grow-only scenarios in our optimization (Figures 17 & 18). If grow-only scenarios are included, then under the CARB baseline scenario the State could potentially store 17.2 million tons of carbon for a total cost of about $300,000 at the current price of carbon in the cap-and-trade program. This is because the selected grow-only treatments have no cost (as shown by the long flat line in Figure 17) and only a few plots were selected as having a cost below $15/ton, hence, the low cost for the relatively high amount of carbon stored. Comparatively, when grow-only scenarios are not included, only 0.42 million tons of carbon are stored at a cost of approximately five million dollars.

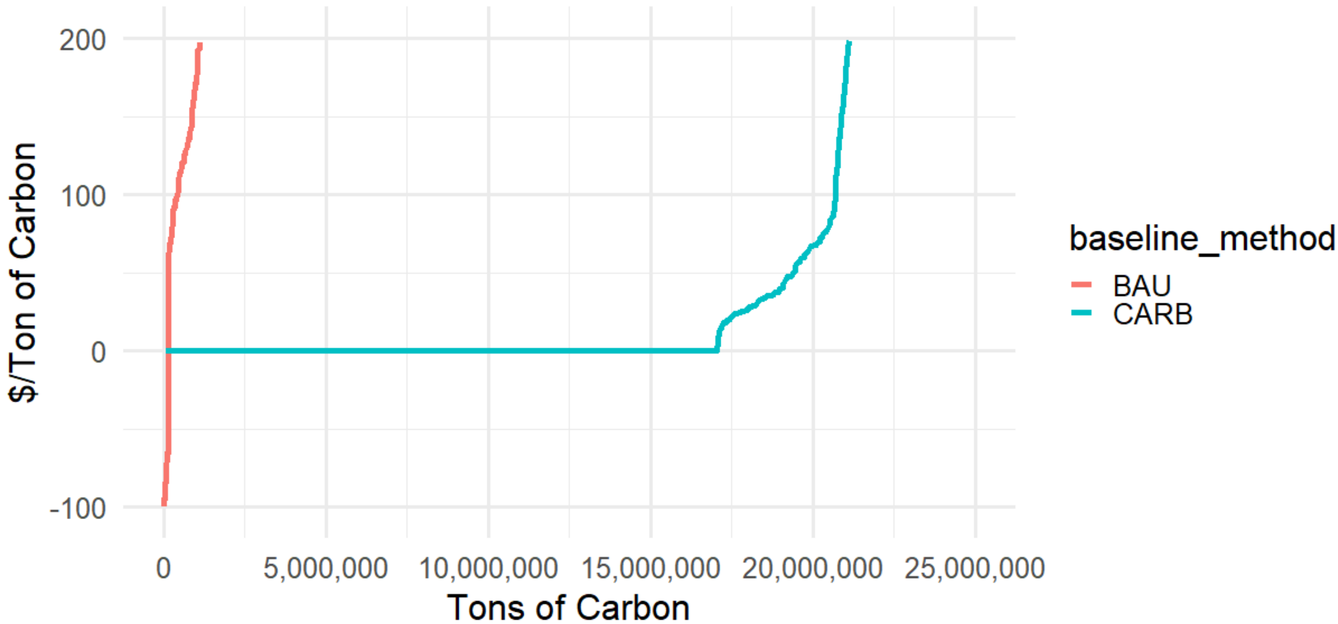

Figure 17. Marginal cost curve of chosen plots relative to a BAU and CARB baseline with grow-only included.

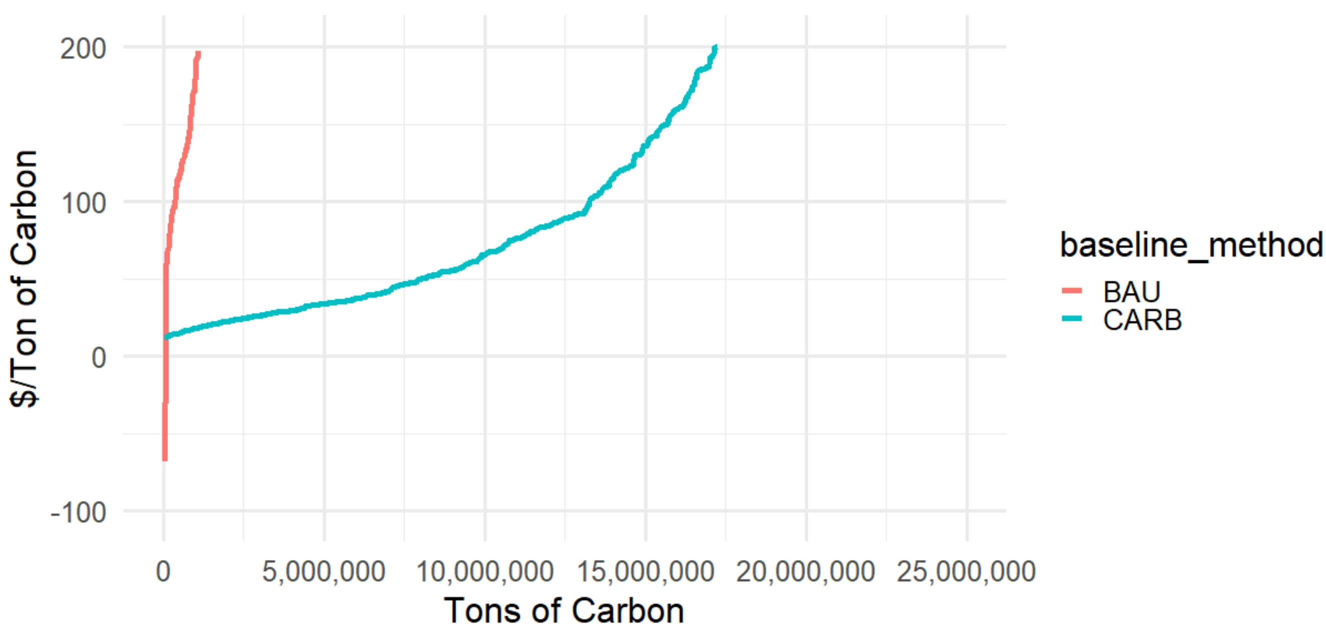

Figure 18. Marginal cost curve of chosen plots relative to a BAU and CARB baseline excluding grow-only.

Sensitivity Analysis

A key area of uncertainty is the effect of discounting costs and carbon flows on our results. Interestingly, when varying the discount rate, we see that with a lower rate, less plots are chosen as meeting our selection criteria. The magnitude of this effect is particularly apparent with plot selection under the CARB baseline. This makes sense because as we discount less, we increase the baseline carbon. The effect on the treatments is not as strong because of the negative carbon flows due to wood product decay. Thus, the net effect of these two interactions is that the baseline (which is flat in the CARB baseline and mostly grow-only in the BAU baseline) has a relatively higher benefit as a result of the reduced discount rate.

Discussion

Major Findings and Trends

Baseline matters for carbon storage

As shown in our MCC, (Figure 18) for the scenarios relative to the BAU baseline excluding grow-only scenarios, for the majority of forested plots in California, actively managing with thinning treatments results in less overall carbon storage than the BAU baseline. Additionally, the forested plots that would increase carbon storage following thinning treatments would do so at a relatively high cost per ton of carbon storage. However, our CARB scenario results indicate that much more carbon would be stored in California's forests following the implementation of cost-effective, carbon increasing treatments compared to the Common Practice management that defines the baseline. The difference in carbon storage between our BAU and CARB scenarios show the baseline the State chooses to utilize is very important in terms of accounting for how much additional carbon the State's forests will store following a treatment.

Timeframe of our analysis may have impacted forest regrowth results

Our results seemingly contradict a wide body of research indicating that, generally, thinning unmanaged forests increases the growth rate of trees in forests due to a reduction in competition. However, this increased growth rate is highly dependent on the degree of thinning (e.g. heavy vs. light thinning) and the ecosystem type where the treatment is applied (Zhou et al., 2013). For example, in the yellow-pine and mixed coniferous forests in the Sierra Nevada range, forest regrowth is relatively slow following a fuels treatment (Winford et al., 2015). This increased growth rate (along with the assumption that a large percentage of carbon removed from the forest and manufactured into wood products would decay at a relatively slow rate) should then allow forests to recover the carbon lost from the thinning treatment in the forest stands, and result in an overall net increase in carbon storage (Zhou et al., 2013).

One explanation for our results differing from this projected outcome is that our analysis used a relatively short time frame. The 32-year time frame used (treatments applied based on minimum basal area requirements every 10 years for previously untreated plots and 20 years for previously treated plots) may have been too short to allow the recovery of forest stand carbon. On the other hand, a longer study period would discount future carbon more, which reduces its addition to total carbon storage.

Geographic location influences treatment type

As shown in Figures 12 and 13, for both the BAU baseline and the CARB baseline, different treatments are selected for cost-effective carbon storage across forested plots in California. This is likely due to the fact that 1) Forested plots throughout the State have different ecosystem types that will store varying amounts of carbon depending on the treatment type implemented; 2) Forested plots are in different geographic regions where costs for treatment types can vary based on topography as well as the location of the nearest processing facility.

Additionally, for both baselines, certain treatments were selected much more frequently than others. Treatment #11, a thinning treatment that requires the highest relative initial stand density with surface fuels lopped and scattered, was selected on more than 40 plots under the BAU baseline. Under the CARB baseline, Treatment #18 was selected on more than 200 plots. Treatment #18 is almost exactly the same thinning treatment as Treatment #11, with the notable difference that only Treatment #18 calls for 20 percent of the initial basal area of the forested stand to be thinned as compared to 33 percent thinning under Treatment #11 (and all other thinning treatments). The frequency of these specific treatments suggests that certain geographic regions (e.g. Sierra Nevada range) are overstocked and qualify for similar treatment across many different forested plots for cost-effective carbon storage.

Federal lands may be most cost-effective for carbon storage

Our results show that in almost all instances under both the BAU and CARB baselines, federal plots are almost exclusively chosen for cost-effective treatment over private lands—suggesting that federal lands are more cost-effective for carbon storage as compared to private lands. This is an important finding, given that the State owns less than half of forested land in California yet has goals to increase the pace and scale of forest management in the coming years. Federal forests may be more cost-effective for treatment because they are generally overstocked and arguably less productive than private forests following nearly a century of fire suppression and less intensive management (Forest Climate Action Team, 2018).

Distribution of carbon storage

In both the CARB and BAU baseline scenarios, the most carbon stored per acre on average was in forest biomass. However, treatments with a CARB baseline on average stored more carbon in chips and merchantable wood than treatments with a BAU baseline. The reason for this finding is not yet fully clear: Given that grow-only is, generally speaking, the best carbon focused management, one would expect that treatments that lead to more in-stand carbon storage would most often be chosen regardless of baseline.

Forest management as a carbon abatement strategy is costly and may not contribute considerably to carbon neutrality

Both marginal cost curves for forest management in California are sensitive to the baseline (Figures 17 and 18). Under the BAU baseline, only 1 million tons of carbon would be stored at a price of $200 per ton of carbon. Comparatively, approximately 17.5 million MT of carbon would be stored at a price of $200 per ton of carbon under the modeled CARB baseline scenario, reflecting the important implications of the assumed baseline management scenario.

However, in light of the planned expansion of forest management across California, the State will also need to determine whether it will allow grow-only to be implemented as a treatment on some forested lands. This is an important consideration because under the CARB baseline, if grow-only as a treatment option is permitted, the State could increase carbon storage by 22 million MT of carbon. Comparatively, if grow-only is *excluded* from the CARB baseline, only 17.5 million MT of carbon could be stored (Figure 17 & 18). Therefore, by including grow-only as a management option, the State can sequester substantial additional carbon at no cost (since grow-only requires no intervention and for some forested plots is the optimal treatment). In light of State forest management goals, we suggest that grow-only as a management option be targeted to certain plots but not be the predominant management option.

Overall, our MCC suggests that forest management contributes a relatively small amount of carbon storage and is a fairly expensive method to achieve carbon neutrality. It can be helpful to examine these costs within the current CARB forest offset program using the price of $15/ton of carbon offset. Under the modeled CARB baseline scenario including grow-only treatments, only 17.2 million tons of carbon could be stored cumulatively across 30 years at a net present cost of $300,000. Comparatively, when grow-only is excluded as a treatment option, only 0.42 million tons of carbon can be stored for approximately five million dollars at $15/ton of carbon ($15 is approximately the price of a forest offset under Cap-and-Trade). This is much more expensive and falls considerably short of the State's recent estimate of forest management contributing 15.5 million tons of negative emissions *per year* by 2045 (Baker et al., 2019). Although it remains to be seen what the abatement costs for other sectors of the economy look like, our results suggest that forest management will play a smaller role in achieving carbon neutrality.

Limitations of analysis could change long-term forest carbon outputs

Although our analysis simulated cost-effective thinning treatments for carbon storage on the majority of forested plots in California, our results do not include any landscape-scale effects of these treatments. Our results, therefore, only include "project-level" carbon effects of thinning treatments. In reality, if California's forests were to be thinned at a landscape-scale, overall forest health (and therefore the stability of sequestered carbon) may increase, and wildfire severity and resulting carbon emissions may decrease (Forest Climate Action Team, 2018).

Forest health is defined to mean that the "composition, structure, and function [of the forest ecosystem] are within the range of conditions expected under natural disturbance regimes." Because of our long history of mismanagement, and our need to actively manage the forest for both economic and human safety reasons, restoring natural processes to the forest requires active management. By increasing forest health through management interventions, forest resilience is also increased. Forest resilience is the capacity of a forest ecosystem to return to a pre-perturbation state, including perturbations such as climate change, wildfire events, drought and disease. Of the perturbations that affect forests in California, wildfire results in the largest amount of carbon emissions. In general, forest management that reduces the amount of fuel on forested land reduces the severity of a potential wildfire and the resulting emissions (Forest Climate Action Team, 2018).

Our analysis did not include a reduction in wildfire emissions from thinning treatments because of the difficulty in quantifying avoided wildfire emissions, both at the project-level and landscape scale. Therefore, our analysis did not include a metric for emissions that would be avoided compared to the BAU baseline. Assuming that 1) these reductions in fire severity equate to reduced emissions, and 2) these avoided emissions could be quantified and included in our analysis, it is possible that thinning treatments could be cost-effectively applied on additional plots and reduce the cost of treatments on existing plots.

Additionally, thinning has been shown to increase forest carbon stability under future climate change scenarios. As discussed in the Background, a recent study focusing on the Sierra Nevada has shown that landscape-scale restoration and thinning operations can result in increasing forest carbon stability under future climate change scenarios (Liang et al., 2018). All of these landscape-scale forest carbon benefits, in addition to the carbon substitution benefits of wood products produced from thinning projects, are not quantified in our analysis. Therefore, our results may understate the cost-effective opportunities for carbon storage relative to the BAU baseline.

Policy Implications

California has committed to actively managing its 33 million acres of forest land for multiple purposes, including forest health, wildfire, biodiversity, meadow habitat, and sustainable timber harvest (Forest Carbon Action Team, 2018). Many of these commitments have a 2030 target date for full implementation and are outlined in the 2018 California Forest Carbon Plan. In terms of forest management practices related to this analysis, the plan commits the State to increase the rate of non-restoration treatments on private lands to approximately 500,000 acres per year, and suggests that treatments be applied to federal forests at a similar rate of 500,000 acres per year (Forest Carbon Action Team, 2018). Recognizing that forest management in California is occurring and is set to expand in the near future, it is important to identify and evaluate forestry policies that could motivate cost-effective forest management for increased carbon storage.

Forest policy should be motivated by co-benefits in addition to carbon sequestration

Because forests play a critical role in the carbon cycle, policymakers are keen to understand their potential contribution among a variety of sectors in order to design cost-effective climate policy. However, it is unclear if in California, managing forests for carbon sequestration goals alone makes for cost-effective policy, or if perhaps policy should be designed to incorporate the co-benefits of thinning treatments.

Although our analysis is limited by not quantifying and incorporating avoided fire emissions, the literature broadly supports the assumption that thinning practices can lead to general improvements for a variety of co-benefits. For example, multiple studies have shown that thinning supports avoided fire emissions (Liang et al., 2018), improved air quality from reduced wildfires (Bales et al. 2011; Collins et al. 2014), and increased water yields (Podalak et al., 2015). This suggests that the carbon optimal treatments in our analysis may support these other services, however our analysis does not quantify these relationships.

As is, our results suggest that forest policy motivated by carbon goals alone may not be cost-effective as compared to other sectors, although the marginal cost curves for other sectors of the economy remain unknown. Our results, even under a CARB baseline, suggest low cost-effectiveness: California's forests could sequester roughly 17.5 million tons of carbon for under $200/ton of carbon. In contrast, under a BAU baseline, it is only possible to sequester up to 1 million tons of carbon for less than $200 per ton (Figure 18). In either scenario, not only is little carbon stored, but $200 per ton is extremely expensive as compared to the current price of auction permits (about $18 per ton) and forest offsets (about $15 per ton) under California's cap-and-trade market.

Although forest management for carbon storage under the CARB baseline is somewhat more cost-effective (less than $50 per ton) in certain geographic locations in the State, these plots are limited (n=168). Additionally, our results suggest that land ownership is important to address in statewide forest policy. The high number of federal plots selected as cost-effective in our analysis highlights the conundrum facing the State: it is largely unable to directly influence forest management on lands that may best support cost-effective carbon storage, though these areas may help most to reach carbon neutrality. However, though private plots are not generally selected for cost-effective carbon storage in our model, forest management continues to be planned and performed for other reasons, including wildfire. This suggests that policy for private forests remains relevant and motivation may need to include co-benefits of management in addition to carbon storage. If co-benefits were included in our model, the carbon benefits of forest management could be greater for both federal and private plots and could support policy cost-effectiveness.

To complement our analysis, we examined the existing policy landscape in California to determine if policies exist to incentivize forest management for co-benefits beyond carbon sequestration. Our research process involved a literature review of existing and past forest policies (see Appendix Table A-1). In addition, we consulted with more than a dozen experts in forestry, carbon sequestration, and wood products industries across government, business, and the non-profit sectors.

Co-benefit approach could be modeled on existing policies

It can be useful to examine existing voluntary conservation programs in the U.S. to guide our thinking about a state program that could similarly incentivize private landowners to engage in forest treatments for carbon storage and other co-benefits.

Cost-share programs for forest health, such as the Environmental Quality Incentives Program (EQIP), are one promising pathway to incentivize this type of management for private landowners. EQIP is a national, voluntary program under the Natural Resources Conservation Service (NRCS) that offers technical and financial support to private landowners to implement improved soil, agriculture, and forest management practices on marginal private land. Landowners consult with NRCS and submit a management plan detailing the accepted management practices that they will implement. If approved, the maximum length of the contract between NRCS and the landowner is 10 years (NRCS, n.d). Payments of up to 50% of the cost of implementation is paid to the landowner (NRCS, n.d.).

Multiple forestry practices that align with the treatments examined in this analysis are covered under EQIP (excluding clear-cutting). “Forest Stand Improvement” is the main treatment under EQIP similar to the thinning treatments examined here. In addition, “Woody Biomass Treatment” and “Prescribed Burns” would be applicable to the post-harvest component of the treatment packages in our analysis (NRCS, Code 666, 2020).

Once found eligible, NRCS has a one-on-one consultation with the landowner to evaluate parcels for their potential environmental benefits. NRCS then offers landowners a list of suggested treatments to meet EQIP’s conservation goals. Landowners submit a plan detailing which treatments they want to apply (how much they are willing to pay under cost-share), and applications are then evaluated and ranked according to environmental benefits and cost-effectiveness under NRCS's national, state, or local program initiatives (NRCS, n.d.)

Limitations and Potential Application in California

The major drawback of a 50 percent cost-share program is that it does not capture the entire costs of forest management in California, such that there is likely insufficient incentive to participate or participants may drop out. Because the cost-share is generally only up to 50% of the approved treatments(s), there is likely not enough incentive to participate in the program as compared to a subsidy program that would cover costs in full. However, some treatments do provide private benefits to the participating landowner which could help to make the cost-share more appealing. For example, a cost-share to help cover the cost of a forest management plan also allows the landowner to comply with state forestry laws, suggesting greater economic benefit than paid for. Under the 2018 Farm Bill, the federal government now allows states to designate up to 10 priority treatments under EQIP that are eligible for 90 percent cost-share (Newton, 2019). This exception could be an opportunity for California to designate forest health treatments as used in our analysis as "priority treatments," which would cover a greater portion of costs to landowners and also align with the State's forest management goals. In theory, if treatments selected as "priorities" aligned with those identified as conducive to carbon storage in our analysis, the pace and scale of forest management for carbon storage could increase.

California, however, could develop a new cost-share program with greater incentives through bidding for environmental benefits such as carbon sequestration and other thinning co-benefits. By developing a cost-share program designed to promote carbon and co-benefits of management rather than practices that are designed for one benefit, the incentives to landowners to participate may be greater than those offered currently through EQIP.

CRP

The Conservation Reserve Program (CRP) is another voluntary federal conservation program that provides a useful framework for policymakers in California to incentivize forest management for carbon and co-benefits. Although the CRP was originally designed to improve marginal agriculture lands, it has evolved to support other important environmental benefits and offers a structure that may be relevant for motivating forest management and its co-benefits.

Overview of Existing CRP

The CRP is a voluntary agriculture-oriented program implemented by the Farm Service Agency (FSA) to improve and protect the productivity of private agricultural land for long-term food security (FSA, 2019). The program is based on 10-15 year contracts between FSA and landowners to take marginal agricultural land out of production and instead implement a variety of best management practices for soil health (FSA, 2019). Landowners consult with FSA and submit applications outlining the management practice(s) they are willing to implement.

There are two major benefits to the CRP program for landowners: rental payments and a cost-share program (FSA, 2019). Generally, rental payments are paid to the landowner by FSA to take the land out of production. In addition, cost-share benefits include up to 50% of the costs of implementing the best management practices listed in the contract. Enrollment into the program is open once per year. However, there is also year-round, continuous enrollment for “environmentally sensitive” lands as determined by NRCS (FSA, 2019). Qualifying landowners receive higher rental payments, sign-up bonuses, and exemption from the competitive bidding process.

FSA works with landowners to evaluate each parcel and determine its environmental benefits score using the Environmental Benefit Index (EBI). The EBI is a ranking system that scores each parcel’s “relative environmental benefits for the land offered” according to various environmental factors, many of which are ecosystem services or co-benefits of improved management (FSA, 2019). Example factors include wildlife habitat, groundwater quality, wind erosion benefits, carbon sequestration, and cost, among others (FSA, 2019).
Due to budgetary constraints, not all eligible land qualifies for enrollment, and FSA administers a competitive bidding process. After EBI scores are calculated, landowners submit bids and have the option of bidding less (“bidding for cost”) for their annual rental payment to increase their chance of acceptance (FSA, 2019). Although this style of bidding was designed for cost-effectiveness (Johansson, 2006), the program does not minimize costs of achieving a given environmental outcome (Miao et al., 2016, Crampton et al., 2018).

CRP Application to Private Forest Management in California
A program similar to the CRP could be considered for forest management on private land in California. This voluntary program could be modeled on the CRP but would be statewide in scope and target forest land for cost-effective carbon storage according to our analysis. Again, although private plots are not generally selected for cost-effective carbon storage in our model, forest management is planned to expand on private land, suggesting that policy could be motivated by co-benefits in addition to carbon storage to promote cost-effectiveness. We therefore outline such a program, hereafter called “Conservation Forestry Program (CFP)” that the State could consider.

The goal of this program would be to incentivize private landowners to implement the cost-effective forest management treatments identified under our CARB baseline scenario to support statewide carbon neutrality. This means that the policy would only include parcels with positive carbon storage but would also account for co-benefits of management (i.e. avoided fire emissions) especially in cases where cost per unit of carbon is high. The program would require landowners to submit bids to an implementing state agency to conduct approved forest management treatments for carbon and other co-benefits on their land. Contract length is undetermined; however, in the interim contracts are proposed to extend to mid-century to align with the statewide carbon neutrality goal.

Similar to the CRP, there could also be two enrollment options: 1) Interested landowners could apply and submit bids once a year; 2) Similar to the CRP, one could also imagine a year-round continuous enrollment to align with statewide ecological priorities. For example, California could offer continuous enrollment to landowners located in “High Hazard Zones” as designated by the State.

Contracts would be developed after technical consultations between the implementing State agency and the landowner to discuss which of the top treatments would be most suitable to implement. These treatments would come directly from our analysis using the simplified CARB baseline and would represent the most cost-effective methods for sequestering carbon in the county in which the landowner lives. The implementing agency could also look to our tool for a ballpark estimate of how much funding to request per county from the legislature based on the amount of carbon they aim to store in forests. However, it is important to note that in its current state, our model is limited because it does not account for wildfire emissions or other thinning co-benefits.

The major benefit, however, to landowners of a CFP would be an annual rental payment to implement cost-effective forest management treatments for carbon sequestration and other co-benefits. Payments would be partially based on our MCC results (cost in dollars per ton of carbon) identified under the CARB baseline, for the county in which the parcel is located. Unlike the CRP, cost-share benefits could be folded into this price since our analysis includes implementation costs.

Each parcel of land could be evaluated and ranked according to a modified EBI score based on the quantification of ecosystem services or co-benefits of management on the particular parcel. Although our MCC informs us roughly at what prices to set rental payments, the program may be made more cost-effective through an auction due to the heterogeneity in landowner costs and asymmetric information among forest landowners (Plantinga, 2020). Landowners could bid less to increase their chance of acceptance, although program design should support "bidding for environmental benefits" as well as cost to support cost-effectiveness as in the CRP (Johansson, 2006). This means that landowners focus both on maximizing their EBI score for thinning co-benefits and bidding lower than NRCS rates if possible to increase their chance of acceptance.

CFP Application to Federal Forest Management

The CFP is designed for private lands, but such a program could be modified to address federal forest management. Because the federal government owns 57 percent of forest land in California, the State has a vested interest in federal forest management: Federal lands borders state, local, and private lands. The State also recognizes that timber harvests and wildfires on federal lands can have critical carbon implications for California's climate policy goals. These carbon implications are important at the State level because under AB 1504, California includes federal forests in its carbon accounting. With respect to this analysis, federal forest policy is also important to consider because almost all plots chosen for cost-effective treatment under both baseline scenarios are on federal lands, even when the grow-only treatment option is excluded.

Due to the different stakeholders, laws, and regulations involved in federal forest management, a separate program or fund may be developed for coordination between the state and federal governments for federal forest projects. A program similar to the CFP could apply, but likely without the competitive bidding process, unless the State contracts the work to a third party to generate bids. This is recently permissible through Good Neighbor Authority (GNA) under the 2018 Farm Bill but remains to be seen if it will be a widespread practice (USFS, 2015).

To facilitate this collaborative process between the two entities, several implementing mechanisms currently exist. One notable mechanism is GNA. GNA allows state forestry agencies to partner with USFS to share the costs and labor of implementing forest management treatments (such as those used in our analysis) on federal land, with costs reimbursed through timber sales (USFS Pacific Southwest Region, 2017). Importantly, sharing costs and coordinating labor across agencies can help to increase the pace and scale of forest management as desired by the State (USFS Pacific Southwest Region, 2017). Our MCC results under the modified CARB baseline could roughly inform the State how much to pay (in dollars per ton of carbon) for particular treatments to promote cost-effectiveness. Should the State decide to partner with the federal government to implement cost-effective carbon projects such as those in our model, GNA could act as the legal mechanism through which collaboration across these two ownership classes is possible.

Limitations of a Conservation Forestry Program

1. **Budget Constraints**

Naturally the State will face budget constraints such that not all forest land identified as cost-effective for carbon can be included in the program. With the CRP, there are caps on the total number of acres enrolled, or the total number of acres in any one county (Hellerstein, 2010). California might consider avoiding caps per county in high-hazard zones.

2. **Perceived Limited Profitability**

There will likely be doubts of the efficacy of such a program, considering that the land could be managed differently for timber harvest and potentially generate more revenues for the landowner. In the case of the CRP program, when agricultural commodity prices increased in 2007, many farmers dropped out of the program (Hellerstein, 2010). In the case of a forestry CFP, payments could change based on timber markets to prevent attrition.

3. **Timeline of the Program Related to Long-Term Efficacy**

The relatively short timeline of projects under such a program may reduce the long-term efficacy of the program, since longer timelines are typically needed for permanent carbon sequestration. If contracts only extend until mid-century, the State would need to evaluate how it could prevent landowners from turning to other types of management. At the same time, climate change is altering the fire regime in California, which already has been impacted by decades of fire suppression. Rental payments would need to be adjusted and treatments would need to be re-examined periodically to ensure that the cost-effective carbon storage is still being achieved.

4. **Data Collection**

Currently, our analysis is at a coarse scale (plots are roughly 5000 acres). This is a good starting point, however, for actual implementation a finer-scale model is needed. This is important because landowners in such a program could submit bids that are for smaller parcels. To best quantify the co-benefits of implementing these treatments, additional data may be required at the parcel level to inform the ranking system (Hellerstein, 2019).

State should consider a statewide forest carbon inventory instead of project-level accounting

Existing Forest Policy Framework (Project-Level)

The main existing mechanism within California used to incentivize forest carbon storage is the CARB Compliance Offset Program. This program allows entities to purchase GHG offset credits from offset projects in order to partially fulfill their GHG reduction requirements under California's Cap-and-Trade program. Currently, entities are able to meet eight percent of their compliance obligation through the purchase of offset credits. Starting in 2021 through 2025, entities will only be able to meet four percent of their compliance obligation through offset credits (CARB, 2020).

Of the different project types that provide offsets through the approved Offset Project Registry, U.S. forest offset projects are by far the largest issuers of offset credits. As of September 2019, they constituted approximately 84 percent of issued offset credits (approximately 117 million offset credits, which is equal to 117 million MT of CO_2) (CARB, 2020a). In order for a forest project to be eligible as an offset credit, the project must be in compliance with CARB's compliance offset protocol for forest projects. The protocol identifies four different forest project types that are eligible to attain offset credits: reforestation, improved forest management and avoided conversion of forested land to non-forested land. Improved forest management includes "activities that maintain or increase carbon stocks on forested land relative to baseline levels of carbon stocks," which includes forest thinning projects. Additionally, improved forest management projects can be implemented on private land or state and municipal public land (i.e., forest management projects implemented on federal land are not eligible for offset credit issuance) (CARB, 2014).

Policy Barriers Associated with Forest Offset Projects

Although the CARB Compliance Offset Program provides a mechanism to incentivize forest carbon storage, the cost of certifying and implementing a forest offset project may be too costly and time intensive for most eligible land managers and forest contractors to participate in. According to a Registered Professional Forester in California, the cost of developing a forest project within the offset program ranges between approximately $250,000 and $500,000 (Anonymous, 2020). Additionally, California projects compete with improved forest management projects in other states where the costs associated with certification and implementing the project can be considerably lower (CARB, 2020b). Lastly, these forest offset projects may not fully address issues of additionality (i.e., would a landowner/contractor complete a forest management treatment that increases carbon storage without any form of policy incentive) and leakage (decreased forest carbon elsewhere as a result of an offset project) (Plantinga and Richards, 2008).

Given these challenges with the current mechanism for accounting for large-scale forest carbon storage in California, a new mechanism in the State may be necessary. One approach (outlined below) would be to utilize a statewide inventory approach for forest carbon accounting in California.

Alternative Forest Policy Framework (Statewide Carbon Inventory Approach)

An alternative approach to the current project-by-project mechanism implemented under CARB would be to determine a baseline for the forest carbon stock in California, implement statewide policies that incentivize forest management practices that increase carbon storage, and then measure the forest carbon stock in California at a future date after these policies have been implemented. The difference in forest carbon (including carbon stored in wood products produced from wood harvested as part of the forest management practices) between the baseline and what is measured at the designated future time point would be the "additional" carbon California's forests have stored. This process could minimize implementation costs as forest management projects would not have to undergo as stringent a certification process as is the case with the existing CARB Compliance Offset Program. Although landowner and contractors would be required to show that their projects would increase long-term forest carbon storage, certification and verification would not be the dominant mechanism used to quantify a project's effect on forest carbon storage (Plantinga and Richards, 2008).

This State carbon inventory approach could solve the problem of additionality as by definition it involves measuring additional carbon from one time period to the next. The increase in carbon storage by each individual project becomes much less important to track and verify. This approach would solve the problem of measuring the permanence of carbon storage as any carbon released after the baseline measurement will be measured during a designated future inventory. Additionally, a statewide inventory approach would solve the problem of within-California leakage as all forest carbon fluxes within the State would be captured by the inventory (Plantinga and Richards, 2008).

Under AB 1504, California already completed a forest carbon inventory that could be used as a framework for this state carbon inventory approach. This inventory utilizes data from the FIA program to estimate carbon within California's forest lands. Carbon stored in harvested wood products is also included in the inventory. Carbon stocks identified in this inventory are a ten-year "rolling average" of carbon and not a yearly stock of carbon. Additionally, the forest carbon inventory completed under AB 1504 does not include emissions from wildfires - the largest source of carbon emissions from California forests. This existing mechanism for calculating a forest carbon inventory within California would provide a valuable starting point to transition to this new approach and determine the extent the State's forests will contribute to the carbon neutrality goal (Forest Climate Action Team, 2018).

Conclusion

Our results indicate that grow-only management scenarios generally store the most carbon and were most commonly chosen as cost-effective treatments for carbon storage under the BAU and CARB baselines. However, as California has chosen to actively manage its forests for reasons besides carbon storage, we removed grow-only scenarios from our analysis. Not surprisingly, the most commonly chosen treatments excluding grow-only were still those that had very little management. In this way, our findings still show that less management is often better for carbon storage. One potential caveat relates to the fact that in California, the typical time horizon for carbon storage projects is about 100 years. However, our analysis only spanned a 30-year time period and therefore does not account for how continued management over a longer time period may affect these carbon storage dynamics.

We analyzed and compared the impacts of different forest management treatments on cost-effective carbon storage under two distinctly different baseline scenarios. While it is true that grow-only treatments store more carbon compared to thinning or clear-cutting, the choice of baseline changes both how much additional carbon is stored as well as which treatments are chosen as ideal for carbon storage. Our results therefore demonstrate how sensitive any forest management metric, such as carbon stock, is to the baseline chosen for comparison. Thus, if the State uses a baseline that assumes more initial management, the amount of additional carbon sequestered could be much higher than if the State used a baseline that assumes minimal management.

This sensitivity to baseline selection leads us to propose a common statewide baseline for use in any landscape-scale carbon policy scenarios. This statewide baseline would allow for better tracking of carbon neutrality goals in the forest, as compared to project-level accounting, which may have different standards of baselines and is costly. We also propose incorporating the co-benefits of management into forest policy, such that forests are not only managed for carbon. More specifically, avoided fire emissions and improved air quality are also priorities that the State could consider alongside carbon storage when determining the most suitable forest management practices across the landscape. Including these goals may make more management economically viable. Finally, we highlight the need for updated FIA data as well as data on the carbon substitution benefits of wood products in future analysis. With this additional information, more complete forest carbon flows can be modeled, allowing California to design actionable and comprehensive carbon neutrality policy for forest management.

Limitations

1. **Data**
    a. This analysis utilizes outdated (2001-2010) FIA data, which may limit the accuracy of our results considering the 2012-2017 drought, numerous recent forest fires, and considerable insect infestations contributing to tree mortality. Current data with higher resolution over a longer period of time (i.e. at least 100 years) is ideal to ensure accurate calculations of the marginal cost of forest management.
2. **Inclusion of Avoided Fire Emissions**
    a. Our analysis does not include avoided fire emissions as a result of treatments applied to the landscape. This information is especially difficult to predict and interpret and is an ongoing area of research. However, it would be ideal to include because we believe some of the carbon benefits of thinning come later in the form of avoided fire emissions- by not including these, the entire picture of carbon is not fully present in this analysis.
3. **Uncertain BAU Scenario**
    a. Our business-as-usual scenario was a randomized simulation based on county-level harvest data. However ideally, we would want to know exactly what quantities were harvested and where. Additionally, we do not know where current forest management is taking place throughout the state. We therefore are not able to incorporate this into our baseline but feel that this is important to ensure accurate results.
4. **Incomplete Wood Products Carbon Life Cycle Assessment**
    a. Our analysis of post-harvest wood products assumes that merchantable wood is all softwood tree species and all wood chips produced from management remain wood chips (and naturally decay). Decay rates are included in our modeling; however, until the full lifecycle, specifically the carbon benefits of wood products substitution, is better understood and quantified, any model of forest carbon is incomplete.

Future Work

Our analysis represents a first step toward understanding the costs of forest management in California. Importantly, our analysis and results offer a solid base from which to expand and refine future work on managing forests for carbon sequestration. Suggested next steps include:

1. Replicate the analysis with updated FIA data
2. Quantify and incorporate avoided fire emissions into the model to more completely understand the carbon benefits of forest management
3. Incorporate complete life cycle analyses of wood products into the model, specifically the carbon benefits of wood products substitution, to more completely understand the carbon benefits of forest management

Appendix

Equation A-1. Formula used to calculate the change in carbon for each treatment on each site

$$\Delta C(total) = \left(\sum_{i=1}^{t} \frac{\Delta C_t(forest)}{(1+r)^t} + \sum_{i=1}^{t} \frac{\Delta C_t(harv) * decay_t}{(1+r)^t} - \sum_{i=1}^{t} \frac{\Delta e_t}{(1+r)^t} \right) - \sum_{i=1}^{t} Baseline_t \quad (1)$$

Table A-1. Stakeholders and organizations consulted about forest, climate, and wood products policy.

Name	**Organization/Affiliation**	**Name**	**Organization/Affiliation**
Bob Hambrect	Anderson Biomass Complex	Teal Zimring	Galvanize Partners
Jim Turner	American Renewable Power	Dr. Daniel Sanchez	Joint Institute of Wood Products Innovation (client)
Josiah Hunt	Pacific Biochar Plant Manager,)	Kristin York	Sierra Business Council (Head of Policy)
Matthew Taborski	Sierra Pacific Industries (Division Manager)	Eric Holst	Environmental Defense Fund (EDF)
Andrew Plantinga	UCSB	Bill Stewart	UC-Berkeley
Ricky Satomi	UC ANR	Ryan Tompkins	UC ANR
Katie Harrell	CalFire	Alex Yiu	CARB
Rachel Hedges	Berkeley Forests	Stephen Shelby	CARB

Table A-2. Pyrolysis Products Matrix. Source*:* Joint Institute of Wood Products Innovation, 2020.

Pyrolysis: non-energy products					
Product Classification: Pyrolysis-non-energy products	**Wood Vinegar (Pyro-ligneous Acid)**	**Carbon Black**	**Biochar**	**Activated Carbon**	**Carbon Black**
Representative feedstock required (BDT/year)	35,000 (Corigin LLC)	Unknown	150,000 (National Carbon Technologies)	150,000 (National Carbon Technologies)	Unknown
Carbon storage	No	Yes (product)	Yes (char)	Yes (char)	Yes (product)
Technology readiness	5	4-5	9	9	4-5
Commercial readiness	3	3	5	9	3
Feedstock use	Non-merchantable	Non-merchantable	Non-merchantable	Non-merchantable	Non-merchantable
International markets	Yes	Yes	Yes	Yes	Yes
Potential market size	Uncertain	Large	Uncertain	Large	Large

Research or analysis need	High	High	High	Medium	High
Can JIWPI influence outcomes?	Low	Medium	Medium	Low	Medium

Pyrolysis: solid and gaseous fuels

Product Classification: Pyrolysis – Solid and gaseous fuels	**Torrefied Wood / Biocoal**	**Renewable Natural Gas**	**Renewable Hydrogen**
Representative feedstock required (BDT/year)	149,000 (Restoration Fuels)	250,000 (GTI Stockton)	45,000 (Clean Energy Systems)
Carbon storage	No	Yes (CCS)	Yes (CCS)
Technology readiness level	8	6	5
Commercial readiness level	6	5	5

Feedstock use	Non-merchantable	Non-merchantable	Non-merchantable
International markets	Yes	Yes	Yes
Potential market size	Medium	Large	Uncertain
Research or analysis need	Low	High	High
Can JIWPI influence outcomes?	Medium	High	High

Liquid fuels					
Product Classification: Liquid Fuels	**Fischer - Tropsch Fuels**	**Gas Fermentation**	**Fast Pyrolysis and Hydroprocessing**	**Lignocellulosic Ethanol**	
Representative feedstock required (BDT/year)	68,000 (Red Rock Biofuels)	133,000 (Aemetis, Inc.)	300,000 (SPI Camino site)	100,000 (Axens/Anderson Biomass)	
Carbon storage	Yes (CCS)	No	Yes (char)	No	

Technology readiness level	7	8	6	8	
Commercial readiness level	6-7	6	5	6	
Feedstock use	Non-merchantable	Non-merchantable	Non-merchantable	Non-merchantable	
International markets	Yes	Yes	Yes	Yes	
Potential market size	Large	Large	Large	Large	
Research or analysis need	Medium	Medium	Medium	High	
Can JIWPI influence outcomes?	High	High	Medium	Low	

Citations

Abatzoglou, J.T., Williams, A.P., 2016. Impact of anthropogenic climate change on wildfire across western US forests. Proceedings of the National Academy of Sciences 113, 11770–11775. https://doi.org/10.1073/pnas.1607171113

Albergotti, R. (2019, November 4). When the power went out during California's wildfires, the air quality monitors turned off, too. Retrieved February 6, 2020, from https://www.washingtonpost.com/technology/2019/11/04/when-power-went-out-during-californias-wildfires-air-quality-monitors-turned-off-too/

Anonymous, 2020. Email exchange with former USFS technician.

Associated Press, 2019. Death toll from Northern California's Camp fire back down to 85. LA Times.

Baker, S.E., et al., 2020. Getting to Neutral: Options for Negative Carbon Emissions in California (No. LLNL-TR-796100). Lawrence Livermore National Laboratory.

Bales, R.C., Battles, J.J., Chen, Y., Conklin, M.H., Holst, E., O'Hara, K.L., Saksa, P. and Stewart, W., 2011. Forests and water in the Sierra Nevada: Sierra Nevada watershed ecosystem enhancement project. *Sierra Nevada Research Institute report*, *11*.

Blazing Battles: The 1910 Fire and Its Legacy. Retrieved February 6, 2020, from https://www.nationalforests.org/our-forests/your-national-forests-magazine/blazing-battles-the-1910-fire-and-its-legacy

Brauman, K.A., Daily, G.C., Duarte, T.K.E. and Mooney, H.A., 2007. The nature and value of ecosystem services: an overview highlighting hydrologic services. *Annu. Rev. Environ. Resour.*, *32*, pp.67-98.

Brown, Edmund G Jr, 2018. Executive Order B-55-18 to Achieve Carbon Neutrality.

Brown, T.C., Froemke, P., Mahat, V. and Ramirez, J.A., 2016. Mean annual renewable water supply of the contiguous United States. *Briefing paper. Rocky Mountain Research Station, Fort Collins, CO*.

Butsic, V., McCann, H., Axelson, J., Gray, B., Jin, Y., Mount, J., Stephens, S., Stewart, W., 2017. Improving the Health of California's Headwater Forests. Public Policy Institute of California, Water Policy Center.

CalEPA, 2019. JANUARY 2019 DRAFT California 2030 Natural and Working Lands Climate Change Implementation Plan. CalEPA.

CalFire, 2018. California's Forests and Rangelands 2017 Assessment. CalFire - FRAP.

CalEPA, 2019. Carbon Neutrality Studies – Public Notice and Agenda [WWW Document]. URL https://calepa.ca.gov/climate/carbon-neutrality-studies/public-notice-and-agenda/ (accessed 1.20.20).

California Fuel Cell Partnership (2019). "List of Hydrogen Fueling Stations" URL https://cafcp.org/sites/default/files/h2_station_list.pdf

Canadian Forest service, 2013. The State of Canada's Forests: Annual report 2013. Natural resources Canada. Ottawa, Canada.

California Governor's Office of Planning and Research, 2018. California's Fourth Climate Change Assessment (Statewide summary report).

CARB, 2020a. ARB Offset Credit Issuance [WWW Document]. URL https://ww3.arb.ca.gov/cc/capandtrade/offsets/issuance/issuance.htm

CARB, 2020b. Cap-and-Trade Program Data [WWW Document]. URL

https://ww2.arb.ca.gov/cap-and-trade-program-data
CARB, 2017. Scoping Plan [WWW Document], n.d. URL https://ww3.arb.ca.gov/cc/scopingplan/scopingplan.htm.
CARB, 2015. CARB - Compliance Offset Protocol U.S. Forest Projects. CARB.
CARB, 2019. *California Greenhouse Gas Emissions for 2000 to 2017 Trends of Emissions and Other Indicators*, California Air Resources Board. Available at: https://ww3.arb.ca.gov/cc/inventory/pubs/reports/2000_2016/ghg_inventory_trends_00-16.pdf.
Christensen, G.A., Gray, A.N., Kuegler, O., Tase, N.A. and Rosenberg, M., 2017. AB 1504 California Forest Ecosystem and Harvested Wood Product Carbon Inventory: 2006-2015. *Final Report. California Department of Forestry and Fire Protection agreement*, (7CA02025).
Ciais, P., Sabine, C. and Bala, G., 2013. Bopp. *L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., Jones, C., Le Quéré, C., Myneni, R., Piao, S., and Thornton, P.: Carbon and Other Biogeochemical Cycles, in: Climate Change*.
Collins BM, Das AJ, Battles JJ, et al. 2014. Beyond reducing fire hazard: fuel treatment impacts on overstory tree survival. Ecol Appl 24:1879–86
Conor K. Bell, Robert F. Keefe & Jeremy S. Fried (2017) Validation of the OpCost logging cost model using contractor surveys, International Journal of Forest Engineering, 28:2, 73-84, DOI: 10.1080/14942119.2017.1313488
Cramton, P., Hellerstein, D., Higgins, N., Iovanna, R., López-Vargas, K., Wallander, S., n.d. Improving the Cost-Effectiveness of the Conservation Reserve Program: A Laboratory Study 45.
Farm Service Agency, 2019a. Conservation Reserve Program Fact Sheet Dec 2019 [WWW Document]. Conservation Reserve Program. URL https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/FactSheets/2019/conservation-reserve_program-fact_sheet.pdf (accessed 2.28.20).
Farm Service Agency, 2019. CRP: Status, End of December 2019 [WWW Document]. URL https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/Conservation/Excel/Dec%202019%20One-Pager.pdf (accessed 2.28.20).
Farm Service Agency, 2019b. Conservation Reserve Program General Enrollment Period [WWW Document]. URL https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/FactSheets/2019/crp_general_enrollment_signup-fact_sheet.pdf (accessed 2.28.20).
Farm Service Agency, 2019c. Conservation Reserve Program: Continuous Enrollment Period [WWW Document]. URL https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/FactSheets/2019/crp_continuous_enrollment_period-fact_sheet.pdf (accessed 2.28.20).
Farm Service Agency, 2019d. Conservation Reserve Program: Environmental Benefits Index [WWW Document]. URL https://www.fsa.usda.gov/Assets/USDA-FSA-Public/usdafiles/FactSheets/2019/crp_environmental_benefits_index-fact_sheet.pdf (accessed 2.28.20).
Forest Climate Action Team, 2018. California Forest Carbon Plan: Managing Our Forest Landscapes in a Changing Climate 178.
Fried, Jeremy, Sara Loreno, Benktesh Sharma, Carlin Starrs, William Stewart. (University of

California, Berkeley). 2016. Inventory Based Landscape-Scale Simulation to Assess Effectiveness and Feasibility of Reducing Fire Hazards and Improving Forest Sustainability in California With Biosum. CEC-600-11-006

Gas Technology Institute (GTI), (2019). *Low-Carbon Renewable Natural Gas (RNG) from Wood Wastes*. URL https://www.gti.energy/wp-content/uploads/2019/02/Low-Carbon-Renewable-Natural-Gas-RNG-from-Wood-Wastes-Final-Report-Feb2019.pdf Hellerstein, D., 2010. Challenges Facing USDA's Conservation Reserve Program [WWW Document]. USDA ERS. URL https://www.ers.usda.gov/amber-waves/2010/june/challenges-facing-usda-s-conservation-reserve-program/ (accessed 2.28.20).

Huntsinger, L. and McCaffrey, S., 1995. A forest for the trees: forest management and the Yurok environment, 1850 to 1994. *American Indian Culture and Research Journal*, *19*(4), pp.155-192.
Johansson, R., 2005. Participant Bidding Enhances Cost Effectiveness. USDA Economic Research Service 6.

Kenny, A. Ecosystem Services in the New York City Watershed. Retrieved February 6, 2020, from https://www.ecosystemmarketplace.com/articles/ecosystem-services-in-the-new-york-city-watershed-1969-12-31-2/

Kreutz, T.G., Larson, E.D., Liu, G. and Williams, R.H., 2008, September. Fischer-Tropsch fuels from coal and biomass. In *25th annual international Pittsburgh coal conference* (Vol. 29, pp. 2-10). International Pittsburgh Coal Conference Pittsburgh, Pennsylvania.

Krofcheck, D.J., Hurteau, M.D., Scheller, R.M., Loudermilk, E.L., 2018. Prioritizing forest fuels treatments based on the probability of high-severity fire restores adaptive capacity in Sierran forests. Glob. Change Biol. 24, 729–737. https://doi.org/10.1111/gcb.13913

Liang, S., Hurteau, M.D., Westerling, A.L., 2018. Large-scale restoration increases carbon stability under projected climate and wildfire regimes. Front. Ecol. Environ. 16, 207–212. https://doi.org/10.1002/fee.1791

Luna, T., 2019. Newsom declares wildfire emergency, waives environmental rules to expedite projects [WWW Document]. latimes.com. URL https://www.latimes.com/politics/la-pol-ca-gavin-newsom-wildfire-20190322-story.html (accessed 5.5.19).

McIver, C.P., Meek, J.P., Scudder, M.G., Sorenson, C.B., Morgan, T.A. and Christensen, G.A., 2015. California's forest products industry and timber harvest, 2012. *Gen. Tech. Rep. PNW-GTR-908. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station. 49 p.*, *908*.

Miao, R., Feng, H., Hennessy, D.A., Du, X., 2016. Assessing Cost-effectiveness of the Conservation Reserve Program (CRP) and Interactions between the CRP and Crop Insurance. Land Economics 92, 593–617. https://doi.org/10.3368/le.92.4.593

Nabuurs, g. J., O. Masera, K. andrasko, P. Benitez-Ponce, R. Boer, M. dutschke, e. elsiddig, J. Ford-Robertson, P. Frumhoff, t. Karj- alainen, O. Krankina, W. a. Kurz, M. Matsumoto, W. Oyhantca- bal, n. H. Ravindranath, M. J. Sanz Sanchez, and X. Zhang. 2007. Forestry. In Climate Change 2007: Mitigation. Contribution of Working group III to the Fourth Assessment Report of the Inter- governmental Panel on Climate Change. B. Metz, O. R. david- son, P. R. Bosch, R. dave, L. a. Meyer (eds), Cambridge University Press, Cambridge.

Newton, J., 2018. EQIP and CSP Conservation Programs in the 2018 Farm Bill [WWW Document]. FB Market Intel. URL https://www.fb.org/market-intel/eqip-and-csp-

conservation-programs-in-the-2018-farm-bill (accessed 2.28.20).
Nordhaus, William. 2007. A Review of the Stern Review on the Economics of Climate Change. Journal of Economic Literature 45: 686–702.
Nowak, D.J., 2002. The effects of urban trees on air quality. *USDA Forest Service*, pp.96-102.
Nowak, D.J., Hirabayashi, S., Bodine, A. and Greenfield, E., 2014. Tree and forest effects on air quality and human health in the United States. *Environmental pollution*, *193*, pp.119-129.
NRCS, n.d. Environmental Quality Incentives Program | NRCS [WWW Document]. USDA NRCS. URL https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/financial/eqip/ (accessed 2.28.20a).
NRCS, n.d. EQIP Financial and Technical Assistance [WWW Document]. USDA NRCS. URL https://www.nrcs.usda.gov/wps/portal/nrcs/main/ca/programs/financial/eqip/ (accessed 2.28.20).
NRCS, 2015. Conservation Practice Standard 666, Forest Stand Improvement (No. 666- CPS-1). USDA NRCS. https://www.fb.org/market-intel/eqip-and-csp-conservation-programs-in-the-2018-farm-bill (accessed 2.28.20).
NRCS, n.d. Ranking Criteria | NRCS California [WWW Document]. USDA NRCS. URL https://www.nrcs.usda.gov/wps/portal/nrcs/detail/ca/programs/financial/eqip/?cid=nrcseprd1545441 (accessed 2.28.20b).
Outdoor Industry Association (2017). Outdoor Recreation Economy: California. Retrieved from https://outdoorindustry.org/wp-content/uploads/2017/07/OIA_RecEcoState_CA.pdf.
Podolak, K., D. Edelson, S. Kruse, B. Aylward, M. Zimring, and N. Wobbrock. 2015. Estimating the Water Supply Benefits from Forest Restoration in the Northern Sierra Nevada. An unpublished report of The Nature Conservancy prepared with Ecosystem Economics. San Francisco, CA.
Plant, L. B. Loyalton Biomass Plant. Retrieved February 6, 2020, from https://www.amerpower.com/facilities-detail/6
Plantinga, A.J., Richards, K.R., 2008. International forest carbon sequestration in a post-Kyoto agreement.
Potts, L., Bross, L., Loreno, S., Mozelewski, T., Fried, J., 2018. FIA BioSum: A User's Guide (DRAFT) (User guide). USFS.
Pritzker, B., 2000. *A Native American encyclopedia: History, culture, and peoples*. Oxford University Press on Demand.
Red Rock Biofuels. (n.d.). Lakeview Site. Retrieved December 4, 2019. URL https://www.redrockbio.com/lakeview-site.html.
Sanchez, D., Harrell, K., Zimring, T., Mater, C., 2020. Literature Review & Evaluation of Research Gaps to Support Wood Products Innovation (No. Agreement # 9CA04450). California Board of Forestry and Fire Protection, Joint Institute of Wood Products Innovation.
S.B. 1440, Energy: biomethane: biomethane procurement. (Ca. 2018). URL https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB1440
Schultz, C.A., Thompson, M.P., McCaffrey, S.M., 2019. Forest Service fire management and the elusiveness of change. fire ecol 15, 13, s42408-019-0028–x. https://doi.org/10.1186/s42408-019-0028-x
Shelby, S., 2020. Email exchange with Stephen Shelby at CARB.
Sierra Nevada Conservancy, 2014. The State of the Sierra Nevada's Forests. Sierra Nevada

Conservancy, 11521 Blocker Dr., Ste. 205, Auburn, CA 95603.
Sierra Pacific Industries Site Search. Retrieved February 6, 2020, from https://www.spi-ind.com/OurForests/ForestManagement
Smith, J.E., Heath, L.S., Skog, K.E., Birdsey, R.A., 2006. Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States (No. NE-GTR-343). U.S. Department of Agriculture, Forest Service, Northeastern Research Station, Newtown Square, PA. https://doi.org/10.2737/NE-GTR-343
Smith, W.B., Miles, P.D., Perry, C.H. and Pugh, S.A., 2009. Forest resources of the United States, 2007: A technical document supporting the forest service 2010 RPA Assessment. *General Technical Report-USDA Forest Service*, (WO-78).
SoCalGas. (n.d.). Biogas and Renewable Natural Gas: SoCalGas. Retrieved December 4, 2019, URL https://www.socalgas.com/smart-energy/renewable-gas/biogas-and-renewable-natural-g
Stratmann, P. (n.d.). From waste woody biomass to carbon negative transportation fuels via CCUS. Retrieved December 4, 2019. URL http://www.biofuelsdigest.com/bdigest/2019/12/02/from-waste-woody-biomass-to-carbon-negative-transportation-fuels-via-ccus/.
Stewart, W., Sharma, B., York, R., Diller, L., Swiers, N., Powell, R., & Swiers, R. (2015). Forestry. Thirty-six. *Ecosystems of California*, 817–834. http://doi.org/10.1525/9780520962170-040
Taylor, M., 2018. Improving California's Forest and Watershed Management. Legislative Analyst's Office. (2018, April 4). Retrieved February 6, 2020, from https://lao.ca.gov/Publications/Report/3798
Thompson, D., 2019. California Eases Way for Land Clearing to Prevent Wildfires. U.S. News.
Thompson, M.P., MacGregor, D.G., Dunn, C.J., Calkin, D.E., Phipps, J., 2018. Rethinking the Wildland Fire Management System. Journal of Forestry 116, 382–390. https://doi.org/10.1093/jofore/fvy020
UC ANR, 2020. California Forests [WWW Document]. Forest Research and Outreach - California Forests. URL https://ucanr.edu/sites/forestry/California_forests (accessed 1.20.20).
USDA, 2015. California's Forest Products Industry and Timber Harvest, 2012 58.
USDA, 2016. Forest Service National Visitor Use Monitoring Program. (https://www.fs.fed.us/recreation/programs/nvum/)
USFS, 2015. Good Neighbor Agreement Questions and Comments [WWW Document]. URL https://www.fs.fed.us/farmbill/documents/gna/GNA-FAQs20151214.pdf
USFS Pacific Southwest Region, S.I., 2017. Good Neighbor Authority [WWW Document]. URL https://scale.sierrainstitute.us/wp-content/uploads/2017/04/SCALE_GNA1pager-1.pdf (accessed 2.10.20).
USFS, n.d. Ecological Restoration and Partnerships—Our California Story [WWW Document]. Region 5. URL https://www.fs.usda.gov/detail/r5/landmanagement/?cid=stelprdb5412095 (accessed 1.20.20).
Visit California (2016). California Travel Impacts by County, 1992-2015p. Visit California and the Governor's Office of Business Development (GO-Biz). Prepared by Dean Runyan Associates, Inc. Retreived from http://industry.visitcalifornia.com/media/uploads/files/editor/CAImp15rev1.pdf.

Winford, E.M., Gaither, J.C., 2012. Carbon outcomes from fuels treatment and bioenergy production in a Sierra Nevada forest. For. Ecol. Manag. 282, 1–9. https://doi.org/10.1016/j.foreco.2012.06.025
Winford, E.M., Stevens, J.T., Safford, H.D., 2015. Effects of fuel treatments on California mixed-conifer forests. Calif. Agric. 69, 150–156. https://doi.org/10.3733/ca.v069n03p150
Walsh, M.W., 2018. How Wildfires Are Making Some California Homes Uninsurable. The New York Times.
Yiu, A., 2020. Email exchange with Alex Yiu at CARB.
Zimring, T., 2019. Barriers to Federal Forest Management.
Zhou, D., Zhao, S.Q., Liu, S., Oeding, J., 2013. A meta-analysis on the impacts of partial cutting on forest structure and carbon storage. Biogeosciences 10, 3691–3703. https://doi.org/10.5194/bg-10-3691-2013