FUEL TREATMENT FOR FOREST RESILIENCE AND CLIMATE MITIGATION: A CRITICAL REVIEW FOR CONIFEROUS FORESTS OF CALIFORNIA

A Report for:

California’s Fourth Climate Change Assessment

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PREFACE

California's Climate Change Assessments provide a scientific foundation for understanding climate-related vulnerability at the local scale and informing resilience actions. These Assessments contribute to the advancement of science-based policies, plans, and programs to promote effective climate leadership in California. In 2006, California released its First Climate Change Assessment, which shed light on the impacts of climate change on specific sectors in California and was instrumental in supporting the passage of the landmark legislation Assembly Bill 32 (Núñez, Chapter 488, Statutes of 2006), California's Global Warming Solutions Act. The Second Assessment concluded that adaptation is a crucial complement to reducing greenhouse gas emissions (2009), given that some changes to the climate are ongoing and inevitable, motivating and informing California's first Climate Adaptation Strategy released the same year. In 2012, California's Third Climate Change Assessment made substantial progress in projecting local impacts of climate change, investigating consequences to human and natural systems, and exploring barriers to adaptation.

Under the leadership of Governor Edmund G. Brown, Jr., a trio of state agencies jointly managed and supported California's Fourth Climate Change Assessment: California's Natural Resources Agency (CNRA), the Governor's Office of Planning and Research (OPR), and the California Energy Commission (Energy Commission). The Climate Action Team Research Working Group, through which more than 20 state agencies coordinate climate-related research, served as the steering committee, providing input for a multisector call for proposals, participating in selection of research teams, and offering technical guidance throughout the process.

California's Fourth Climate Change Assessment (Fourth Assessment) advances actionable science that serves the growing needs of state and local-level decision-makers from a variety of sectors. It includes research to develop rigorous, comprehensive climate change scenarios at a scale suitable for illuminating regional vulnerabilities and localized adaptation strategies in California; datasets and tools that improve integration of observed and projected knowledge about climate change into decision-making; and recommendations and information to directly inform vulnerability assessments and adaptation strategies for California's energy sector, water resources and management, oceans and coasts, forests, wildfires, agriculture, biodiversity and habitat, and public health.

The Fourth Assessment includes 44 technical reports to advance the scientific foundation for understanding climate-related risks and resilience options, nine regional reports plus an oceans and coast report to outline climate risks and adaptation options, reports on tribal and indigenous issues as well as climate justice, and a comprehensive statewide summary report. All research contributing to the Fourth Assessment was peer-reviewed to ensure scientific rigor and relevance to practitioners and stakeholders.

For the full suite of Fourth Assessment research products, please visit www.climateassessment.ca.gov. This report advances the understanding of fuel treatments as a potential mitigation for wildfire hazard and risk, associated carbon storage, and wildfire emissions.

ABSTRACT

Forest ecosystems in California contain some of the highest densities (mass per unit area) of carbon anywhere in the world (Gonzalez et al. 2015) as well as some of the highest rates of forest productivity of any temperate forest in the world (Hudiburg et al. 2009). Gonzalez et al. (2015) reported a net aboveground live carbon loss in California from 2001 to 2010 that was driven by wildfire occurrence on 6% of the state's land area. Climate change is expected to increase the frequency and intensity of wildfires which increases the probability that California's forests will be a net emitter of carbon. Fuel reduction treatments that reduce stand density and restore beneficial fire to the landscape can improve climate change resilience of forests and potentially minimize future emissions by reducing the amount of large and severe wildfires. As part of California's Fourth Climate Change Assessment, this project reviewed what is known about the effects of fuel treatments on carbon dynamics in California's forests. The project also summarized geo-spatial data gaps to be filled to make sound fuel treatment decisions to increase both forest resilience and carbon sequestration. Finally, the work helps provide a scientific basis for the development of offset methodologies in the voluntary and regulatory marketplace that could generate much-needed revenue to implement beneficial climate projects in California. This report summarizes the findings from 12 key questions that focus on fuel treatments as a potential mitigation for wildfire hazard and risk, associated carbon storage, and wildfire emissions. The findings reported are based on a detailed review of over 150 peer-reviewed scientific papers and reports. To the extent possible, all reports are sourced from research conducted on forest types within California.

Keywords: Wildfire, carbon, California, fuel treatment, wildfire emissions

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HIGHLIGHTS

- Fuel treatments that use a combination of thinning from below and prescribed fire or prescribed fire alone with adequate consumption of surface fuels and increased crown separation have been shown to reduce fire severity within and adjacent to treated areas.
- Fuel treatments can also be integrated with suppression actions to facilitate the movement of personnel and equipment or to gain efficiency in rates of fire line construction and aerial retardant penetration to surface fuels.
- Under extreme fire weather conditions, specifically with high winds, fires may simply burn through or spot over a fuel treatment and continue burning into adjacent untreated fuels.
- Under extreme fire weather and behavior, conditions in the fuel treatment itself may still be too dangerous to effectively utilize in conjunction with suppression resources.
- The areas of the landscape most prone to facilitating fire spread must be effectively treated in terms of overall scale to mitigate high severity fire at the landscape level.
- Whether or not fuel treatments safeguard enough carbon to offset their carbon cost depends on many factors including forest structure, existing fuel loads, expected wildfire frequency and severity, regeneration rates, fuel treatment type and intensity, and the fate of merchantable forest products. A key issue is the probability of fire occurring after treatment implementation; treatments that are not impacted by wildfire will not result in reduced potential wildfire emissions.
- Bark beetles have a narrow host range or are host specific and at endemic population levels colonize overstocked, weakened, stressed, and/or previously damaged trees; therefore, fuel treatments that target stand composition and density can impact the amount and severity of bark beetle attack and can also reduce stand susceptibility to bark beetle attack.
- The effect of salvage logging on individual carbon pools is not always predictable. Soil carbon is generally stable. Salvage harvesting will decrease the dead tree carbon pool, but other pools such as surface fuels may increase or decrease depending on the implementation of the salvage operation. Overall, however, total carbon would be expected to decrease in the short-term as a result of salvage logging but may equal or exceed pre-fire/pre-salvage levels in the long-term.
- Black carbon is a topic of growing research and considerable uncertainty, making it difficult to generalize about its significance for evaluating the GHG benefits of various treatment practices.
- To the extent that the fate of forest biomass is to be burned, science suggests that the global warming effects can be minimized through controlled combustion in a biomass facility rather than in open burning. In wetter forest environments, decomposition might be a more effective means of mitigating global warming potential than burning, but leaving forest residues such as slash piles in the woods is generally considered hazardous because of the potential for wildfires.

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EXECUTIVE SUMMARY

This report summarizes the findings from 12 key questions that focus on fuel treatments as a potential mitigation for wildfire behavior hazard and risk, associated carbon storage, and wildfire emissions. The findings reported are based on a detailed review of over 150 peer-reviewed scientific papers and reports. To the extent possible, all reports are sourced from research conducted on forest types within California.

The ecosystems of California have experienced lightning and human caused fires for millennia. Prior to 1800, it is estimated that an average of 1,800,000 hectares (ha)(4,400,000 acres) of California burned per year. The reported variation in area burned per year was 1,814,614 to 4,838,293 ha (4,484,008- 11,955,682 acres). Many of those fires burned over days, weeks, and months during the summer and fall months until they were extinguished by precipitation. Over centuries, these fires helped create and maintain a diverse range of vegetation types and structures across the state, and their ubiquity across the landscape influenced the behavior, extent, and severity of future fires. Fire has been excluded as a frequent ecosystem process through active suppression over much of the 20th century and continuing today. This has resulted in live and dead fuel buildup with the risk of more intense wildfires increasing in many areas that formerly experienced frequent, low severity fires. Conducting fuel treatments to moderate the impacts of wildfires and to restore forests in California involves a fundamental tension with mitigating impacts of forest emissions that can exacerbate climate change.

Today, paradoxically, California is faced with the conflicting challenges of simultaneously restoring the forest structure of, reintroducing fire into, and keeping wildfire out of fire adapted ecosystems over millions of acres. These challenges are exacerbated by the level of live and dead fuel buildup, forest stand structure, climate change, the amount and value of residential and commercial development in the Wildland Urban Interface (WUI), the desire to maintain and enhance forest carbon, the public health concerns posed by wildfire emissions, the potential for post wildfire debris flows, and associated loss of life and property in and adjacent to areas that have burned. In an effort to reduce the wildfire threat, there has been an extensive statewide effort on both public and private lands to implement fuel treatments that alter stand characteristics that can contribute to severe wildfires, including the stand density and configuration of live trees, the presence of ladder fuels, and surface fuel loading. Reducing wildfire hazard and restoring fire as an ecological process at the landscape scale involves killing trees and converting their biomass (stored carbon) into emissions, energy, and wood products. However, over the long-term, such treatments have the potential to protect residual live tree carbon, increase residual tree growth, and reduce potential future insect, wildfire, and disease related mortality.

Forest fuel treatments can be effective in modifying wildfire behavior in ways that can mitigate carbon losses, despite the fact they exact an upfront cost in terms of lost carbon. Many factors influence the likelihood that such treatments could have a net benefit in terms of global warming potential. Of these, the expected frequency of wildfire is one of the most important. For that reason, spatial variation within California forest ecosystems is important for understanding the potential benefits of fuel treatments from a global warming perspective. Specifically, areas that are predisposed to a more frequent fire regime, and areas that are severely departed from their expected fire regime, are most likely to realize benefits from fuel treatments. This view helps to explain some of the considerable disagreement in forest carbon literature; for example, researchers focused on moister forests in the Pacific Northwest are likely to see treatments as having little chance for a payoff, given less frequent fires and other climate-related influences. However, researchers focused on more frequent fire systems, as well as systems in which forest density contributes to non-fire mortality (e.g., bark beetles) as found in parts of the Sierra Nevada and the southwestern U.S., are likely to find that treatments are more favorable.

Forest managers on private and public lands apply a combination of tools to achieve complex objectives which may include mitigation of carbon emissions that contribute to climate change. Management to maximize carbon storage is likely to conflict to some degree with other objectives such as ecological restoration, avoiding risk from wildfires, and utilizing forest products. On the other hand, there may be many opportunities to promote multiple benefits through accelerated thinning and greater use of fire to shift carbon stores toward a smaller number of larger trees. This strategy seeks to sequester carbon in more recalcitrant forms, such as large tree boles of fire-resistant trees.

Information currently exists to estimate many of the potential tradeoffs, although further research is needed to better evaluate the likely consequences of particular strategies. Other factors have considerable uncertainty, such as the effect of aerosolized black carbon from fires, which may have significant effects given the global warming potential of such emissions (Myhre et al. 2013; Sasser et al. 2012), or in-forest black carbon, which may have relatively small but nevertheless important long-term effects on ecological processes including carbon storage and forest productivity. Even processes that have been studied, such as the decomposition rates of dead trees, are important to study over long periods and different ecological contexts to better understand carbon dynamics and the efficacy of different management strategies. These are important research gaps that should be considered.

Many factors considered in this review can influence the relative payoff of fuel treatments, including the fate of harvested biomass. Where thinning forests to reduce risks from wildfire are expected, biomass removal can then be managed to minimize greenhouse gas emissions through a combination of converting to long-lived wood products and offsetting more carbon-intensive energy production. Information to evaluate assumptions in proposed treatments can be used to inform and improve carbon calculators used to evaluate proposals. It is important to consider the wide variety of treatments that may be considered as part of fuel treatments, including many different kinds of thinning treatments, mastication, prescribed burning, and wildfires that are intentionally managed.

1: Introduction

1.1 Background

The ecosystems of California have evolved with lightning- and human-caused fires for millennia. Prior to 1800, it is estimated that annually 1,800,000 hectares (4,400,000 acres) of California burned per year (Stephens et al. 2007); the reported variation in area burned per year was 1,814,614 to 4,838,293 ha (4,484,008- 11,955,682 acres) (Stephens et al. 2007). Forested regions of California were frequently burned by lighting- and anthropogenic-caused fires every 10-20 years (Forrestel et al. 2017; Vaillant and Stephens 2009). Over centuries, these fires helped create and maintain a diverse range of vegetation types and structures across the state, and their ubiquity across the landscape influenced the behavior, extent, and severity of future fires (Sugihara 2006). Over much of the 20th century, fire has actively been reduced as a frequent natural ecosystem process through active suppression. As a result, the risk of more intense wildfires has increased in many areas that formerly experienced frequent, low severity fires. Conducting fuel treatments to moderate the impacts of wildfires and to restore forests in California involves a fundamental tension with mitigating impacts of forest emissions that can exacerbate climate change.

Forest ecosystems in California contain both high densities (mass per unit area) of carbon and rates of forest productivity (Gonzalez et al. 2015; Stewart et al. 2015). While California forests have the potential to sequester large amounts of carbon in the form of woody biomass, many of these forests are also composed of high density stands at risk of large, severe wildfires, where more than 90% of live tree basal area is directly killed by fire (Miller and Safford 2012; Miller et al. 2009), an uncharacteristically large portion of the landscape (Collins and Skinner 2014; North et al. 2017). A recent study reported a net aboveground live carbon loss in California from 2001 to 2010 that was primarily driven by wildfire occurrence. There are several factors driving contemporary fire risk including anthropogenic changes from over a century of timber harvest and the exclusion of fire as an ecosystem process. At the same time that these forests face a threat of extensive, high severity wildfire, many are also managed with a goal of sequestering carbon for climate change mitigation efforts through carbon offset markets and statewide conservation policy.

With the enactment of the California Global Warming Solutions Act of 2006 (SB 32, 2006) and the recent implementation of the State's emissions trading program, California is at the forefront of efforts to value carbon benefits resulting from climate change mitigation and adaptation activities. However, while activities that remove forest biomass for protection from wildfire are considered emissions, carbon commodity registries such as the California Climate Action Registry (CCAR) and the American Carbon Registry (ACR) have yet to establish protocols that recognize avoided or reduced wildfire emissions resulting from treatment activities as a carbon benefit. In theory, projects that reduce potential emissions from wildfire could be incentivized with carbon emission offsets. However, doing so requires accounting for many factors including forest growth (carbon sequestration), the risk of wildfire, expected effects of fuel treatments, and life cycles of removed forest biomass (Winford and Gaither 2012).

In an effort to reduce the wildfire threat, there has been an extensive statewide effort on both public and private lands to implement fuel treatments that alter stand characteristics that can contribute to severe wildfires, including the stand density and configuration of live trees, the presence of ladder fuels (including small trees and dead needles), and surface fuel loading. The term "fuel treatments" covers a wide range of fire based, mechanical, and combinations of fire and mechanical treatments that are generally implemented to reduce the surface (dead) fuel loading, rearrange/chip/compact surface fuels, reduce live shrub vegetation cover and depth, reduce tree density by "thinning from below" (removing relatively smaller diameter trees while retaining larger diameter trees), generally increase tree height to crown base, and decrease overall residual post-treatment density (Agee and Skinner 2005).

These treatments are implemented to protect forests and human communities as part of larger landscape strategies, but they increasingly have an expectation of reducing potential future wildfire emissions (including smoke and carbon) (Long et al. 2017). Fuel treatments intended to reduce the risk of severe wildfire and associated emissions, by definition, remove live and dead woody biomass available for burning, thereby reducing stored carbon (Hurteau and Brooks 2011; Carlson et al. 2012). Fuel treatment operations themselves can also result in direct and delayed atmospheric carbon emissions, as with biomass transportation and prescribed broadcast or pile burning. A number of recent studies have investigated the seemingly competing values of carbon sequestration and fuel treatment, examining whether and to what extent reduced carbon sequestration from treatment is mitigated by avoided carbon emissions from wildfire (Krofcheck et al. 2017a; Liang et al. 2017; Loudermilk et al. 2014). Improving the accuracy and usefulness of forest carbon storage assessments that analyze the trade-offs between fuel treatment and wildfire requires understanding the effects of multiple management and disturbance scenarios, including post wildfire treatments (e.g., tree removal and reforestation) over time. Compounding the risk of high severity fire are projections that climate change may increase the frequency and intensity of wildfires which may increase the potential for California's forests to become a net emitter of carbon. In addition to the direct risk of loss of live forest vegetation, there is the potential for forested areas to be converted to and maintained as lower carbon density vegetation types such as shrublands (Coppoletta et al. 2016), thereby reducing long-term potential carbon sequestration.

1.2 Goals and Objectives

This project had several major goals:

- Summarize what is known about the effects of fuel treatments on carbon dynamics in California's forests.
- Identify research and geospatial data gaps to be filled in order to make sound fuel treatment decisions that can increase both forest resilience and carbon sequestration.
- Synthesize estimates of the effects of forest management and fuel treatment activities on forest carbon dynamics and the resulting avoided or reduced wildfire emissions.
- Support decision-making processes that require an understanding of the greenhouse gas implications of implementing fuel reduction treatments (e.g., Greenhouse Gas Reduction Fund forestry projects that are intended to reduce or avoid greenhouse gas (GHG) emissions).
- Help state agencies, Fire Safe Councils, and forestry and resource management companies evaluate the co-benefits of forest management activities.

- Provide a scientific basis for the development of offset methodologies in the voluntary and regulatory marketplace which could generate much needed revenue to implement climate beneficial projects in California.

The primary objective of the project was to prepare a review and synthesis report regarding the effects of fuel treatments on global warming potential in major coniferous forest types of California, specifically addressing the following questions:

- Are fuel treatments effective in reducing wildfire severity under severe weather conditions?
- Do fuel treatments have a direct impact on stand level potential carbon sequestration?
- How do the impacts above vary over the immediate- (within 5 years of treatment), short- (5-20 years), and long-term (>20 years) timeframes? For example, forest treatments typically have a short-term (<20 year) cost, yet can provide long-term benefits that may be significant from a greenhouse gas reduction strategy.
- Do different types of wood and biomass utilization affect the overall carbon balances of a particular fuel treatment? This would include the use of removed materials for lumber, manufactured wood products, electricity production, mulch, or firewood, especially when compared with using on-site, pile, or broadcast burning to dispose of these materials.
- Can fuel treatments modify the frequency, intensity, size, and duration of disturbances, thereby influencing effectiveness for climate change mitigation? Disturbances may include:
    - Stand-replacing, high severity wildfire
    - Low or moderate severity wildfire
    - Pests, droughts, and other non-fire mortality agents
    - Influence of climate change on these disturbances in treated stands
- How do the carbon balances, including in-forest black carbon in areas burned by wildfire, vary under different post-wildfire treatments (e.g., salvage, reforestation) over time?
- Can fuel treatment parameters (intensity, age, extent) be used to predict potential post-treatment biomass consumption (carbon loss) and emissions by wildfires?
- Are there other potential effects and tradeoffs with other influences on non-carbon GHG emissions such as methane (CH_4), nitrous oxide (N_2O), and ozone (O_3)?
- How do the factors above vary in spatial-ecological terms across California forests?
- What geospatial datasets currently exist or are needed to help answer these questions using spatial analysis?

The focus of the review is on forest carbon (including live and dead, aboveground and belowground biomass) but also considers other potential impacts such as surface albedo (reflectivity) effects of black carbon. The review assesses the full life cycle of the fuels being treated, including materials that are burned in place, converted to wood products, energy, or left on-site to decompose. The review focuses on yellow pine mixed conifer forests, including those typically found in the Sierra Nevada, Cascade, Interior Coast Range, Klamath, and Transverse Mountain ranges (Figure 1). Results should not be directly applied to coastal mesic forests or higher elevation coniferous (red fir) forests. The term "resilience" as used in this paper is defined as "The amount of disturbance an ecosystem can absorb without shifting to a different stable state". From a land management perspective, resilience includes "Maintenance of the capacity of an ecosystem to "snap back" to a desired, or at least well-known, state." (Safford et al. 2012).

Gaps in knowledge where future research may be needed are identified. Findings are summarized by geographical location of the state where information is available and relevant. The final list of references and data are being presented in an interactive online "literature map," allowing users to see the geographic location of the data or study site(s) used in the publication, and will provide direct web links for downloading the publication(s).

Figure 1: Focus Area for Literature Review

2: Review of Literature by Research Question

The topics and questions covered in this report are answered in detail on the following pages.

2.1 Overview of Carbon in California Forest Ecosystems

2.1.1 Forest Carbon Pools

Carbon sequestered in forests can be divided into the following pools: 1) standing live and dead trees, 2) understory vegetation, 3) down dead wood, 4) forest floor, and 5) soil organic matter. Biomass that is removed from forests as part of fuel treatments also needs to be considered when tracking carbon and other greenhouse gas emissions. Pools that best resist losses due to decomposition and burning include live (large-diameter) trees (aboveground and belowground), dead trees (snags/stump, both above and belowground), coarse wood, and organic matter in mineral soil (e.g., Boerner et al. 2008; Campbell et al. 2007). Other pools decompose or are volatilized more rapidly, including foliage, litter, duff, twigs, and understory plants (e.g., Boerner et al. 2008).

2.1.2. Totals

California contains roughly 5% of U.S. forested area and has approximately 19% greater average carbon density for its forest types than the U.S. average (U.S. EPA 2009). The state's roughly 2.65 Petagrams carbon (Pg C) stored in forests is approximately 6% of the U.S. total forest carbon store (U.S. EPA 2009). California's forests are estimated to hold on average 1.47 Pg C in above and belowground biomass (91.4 t C/ha) (U.S. EPA 2009). Different vegetation communities store different amounts of carbon, and they also have different disturbance regimes that affect the tradeoffs involved in evaluating treatment effects on global warming potential.

Of the ten California forest types analyzed by the U.S. EPA (2015, Table 1), redwood has the greatest average total carbon density followed by Douglas-fir, fir/spruce/mountain hemlock, and mixed conifer. However, when the *extent* of each forest type is considered, mixed conifer holds by far the greatest carbon stores of California forests, followed by western oak and fir/spruce/mountain hemlock. The EPA estimate of live and dead aboveground carbon for California mixed conifer forests is about 219 metric tons (t)/ha. However, these figures are also quite variable; Gonzalez et al. (2015) measured about 120 t/ha at a mixed conifer site in the central Sierra Nevada while Winford and Gaither (2012) found 72.5 t C/ha.

Gonzalez et al. (2010) used field-based and remote-sensing methods to measure forest carbon at a site in California's North Coast Range and another site in the Tahoe National Forest of the central Sierra Nevada. Red fir stands in the Sierra Nevada had the lowest tree density yet had much greater carbon density than nearby dense oak/Douglas-fir and mixed conifer forests due to the greater proportion of old trees. Shrubs and coarse woody debris contributed little to total carbon stocks. The portion of total carbon in live tree carbon varied inversely with elevation in the Sierra Nevada, which is opposite to the pattern found in dead tree carbon.

Hudiburg et al. (2009) estimate that live and dead biomass stores are about 0.4 Pg C in the Sierra Nevada ecoregion. Live biomass carbon generally contributed about 80% of live and dead biomass carbon density and a higher portion of total carbon stock. Chiono et al. (2015)

estimated carbon stocks of about 147 t C/ha for their mixed conifer site in the central Sierra Nevada including carbon in the live (aboveground herbaceous, shrubs, tree biomass, belowground tree roots) and dead (litter, duff, surface fuel, snags, and belowground tree roots) pools.

Campbell et al. (2007) surveyed area burned in the 2002 Biscuit Fire in southern Oregon and northern California and found that most of the pre-fire biomass in mature forest stands was stored in large trees. They also found that most of the litter and duff biomass had recovered by 2002 after a 1987 wildfire. The boles of large conifers were the greatest carbon store (27.4% of the total) followed by soil and roots (21.7%), the boles of large hardwoods (14.7%), and the bark of large conifers (5.3%).

Boerner et al. (2008) measured carbon pool distributions at two sites in the Sierra Nevada: one near Georgetown, CA (central Sierra Nevada) and the other in Sequoia-Kings Canyon National Park (southern Sierra Nevada). Their average western U.S. results, which exclude these sites, had a carbon distribution of 38%, 40%, 9%, and 13% for the vegetation, soil, forest floor, and down dead wood carbon pools respectively. In comparison, the California sites, and the southern Sierra Nevada site in particular, had an exceptionally high quantity of carbon stored in aboveground vegetation and down dead wood and approximately twice the total carbon density of the western U.S. average.

Carlson et al. (2012) measured forest stand carbon in part of the Lake Tahoe Basin that burned in the 2007 Angora Fire. They found that stands contained about 180 t/ha of aboveground carbon before the fire.

Table 1: The U.S. EPA (2015) summarized average current carbon density by pool for the major California forest types using FIA (Forest Inventory and Analysis) plot data.

Forest type	Aboveground biomass	Belowground biomass	Dead wood	Litter	Soil organic carbon	Forest area
	carbon density (t C/ha)					(1,000 ha)
Pinyon/juniper	14.9	2.8	2.5	5.7	26.3	553
Douglas-fir	144.5	30.0	23.5	14.1	40.1	446
Ponderosa pine	53.9	11.2	9.9	12.6	41.3	952
Fir / spruce / mountain hemlock	110.7	23.3	29.6	19.0	51.9	855
Redwood	232.8	48.6	33.5	7.8	53.8	291
Other Western softwoods	23.2	4.4	5.5	9.2	49.8	836
California mixed conifer	104.6	21.9	21.2	21.5	49.8	3225

Forest type	Aboveground biomass	Belowground biomass	Dead wood	Litter	Soil organic carbon	Forest area
Western oak	50.1	9.5	5.5	7.7	27.6	3745
Tanoak / laurel	126.2	24.8	12.3	11.7	27.6	767
Minor types / nonstocked	48.6	9.8	16.0	12.0	36.8	1351
All	76.3	15.5	13.9	13.1	39.0	13022

2.1.3 Standing Live and Dead Trees, Understory Vegetation

Christensen et al. (2008) estimated that California contains about 1 Pg C in live tree aboveground biomass. North and Hurteau (2011) measured between 120 and 160 t/ha in standing live trees at mixed conifer sites across the state. Carbon density in old-growth forests is likely to be significantly higher than in similar second-growth forests. Much of the carbon in these forests is stored in the boles of standing live trees. On the other hand, Collins et al. (2017) found that basal area in their central Sierra Nevada study sites had doubled with respect to reference conditions, even though these forests were most likely second-growth. Carlson et al. (2012) estimated untreated, unburned aboveground live tree carbon in the Lake Tahoe Basin to be about 102 t C/ha and snag carbon to be about 6 t/ha. Boerner et al. (2008) reported that the understory vegetation pool comprises a small portion of the total forest-stored carbon (as little as 0.5% of tree carbon in dense mature stands) and is maximized when overstory trees are small.

Safford and Stevens (2017) extensively reviewed the literature on yellow pine and mixed conifer and compared current conditions and reference (i.e., before extensive fire suppression and timber harvest) conditions. Using FIA data, they found current snag densities of 47.7 snags/ha in mixed conifer stands and 20.2 snags/ha in yellow pine stands which was somewhat higher than pre-settlement snag densities. Periodic wildfires likely maintained lower snag densities. They note that snag densities in the recent beetle mortality areas are already orders of magnitude higher than reference conditions.

2.1.4 Down Dead Wood

Carbon stored in the down dead wood pool in California ranges from roughly 3 to 11% of the live tree carbon pool (North et al. 2009), but may experience a pulse after traditional thinning operations where trees are felled by hand versus machine which typically leaves limbs and non-merchantable tree tops (Stephens and Moghaddas 2005). Dead down wood generally increases for a time and then declines, following mortality events (fire, insect outbreaks) and the gradual felling of the resulting dead standing trees unless those dead trees are removed via salvage (Harmon et al. 1987; Ritchie et al. 2013). The dynamics of dead down wood have been shown to vary considerably across areas of different fire regimes, with much more wood in areas that experience fires less frequently due to a combination of factors including decomposition and direct effects of fire (Wright et al. 2002). The size of the dead down wood pool is most directly linked to the aboveground vegetation pool (Boerner et al., 2008). California's forests hold on average 0.24 Pg C (18.1 t C/ha) in down dead wood (U.S. EPA 2009), while Christensen et al.

(2008) estimated that California contains 0.1 Pg C in snags and down dead wood. Carbon amounts vary strongly with forest type as Boerner et al. (2008) found that mixed conifer stands in the southern Sierra Nevada contained on average 109.7 t C/ha of down dead wood. This high density of down dead wood in the Sierra Nevada is likely an artifact of decades of fire suppression. It is also highly variable; Waring et al. (2006) found coarse woody debris (>19.5 cm diameter and >1m length) in the Tahoe National Forest to be between 0.0 and 31.6 t C/ha with an average of 5.2 t C/ha and a median value of 1.1 t C/ha.

Carlson et al. (2012) found untreated, unburned aboveground fine woody debris carbon in their Lake Tahoe Basin study plots to be about 3.7 t/ha and coarse woody debris carbon to be about 3.9 t/ha.

Safford and Stevens (2017) summarized FIA data and found that coarse woody debris (CWD) averages 23 tons/ha of biomass in contemporary yellow pine-mixed conifer forests. In contrast, they cite a number of studies from which they determined that 15.5 tons/ha is a reasonable estimate of pre-settlement CWD biomass (simple conversion of biomass to carbon, multiply biomass by 0.5). As with snags, they point out that CWD levels are already orders of magnitude higher in beetle-killed areas than they were during the pre-settlement era.

The down dead wood carbon pool in California's forests is changing and will continue to do so in response to the recent drought. Approximately 100 million trees died during the 2011-2016 drought, many of which are in the central and southern Sierra Nevada (USFS 2016). In the short-term (1-2 years post-mortality), the primary effect is dying tree canopies but, in the intermediate term (3-10 years), surface fuels are expected to increase as dead canopy biomass falls (Stephens et al. 2018). Larger diameter down dead wood is expected to increase even more in the long-term (11-20 years; Stephens et al. 2018). The down dead wood fuel load could increase by tens to hundreds of tons/ha over the next few decades (J. Battles in Stephens et al. 2018).

2.1.5 Forest Floor

According to Boerner et al. (2008), the forest floor carbon pool, which includes duff and litter, is highly dynamic in response to fire, although this pool may quickly rebuild in a few years. Forest floor biomass can be almost completely consumed by wildfire (Kashian et al. 2006). Without disturbance, this carbon pool tends to be fairly stable. Its size, like that of the down dead wood carbon pool, is closely linked to aboveground vegetation. Carbon content of litter and duff is roughly 40% (Campbell et al. 2007). The U.S. EPA (2009) estimated that California's forests hold 0.44 Pg C in the litter layer (32.6 t C/ha). Carlson et al. (2012) estimated forest floor carbon in their Lake Tahoe Basin study plots to be about 33.5 t/ha.

2.1.6 Soil Organic Matter

The soil carbon pool, while highly variable both spatially and temporally, tends to be relatively stable after disturbance and is only indirectly tied to vegetation biomass (Boerner et al. 2008; Kashian et al. 2006; Woodbury et al. 2007). The incorporation and long-term storage of black carbon in soil may rely more on the rate of black carbon loss from forest carbon pools and the rate of soil mixing (e.g., bioturbation) than recent fire severity itself (Maestrini et al. 2017). Ryu et al. (2009) pointed out that forest soils hold almost half of all belowground carbon, an amount equivalent to the entire atmospheric carbon pool. California's forests hold 0.50 Pg C (37.6 t C/ha) (U.S. EPA 2009). It is important to consider both the direct effect of fuel treatments on soil properties (which are typically small) as well as potential indirect effects on soils from future fires. The soil organic matter pool and productivity for growing vegetation can be particularly vulnerable to soil erosion when fires burn at high severity (Busse et al. 2014; Robichaud et al. 2005). Such impacts may be especially concerning in riparian and meadow areas that may represent important long-term storage of soil carbon (Long and Davis 2016). Mass wasting (the movement of soil, rock, and debris downslope *en masse* due to gravity) may be particularly significant in areas that are vulnerable following fires, including much of southern California (Gartner et al. 2009; Gartner et al. 2008). Even though such areas might not be directly treated, their conditions are linked with the conditions and fire dynamics in upland areas. The fate of soil carbon in such cases are not well-studied in California, although recent work from Alaska suggests that mass wasting processes can be a very significant component of ecosystem losses (Potter 2018).

2.1.7 Summary

California's forested lands, including mixed conifer forests of the Sierra Nevada, contain nationally significant carbon pools that are divided into pools of varying resistance to loss. Live tree biomass, particularly the boles of large-diameter trees, is particularly important because that pool is large and can be modified by treatments and disturbances. While soils are a large pool, they are less prone to change. The down, dead fuel pool can be substantial depending on forest type and history.

2.2 Fuel Treatment Efficacy under Severe Weather Conditions

Question: Are fuel treatments effective in reducing wildfire severity and reducing carbon loss under severe weather conditions?

This question is challenging to address due to the limitations of field studies under highly variable weather conditions; consequently, much of the science relies upon modeling studies. For the purposes of this discussion, severe weather is considered those local conditions (temperature, relative humidity, wind speed, etc.) that meet or exceed 95th percentile conditions (Collins 2014). There are several empirical studies from actual wildfires that demonstrate considerable reduction in fire severity in treated areas, even during extreme fire growth and weather conditions (Ritchie et al. 2007; Safford et al. 2009; Safford et al. 2012; Prichard and Kennedy 2014; Lydersen et al. 2017). Sieg et al. (2017) found that, under high winds, canopy consumption and crowning behavior was consistently high, regardless of the density of dead trees in the stand. This finding suggests that the effects of fuel treatments will be more pronounced in mitigating wildfire severity under relatively less severe weather conditions.

Carlson et al. (2012) found that fuel treatments in the Lake Tahoe Basin successfully reduced fire severity even under severe weather conditions. Three years after the wildfire, treated and untreated stands retained similar levels of carbon, but the allocation of carbon between pools differed greatly. In the post-fire treated stands, 51% of aboveground carbon was stored in live trees while, in untreated stands, live tree carbon dropped to 7%. The authors go on to state that tree mortality in severe wildfires causes the greatest shift in (and eventually losses from) carbon pools. Fuel treatments are therefore often beneficial in high severity wildfires because of their effectiveness in reducing tree mortality, particularly when there is a risk of failed natural tree regeneration leading to long-term type conversion (Carlson et al. 2012).

Winford and Gaither (2012) used a carbon life cycle analysis to compare two fuel treatment scenarios (baseline and project) at a study site in the northern Sierra Nevada. They modeled the long-term (50 years) carbon emissions of treatments and wildfires and found that wildfire rotation (defined as the length of time necessary to burn an area equal to the area of interest, Miller et al. 2012) and wildfire severity were key determinants of whether or not a fuel treatment provides a net carbon gain. The authors performed a sensitivity analysis of modeled fire severity which showed that baseline wildfire emissions – at least in this specific case – were relatively insensitive to severity due to the high initial fuel loads. The authors point out that there is a tipping point between intensive treatment of surface fuel loads to reduce wildfire severity and potentially emitting more carbon through treatment than the forest can eventually sequester to replace that which was lost to treatment. Biomass removal should be tailored to expected wildfire severity on a case-by-case basis (Winford and Gaither 2012).

Chiono et al. (2017) modeled differences in post-fire carbon pools relative to the no-treatment scenario at a mixed conifer site in the central Sierra Nevada. Table 2 below shows the modeling outcomes across different scenarios. The area of modeled fuel treatments was held constant while the land ownership and availability for treatment varied across the scenarios (S). The S3-LF scenario represents the S3 treatments simulated under more extreme fire weather than the other scenarios. Negative values below (Table 2) represent a decline in post-wildfire carbon (C) stocks relative to the untreated scenario.

Table 2: Change in post-wildfire C stocks relative to the untreated scenario. (BG = belowground) (From Chiono et al. 2017).

	%						
Treatment scenario	**Live tree**	**Standing dead tree**	**Herb/shrub**	**Forest floor**	**Down dead wood**	**BG Live**	**BG Dead**
S1	-4	4	14	-13	-17	-3	17
S2	-4	1	14	-12	-16	-4	16
S3	-4	-1	16	-10	-15	-4	17
S3-LF	0	-16	17	-8	-13	0	-4

The authors also compared landscape carbon (live aboveground herbaceous, shrubs, tree biomass, and belowground tree roots plus litter, duff, surface fuel, snags, and dead belowground tree roots) remaining after simulated fuel treatments and three classes of wildfire (low fuel model, high fuel model, and large fires). Table 3 shows the difference in remaining landscape live and dead carbon pools for the no-treatment and S3 (greatest amount of area treated) scenarios. Simulated remaining landscape carbon stocks differed little between the three wildfire classes.

Table 3: Difference in remaining landscape live and dead carbon pools (t C/ha) for the no-treatment and S3 (greatest amount of area treated) scenarios (From Chiono et al. 2017).

	Low fuel model		**High fuel model**		**Large fire / high fuel model**	
Untreated	**NT**	**S3**	**NT**	**S3**	**NT**	**S3**
Live	115.9	91.5	113.7	90.8	106.2	86.8
Dead	36.6	29.3	38.3	29.9	43.9	32.9
Treated						
Live	-	19.2	-	19.8	-	19.6
Dead	-	5.1	-	5.5	-	5.8
Grand Total	152.5	145.1	152.0	146.1	150.1	145.1

Mitchell et al. (2009) studied three forest types in the Pacific Northwest, including a relatively drier east-side pine type that may be more similar to forests in the Sierra Nevada. They contended that more carbon is lost to treatments than what would be spared from loss by wildfire in part because fires often miss treatments and because even a high severity wildfire does not completely consume the primary carbon forest pools (boles, branches, and coarse woody debris). In the Biscuit Fire, which was in a moister environment than much of the Sierra Nevada, Campbell et al. (2007) found that the average combustion factors of small tree (DBH < 7.62 cm) boles were 70%, 70%, and 40% for severe, moderate, and low severity wildfire respectively. Meigs et al. (2009) showed that about 26 t C/ha (22%) of aboveground carbon was lost immediately after wildfires in Oregon mixed conifer stands. They found that low severity wildfires caused about 13% of aboveground carbon to be lost and high severity fires caused a 24% loss.

Research from the Sierra Nevada indicates that high severity fire does consume much of the coarse woody debris, in addition to killing the majority of trees in a stand, which result in the loss of that carbon due to decay. For example, Johnson et al. (2007) report that the 2002 Gondola Fire, which burned in mixed conifer near Lake Tahoe, California, reduced ecosystem carbon by about 31 t/ha (20%). Most of the lost carbon came from the tree carbon pool, whereas soil carbon was relatively unchanged (Table 4).

Table 4: Change in mixed conifer carbon pools due to wildfire (t C/ha, Johnson et al. 2007).

	Pre-fire	**Post-fire**	**Difference**	**Contribution to total loss (%)**
Vegetation				
Live foliage	4.3	0.4	-3.9	
Dead foliage	0	1.9	1.9	
Dropped foliage	0	0.4	0.4	

Branch	13.5	10.4	-3	
Bole	62.4	45.9	-16.6	
Total tree	80.2	60.6	-19.6	63.4
Understory	0.7	0	-0.7	2.3
Total vegetation	80.9	60.6	-20.3	65.7
O horizon + wood	11.6	1.3	-10.3	33.3
Total aboveground	92.5	61.9	-30.6	99.0
Soil	65	64.7	-0.3	1.0
Ecosystem	157.5	126.6	-30.9	100.0

Safford et al. (2012) studied 12 California wildfires that burned across fuel treatment boundaries in yellow pine or mixed conifer forests. They found that in almost all cases fire severity was reduced within 70 m of crossing into a fuel treatment. Several of these fires burned under severe weather conditions (ERC [Energy Release Component] at least 90th percentile). The authors conclude that little doubt remains about the efficacy of fuel treatments in reducing fire severity in these forest types, even under severe weather.

2.2.1 Summary

The effect of wildfire on forest carbon varies with fire severity and by carbon pool. Some carbon pools, such as soil organic matter, are relatively unchanged by wildfire regardless of the fire's severity. Other carbon pools such as tree foliage can be completely consumed in high severity wildfires. Similarly, reduction of the litter and duff carbon pool tends to increase with fire severity. Large tree boles are typically not consumed even in high severity wildfires but may be shifted into the dead carbon pool.

The effects of a wildfire on carbon pools may persist for decades as a result of slowly decaying fire-killed vegetation and shifts in dominant vegetation. Type conversion from forest to lower-carbon density vegetation types such as grassland or shrubland is a particular risk after high severity wildfire (Hurteau and Brooks 2011). Areas burned at high severity often experience a complete failure of conifer regeneration because of increased distance to seed trees and increased shrub competition (Welch et al. 2016). Fuel treatments may immediately reduce carbon storage in a forest stand, but they also help preserve the remaining carbon by decreasing fire severity. Carlson et al. (2012) showed that reducing fire severity may decrease the time required for a stand to return to its pre-fire baseline carbon stock by up to 35 years.

Good fuel treatment design should lead to decreased risk of high severity fire, and reducing surface fuel loads is one of the key components of achieving that goal (Agee and Skinner 2005). Safford and Stevens (2017) conducted a thorough review of pre-settlement and modern surface fuels in yellow pine and mixed conifer forests. The authors summarized numerous studies and showed that average pre-settlement 1- to 100-hr summed fuel loads were about 3.6 tons of biomass/ha, and pre-settlement 1- to 1,000-hr summed fuel loads were about 17.7 tons/ha. In contrast, they summarized contemporary FIA data for yellow pine and mixed conifer forests and showed that 1- to 100-hr summed fuel loads were 7.3 tons/ha on average, and 1- to 1,000-hr summed fuel loads were 30.3 tons/ha. Mixed conifer stands had much higher 1- to 1,000-hr summed fuel loads (36.7 tons/ha) versus yellow pine stands (20 tons/ha). Finally, they cited a study showing that after prescribed fire, 1- to 100-hr summed fuel loads were more than five times lower than pre-treatment levels, while 1- to 1,000-hr summed fuel loads were almost three times lower. In the case of severe weather conditions, mechanical treatments may be required in addition to prescribed fire to effectively reduce fire severity (Schmidt et al. 2008).

2.3 Impact of Fuel Treatment on Potential Stand Level Carbon Sequestration

Question: Do fuel treatments have a direct impact on potential stand level carbon sequestration?

Fuel treatments affect potential stand level carbon sequestration by removing present carbon while often increasing the potential for future carbon sequestration through both increased growth and vigor in the remaining trees and reducing overall vulnerability to disturbance and stressors (Collins et al. 2014). Whether that short-term sacrifice can exceed the long-term benefit is a key question for carbon accounting. An analysis by Campbell and Ager (2013) found that none of their simulated fuel treatment scenarios in forests of the Western U.S. resulted in increased system carbon after 80 years and that their results were largely insensitive to both biological and management variables, including treatment efficacy, treatment lifespan, fire impacts, forest recovery rates, forest decay rates, and the longevity of wood products. These authors found that even the most optimized fuel treatment design did not result in increased system carbon storage with respect to the no-treatment scenario. At the same time, the carbon cost of their simulated fuel treatments was relatively small. On the other hand, in a modeling study focused on the Lake Tahoe Basin, Loudermilk et al. (2017) found that fuel treatments had potential to reduce mortality and increase long-term carbon storage. Their results indicated mortality from drought and wildfires would be reduced through changes in forest structure and composition (shifts from fir toward pine) and, to a lesser degree, increased growth of the remaining trees by increasing available soil water. They emphasized that the climate change increased the likelihood that fuel treatments would help to avoid carbon losses due to wildfire.

Carlson et al. (2012) found that about 38% of the aboveground carbon in their Lake Tahoe Basin plots was immediately lost to fuel treatments (tree removals and pile burning). Depending on the specific modeling methods, the authors state that carbon levels in these stands will return to pre-treatment levels between 10 and 34 years faster than if they had not been treated before the wildfire. They estimate that untreated stands will require about 93 years to return to pre-wildfire carbon density. Treated stands would be expected to return to post-treatment carbon density within about 64 years after a wildfire and at least 35 years more quickly than untreated stands. The authors also provided a summary of recent literature related to short- and long-term effects of fuel treatments and wildfire on carbon stocks. All of the studies they reviewed showed a short-term reduction in carbon stocks due to fuel treatments, and, in most studies (three of five), fuel treatments reduced tree mortality or emissions during simulated wildfires. Over the long-term (100 years), however, they found a lack of conclusive evidence in those studies regarding the carbon costs of fuel treatments due to the complexity of modeling variability in wildfire severity and natural regeneration.

Winford and Gaither (2012) used a carbon life cycle analysis over 50 years to show that fuel treatments had the potential to reduce wildfire emissions by 46% when compared to the no-treatment scenario. Their carbon storage results were highly dependent on fire rotation; when fire rotation was 31 or fewer years, the fuel treatment scenario stored more carbon than the no-treatment scenario. However, with longer fire rotations, the no-treatment scenario stored more carbon. The authors emphasize that many factors must be considered and these results may not apply elsewhere.

Chiono et al. (2017) found that simulated treatments immediately reduced in-forest carbon stocks by about 14% on average. Although these treatments reduced wildfire emissions by about 50%, prescribed fire emissions more than offset these reductions, resulting in an overall carbon loss for the treatment scenarios. The authors note that their simulations were static and do not account for long-term carbon dynamics. Stephens et al. (2009) analyzed the effects of fuel treatments on carbon pools in mixed conifer stands in the northern Sierra Nevada. The mechanical-only and mechanical plus fire treatments significantly reduced live tree carbon; a mean of 31.7 t C/ha was removed to the mill while 8.8 t C/ha was left as slash or chips. None of these treatments significantly reduced dead tree carbon. The fire-only treatment was no different than the control treatment (no treatment) with respect to the live and dead tree carbon pools. The fire-only treatment increased the number of standing dead trees but these were comparatively small and did not significantly affect total carbon. Since dominant and co-dominant tree boles store the majority of live tree carbon, suppressed and intermediate trees (trees in the lowest level of the canopy receiving little to no direct sunlight) can be removed without significant carbon loss. Litter, duff, and surface fuels were significantly reduced by mechanical plus fire and fire-only treatments (>75% of carbon lost), while the mechanical-only treatment was equivalent to the control treatment. The surface mineral soil (soil carbon to a depth of 15cm) carbon pool was not significantly altered by any of the treatments (Stephens et al. 2009). Total carbon was reduced most by the mechanical plus fire treatment; fire-only and mechanical-only treatments reduced total carbon less and by similar amounts. In a follow-up of the same study from Stephens et al. (2009), Collins et al. (2014) demonstrated that tree growth seven years following the mechanical-only treatment allowed for live tree carbon to recover to pre-treatment levels. Furthermore, the overstory trees in the mechanical-only treatment consistently had the greater tree vigor compared to the other two treatments and the control. The authors explained that this would result in the higher likelihood of long-term tree survival in the mechanical only treatment.

Campbell et al. (2009) analyzed the carbon dynamics of nearly pure ponderosa pine plantations in the Tahoe National Forest following fuel reduction thinning treatments (Table 5). Unthinned control stands had the highest biomass, while biomass was lowest in stands measured three years post-treatment, and intermediate in stands measured 16 years post-treatment. Shrubs partially offset the loss of tree biomass. Fine root production also partially offset some of the coarse root loss. The authors found that the ecosystem-level ratio of root, wood, and foliage biomass – 30:60:10 – was surprisingly consistent between treatments.

Table 5: Carbon dynamics of nearly pure ponderosa pine plantations in the Tahoe National Forest (Campbell et al. 2009).

	t C/ha (interpolated from graph)							
	Tree foliage	Shrub foliage	Tree wood	Shrub wood	Coarse roots	Fine roots	Leaf litter	Dead wood
Control	7.9	0.06	55	0.37	25	1	41	11
Thinned three years earlier	3	0.17	20	0.82	10	1	35	13
Thinned 16 years earlier	4.5	0.15	32	0.75	18	1	32	10

In a nationwide study of fire and fire surrogate treatment effects on carbon storage, Boerner et al. (2008) found that prescribed fire did not significantly affect carbon stored in the vegetation pool (standing live and dead trees plus understory vegetation) in the first year (Appendix 5). In the southern Sierra Nevada site (Ca-S), however, carbon decreased by 18% over the next few years. They also found, not surprisingly, that the carbon loss due to mechanical treatment was directly proportional to the prescribed reduction in basal area. The forest floor tends to be the most dynamic pool, especially the litter layer. They found little change in forest floor-stored carbon after non-fire treatments, while fire caused a significant decrease, mostly due to litter consumption (which recovers more quickly than duff). The Ca-S and central Sierra Nevada (Ca-C) sites, which had higher intensity fire treatments than other sites, showed exceptionally high reductions. Because fire can almost entirely consume forest floor biomass, this pool can account for most of the total ecosystem carbon loss. However, it rebuilds rapidly.

The down dead wood carbon pool represents a large carbon store in many forests but Boerner et al. (2008) found that reductions of this pool due to fuel treatments did not persist beyond the first year after treatment. Therefore, typical restoration or fuel reduction treatments are not likely to significantly change the down dead wood carbon pool. A stand-replacing fire, however, can continue to add carbon to this pool for more than a century. As with the forest floor pool, the authors found that the initial reduction of the Ca-S and Ca-C down dead wood pools was exceptionally high, while the soil carbon pool did not respond to either thinning or fire treatments. Finally, the authors found little change in total ecosystem carbon storage due to mechanical or burning treatments. One exception was Ca-C where ecosystem carbon declined 20% in the first year after all treatments. Thinning and burning at the Ca-C site produced a significant reduction; the Ca-S site did not have thinning treatments applied but would likely be similar. Boerner et al. point out that the lack of a response to burning should be expected because these forests contain fire-tolerant tree species and are adapted to frequent, low severity fires.

Hurteau et al. (2009) point out that thinning can be thought of as increasing 'rotation length' by moving more forest carbon into longer residence-time storage. Thinning in Sierra Nevada mixed conifer leads to carbon storage in fewer, but larger, trees which is more representative of pre-settlement forest conditions. Hurteau and North (2008) modeled a number of fuel treatment and wildfire scenarios in Sierra Nevada mixed conifer forests. They found that after 100 years, the unmanaged stands stored the most carbon, at least until wildfires were included. In that case, the unmanaged stands had the greatest carbon emissions and reduction in live tree carbon. Thinning, however, reduced carbon release by wildfire. The greatest wildfire emissions were from the control treatment (no treatment) followed by, in decreasing order: understory thin (removing all trees between 25-76 cm DBH while retaining 40% canopy cover), overstory thin (removal of trees >25 cm DBH while retaining 22 large DBH trees per hectare), and an 1865 reconstruction treatment which was intended to produce large, low density, fire-resistant pines (North et al. 2007). Treatments that included prescribed fire had lower wildfire emissions than thin-only, although total summed prescribed fire emissions were two to three times higher than wildfire-only emissions. Direct prescribed fire emissions were low (about 4.5-18 t C/ha) but, when totaled over 100 years including wildfires, were more than emissions from no treatment. Prescribed fire emissions were tied directly to stocking level; thus, no thinning meant more emissions. More dead biomass also led to more wildfire emissions. Thinning removed 47.8 to 65.0 t C/ha, of which 60% would typically be durable wood products (Hurteau and North 2009). The authors concluded that the 1865 reconstruction stand structure, in which current stand density was reduced while large, fire-resistant pines were retained, may be the best stand structure for achieving high carbon storage while minimizing potential wildfire emissions in fire-prone forests. The authors noted that high severity wildfire may eventually release emissions three times greater than direct CO_2 emissions during the fire itself. They also cautioned that their modeling approach does not include the complex interactions of local fuel conditions, fire behavior, and weather.

Stephens et al. (2012) summarized the effects of common fuel treatments on several forest carbon pools in the Sierra Nevada (Table 6). Fire-susceptible means 75% mortality under extreme (97.5th percentile) weather conditions. These extreme conditions represent the near hottest, windiest, driest conditions experienced during a fire season. The authors point out that the Southern Sierra Nevada control site had the highest live tree carbon stocks in the Fire and Fire Surrogates study network but the fire-susceptibility of those trees is low because much of that carbon is stored in very large, old-growth trees.

Table 6: The effects of common fuel treatments on several forest carbon pools in the Sierra Nevada (Stephens et al. 2012, values inferred from figure in paper).

		t C/ha		
		Duff + Litter	Woody fuels	Total fire-susceptible live tree C
Central SN	Control	25	21	165
	Thin-only	22	22	10
	Thin-burn	5	11	0.1
	Burn-only	5	9	0
Southern SN	Control	44	48	20
	Burn-only (fall)	2	8	0
	Burn-only (spring)	10	18	0.1

2.3.1 Summary

Fuel treatments involve tradeoffs between reducing the risk of carbon loss due to wildfires and increasing carbon emissions due to the fuel treatments themselves. Whether or not fuel treatments safeguard enough carbon to offset their carbon cost depends on many factors including forest structure, existing fuel loads, expected wildfire frequency and severity, fuel treatment type and intensity, and the fate of merchantable forest products. In general, overstory thinning plus prescribed fire removes more carbon than other common fuel treatment types, while prescribed fire-only or understory thinning-only removes the least. North and Hurteau (2009) found that roughly 30-40% of tree carbon was removed by a variety of fuel treatment types. Carlson et al. (2012) found that fuel treatments can help maintain potential carbon sequestration, particularly by reducing tree mortality. Winford and Gaither (2012) point out that fuel treatments can result in a net increase in carbon stocks, but this result is highly dependent on fire rotation. Safford et al. (2012) found that, in general, at least 50% of surface fuels were removed by various types of fuel treatments. Typically, fuel treatments increase carbon emissions in the short-term, but they may reduce carbon losses when wildfires occur. A key issue is the probability of fire occurring after treatment implementation; treatments that are not impacted by wildfire do not mitigate potential emissions and can represent carbon sources as opposed to sinks (Campbell et al. 2012).

2.4 The Efficacy of Different Fuel Treatments over Time

Question: How do the impacts above vary over the immediate- (within 5 years of treatment), short- (5-20 years), and long-term (>20 years)? For example, forest treatments typically have a short-term (<20 year) cost yet can provide benefits over a long-term that may be significant from a greenhouse gas reduction strategy.

As summarized in chapter 2.3, fuel treatments reduce forest carbon stocks compared to an ‘unmanaged’ scenario in the short- and long-term. Forests containing fuel treatments will therefore store less carbon than untreated forests as long as wildfire is excluded from the landscape. However, once a wildfire occurs, forests with a proportion of its stands treated could retain more live and dead carbon than untreated forests due to changes in fire intensity and reductions in fire size induced by the fuel treatments. This effect is highly influenced by assumptions on fire probability. A meaningful carbon analysis of fuel treatments has to therefore include fire probability, treatment longevity, and, preferably, follow-up treatments as well as fossil fuel emissions associated with treatments in its system boundaries.

While Carlson et al. (2012) and Safford et al. (2012) found higher carbon stocking in treated landscapes vs. untreated landscapes following a fire, it is important to also account for temporal uncertainty of wildfires; i.e., fire probability and the condition of a treatment once a fire occurs; i.e., the longevity of treatments. Both the fire behavior in the treated stands and adjacent stands will change over time following treatment (Jain et al. 2012; Campbell and Ager 2013). Fuel treatments initially reduce stand carbon as trees are cut, and carbon from the live carbon pool is shifted towards the detrital pools, wood product pools, or immediately released into the atmosphere (e.g., pile burning, prescribed burns immediately following the treatment). Collins et al. (2011) demonstrated how conditional burn probability (a measure of fire hazard) for differing fuel treatment intensities (three different tree removal diameter limits) changed over time (Figure 2) with a substantial initial decrease in fire hazard irrespective of treatment intensity and a complete loss of effectiveness after 20 years. To affect enduring change in fire behavior on the treated site and adjacent stands (“treatment shadow effect”; Collins et al. 2013), treatments require follow-up applications such as prescribed burns following 10 years after a treatment and a re-entry after 20 years with a mechanical treatment followed by an immediate prescribed burn (Chiono et al. 2012). Due to the restricted longevity of fuel treatments, meaningful carbon analysis over longer periods has to include follow-up treatments. Repeated treatments further reducing landscape carbon elevate the importance of fire probability to assess overall carbon balances of fuel treatments. While Loudermilk et al. (2017) found that fuel treatments would lead to increases in forest C after 5-6 decades under projected climate warming, and that such benefits arrived earlier than under the baseline climate, Winford and Gaither (2012) as well as Safford et al. (2012) stress the importance of fire probability on treated vs. untreated landscape carbon balances. Higher fire probabilities in the range of a few decades may result in improved carbon balances compared to a baseline scenario even when accounting for fossil fuel emissions during treatment execution and if extracted biomass is used to offset fossil fuel use in, e.g., electricity generation.

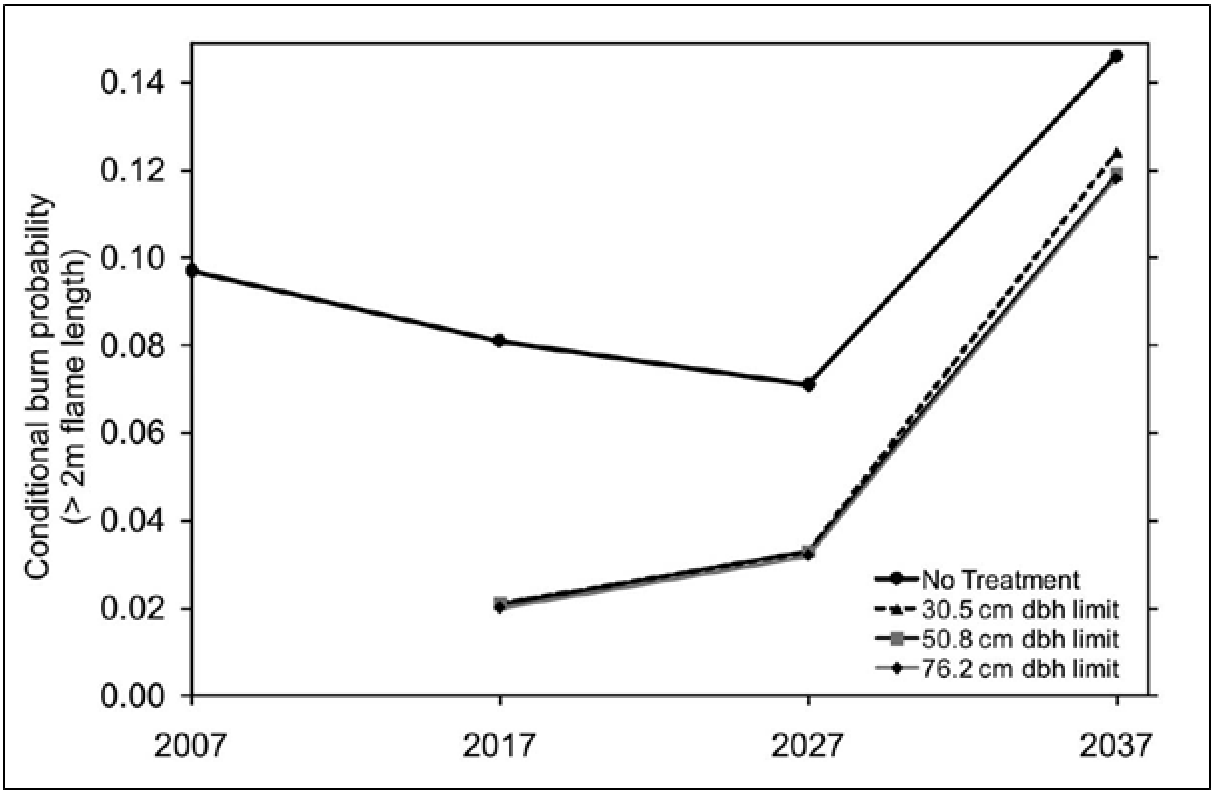

Figure 2: Treatment longevity measured by conditional burn probability (a measure of fire hazard) for differing fuel treatment intensities over time (from Collins et al. 2011).

2.4.1 Summary

Forests containing fuel treatments store less carbon than untreated forests as long as wildfire is excluded from the landscape. If wildfire occurs, forests with a proportion of its stands treated could retain more live and dead carbon than untreated forests. This effect is highly influenced by assumptions on fire probability. A meaningful carbon analysis of fuel treatments has to therefore include fire probability, treatment longevity, and, preferably, follow-up treatments as well as fossil fuel emissions associated with treatments in its system boundaries.

2.5 Impact of Different Types of Wood and Biomass on Overall Carbon Balance

Question: Do different types of wood and biomass utilization affect the overall carbon balances of a particular fuel treatment? This would include the use of removed materials for lumber, manufactured wood products, electricity production, mulch, or firewood, especially when compared with using on-site or pile or broadcast burning to dispose of these materials.

Recent studies suggest that the differences in how residual biomass from treatments are processed does affect the climate implications of different treatment strategies. These findings suggest that different treatment approaches may be most likely to mitigate climate change effects. For example, Stewart and Sharma (2015) demonstrated that forests primarily managed for timber production can provide 30% more total carbon sequestration benefits than forests managed as a reserve. They explain that more than half of the total benefits are a result of wood products substituting for more fossil fuel-intensive products. However, the importance of such variation on net climate benefits is often small compared to other sources of variation or uncertainty. For instance, in a recent study from the Sierra Nevada, Mu (2014) found that wildfire frequency was the most important factor determining carbon implications.

2.5.1 Decomposition of biomass within forests

How residual biomass is utilized is often compared with the baseline decomposition rate of biomass that remains within the forest (Campbell et al. 2011). The recent study by Mu (2014) assumed a constant annual decomposition rate (3%/year) for biomass in California based upon work by Busse (1994), but such rates (and the chemical byproducts of deposition) vary with the size, species, composition (e.g., leaves, branches, boles), and decay state (e.g., standing versus on ground, burned versus unburned) of dead woody biomass as well as local climates, treatments, insects, and other specific conditions as explained in reviews by Harmon et al. (1986) and Harmon et al. (2011). Safford and Stevens (2017) discussed decomposition in yellow pine and mixed conifer forests, explaining in particular that decomposition would be strongly related to the frequency of fire. Relatively short times needed for snag fall in some relatively dry forests of the Sierra Nevada (Ritchie et al. 2013) implies a more rapid initial phase of decomposition than in wetter forest ecosystems that are found in areas further north and west in California. In recognition of such variability, Harmon et al. (2011) caution that complex pulses, rather than monotonic responses of GHG emissions associated with decomposition, ought to be expected in forests following wildfires, and that modelers need to test assumptions that fine-scale variation is not important. However, Mu (2014) found that variation in decomposition rate did not have a significant contribution to overall uncertainty of net GHG emissions compared to other factors such as fire return interval.

2.5.2 Decomposition of harvested wood products

Ranges of the estimated half-life of different types of harvested wood products are available in Skog (2008), ranging from over two years for paper up to ~80 years for housing lumber. Stewart and Nakamura (2012) calculated an average half-life of 52 years for softwood lumber from California. Wood chips used for energy have a much shorter lifespan than sawlogs milled into building lumber; the climate benefits of the latter are also greater when displacing steel or concrete in buildings (Stewart and Nakamura 2012). However, the fraction of wood products displacing steel or concrete materials is unknown. Stewart and Nakamura (2012) also emphasize that earlier assumptions about the fate of harvested wood products need to be updated to reflect current and future industry practices that have reduced the amount of waste wood, as well as in developing newer uses of small trees.

Because the size of trees removed in a fuel reduction treatment will affect the types of wood products that can be generated, these differences in half-lives of different harvested wood products are likely to affect the climate impacts from different treatments based upon the outputs as well as the effects on the remaining trees in the forest. However, Mu (2014) found that carbon accounting was not highly sensitive to changes in the half-life of solid wood products if thinning treatments did not result in large amounts of merchantable material, which may apply to many fuel reduction treatments. In particular, increasing 100 year storage from 36% (Smith et al. 2006) to 46% (Stewart and Nakamura 2012; Gonzalez et al. 2015) to reflect efficiency improvements in the wood products industry results in modest changes to the larger carbon storage picture.

2.5.3 Physical-chemical constituents of emissions

Burning woody biomass as a fuel reduction treatment has different global warming effects than using biomass for electricity or fuels or leaving biomass to decompose because these pathways result in somewhat different emissions. While decomposition is generally expected to primarily release CO2, burning can release other GHG emissions (Ter-Mikaelian et al. 2016, see 2.11). The means of disposal of harvested wood products (e.g., incinerated, composted, dumped, landfilled) also influences emissions; wood and paper products (primarily paper) sent to landfills have been recognized as an important source of methane emissions (Skog 2008). Woody biomass that is burned in broadcast prescribed burns or wildfires will have different emission factors than harvested material that is burned for energy (Springsteen et al. 2011) because of less complete consumption and differences in the composition of the biomass being burned (Urbanski 2014). The implications of such variation on emissions are discussed further in section 2.12.

2.5.4 Summary

To the extent that the fate of forest biomass is to be burned, science suggests that the global warming effects can be minimized through controlled combustion in a biomass facility rather than in open burning. In wetter forest environments, decomposition might be a more effective means of mitigating global warming potential than burning, but leaving forest residues such as slash piles in forests is generally considered hazardous because of the potential for wildfires.

2.6 The Efficacy of Fuel Treatment in Modifying Wildfire

Question: Can fuel treatments modify the frequency, intensity, size, and duration of disturbances, including stand-replacing, high, moderate, and low severity fire?

It is virtually impossible to exclude fire from most fire-prone landscapes, such as those found across the western U.S., over long periods (Reinhardt et al. 2008). During high to extreme weather conditions, initial suppression efforts can become overwhelmed and fires can quickly grow to cover very large areas. Climate change is expected to lengthen fire seasons (Westerling et al. 2006) and shift weather toward more severe burning conditions (Millar et al. 2007; Miller et al. 2009). Suppression efforts can also be hampered under less extreme weather conditions when fuel and forest structure conditions result in forest conditions that are prone to high-intensity burning: for example, accumulations of needles from dead trees during the red-needle phase following a bark beetle outbreak (Sieg et al. 2017; Stephens et al. 2018) or when trees have been killed by sudden oak death (Kuljian and Varner 2010). However, by delaying fire returns, fire suppression may combine with ‘‘no treatment'' or ‘‘passive management'' approaches to exacerbate fire behavior in forests that evolved with frequent fire regimes (Moghaddas et al. 2010).

Various methods for fuel modification, collectively termed “fuel treatments,” can include shredding of understory biomass (mastication), removal of sub-merchantable small diameter trees and understory biomass (e.g., thinning from below), pre-commercial and commercial timber harvest (i.e., whole tree removal), and prescribed fire to remove surface (shrub, grass, down woody debris) and trees with low branches (ladder fuels), (Stephens et al 2012; Winford et al. 2015). These treatments reduce or alter fire behavior, spatial patterns, effects on ecosystems, and GHG emissions mainly by reducing the potential of crown fires and therefore fire severity (Fulé et al. 2001; Peterson et al. 2005; Moghaddas and Craggs 2007; Stephens et al. 2009a; Moghaddas et al. 2010; Safford et al. 2012; Safford et al. 2009; Stephens et al. 2012a). These studies document treatment effects on fire behavior across several treatment types and provide guidance on designing treatments for forest stands.

Efficacy and effects of fuel treatments in real world situations (e.g., wildfire) have been demonstrated in real wildfire conditions (Graham 2003; Moghaddas and Craggs 2007, Ritchie et al. 2007; Safford et al. 2009; Safford et al. 2012; Finney et al. 2005), but the majority of scientific evidence for their use comes from modeling efforts (Stephens and Moghaddas 2005; Schmidt et al. 2008; Stephens et al. 2009a; Vaillant et al. 2009; Ager et al. 2010; Moghaddas et al. 2010; Collins et al. 2011). Overall, there is a strong consensus in the published literature that fuel treatments, specifically those that incorporate thinning from below and treat surface fuels with prescribed fire, reduce potential fire severity under a range of moderate to extreme weather conditions.

Researchers have generally suggested applying a combination of strategies, especially when dealing with complex landscapes and management objectives (Moghaddas et al. 2010; Collins et al. 2011; Collins et al. 2013; Chiono et al. 2017). Management of naturally ignited wildfires for resource benefit is likely to be an important management option that needs to be integrated with mechanical fuel treatments despite management, policy, and regulatory challenges in doing so (Germain et al. 2001; North et al. 2012; North et al. 2015).

In determining how to place fuel treatments to alter fire outcomes, managers should consider current fuels, topography, access, and prevailing weather patterns. When strategically placed, treating even a portion of the landscape can result in an overall decrease in probability of high intensity fire throughout a landscape, including areas outside of treatments (Ager et al. 2007; Moghaddas et al. 2010). Several studies have demonstrated that coordinated landscape fuel treatments can reduce hazardous fire potential, even given “real-world” constraints that limit the overall area and placement of treatments (Collins et al. 2011, 2013; Chiono et al. 2017). But the untreated areas are still prone to burning with high severity. In many cases, lands with designated management emphasis, such as habitat areas and stream buffers, are distributed across the landscape. Creating fuel treatments that exclude these and other land allocations can result in a patchwork of treated areas heavily dissected with untreated areas (Chiono et al. 2017).

2.6.1 Summary

Fuel treatments will not necessarily mitigate the frequency of fire ignitions. The frequency of fire ignitions are heavily influenced by local factors including human and lightning caused ignitions which are not altered by stand structure. As discussed in questions 2.6 and 2.7, fuel treatments have been repeatedly shown to reduce fire intensity and severity in modeled and “real world” examples (Safford et al. 2012; Winford et al. 2015). This is most effective in areas where fuel treatments are integrated with direct and indirect suppression strategies, allowing a particular fire to be contained more quickly (Moghaddas and Craggs 2007). As area burned decreases, there is a general decrease in the overall duration of the fire event, which in turn can reduce overall emissions from live and dead burned fuel consumed during the active and smoldering phase of combustion. As climate change influences regional fire weather, including extended periods of drought, warmer day and night time temperatures, fuel treatments provide potential mitigation for fire intensity, size, and duration when compared with landscapes otherwise left untreated (Moghaddas et al. 2010).

2.7 The Efficacy of Fuel Treatment in Modifying Non-Wildfire Disturbances

Question: Can fuel treatments modify the frequency, intensity, size, and duration of disturbances, pests, droughts, and other non-fire mortality agents?

Fuel-reduction treatments typically have a carbon cost yet have the potential to enhance carbon storage over space and time by reducing impacts from high severity fires and also from non-fire mortality caused by the incidence or outbreak of disturbance agents such as insects and pathogens (Campbell et al. 2011). Forest insects such as bark beetles (Coleoptera: Curculionidae: Scolytinae) can affect larger areas than fire (Raffa et al. 2008) and can impact the frequency and severity of fire (Logan et al. 2003; Jenkins et al. 2013; McCarley et al. 2017). Bark beetles can interact with other disturbances, spatially and temporally, depending on specific landscape and species characteristics (Waters and Stark 1980) and can form complexes with pathogens or other disturbances that can lead to combined or synergistic effects (Kane et al. 2017; Preisler et al. 2017).

Since bark beetles have a narrow host range or are host specific (Furniss and Carolin 1977; Raffa et al. 2015) and preferentially colonize overstocked, weakened, stressed, and/or previously damaged trees, for example from fire, drought, or pathogens (Furniss and Carolin 1977), fuel treatments that target stand composition and density can impact the frequency and severity of bark beetle incidence and reduce stand susceptibility to future bark beetle attack (Furniss and Carolin 1977; Waters and Stark 1980; Samman and Logan 2000; Fettig et al. 2006; Fettig et al. 2010; Raffa et al. 2015). Such indirect treatment strategies (Fettig et al. 2014; Gillete et al. 2014) can be preventative by targeting stand susceptibility in order to limit favorable forest conditions for bark beetle attack, or restorative by targeting stand diversity in species composition, age, and structure in order to promote and reestablish the functional role of endemic populations of bark beetles (Samman and Logan 2000). Regardless, mechanical thinning treatments aimed at reducing density and competition have been widely promoted to reduce the amount of bark beetle-caused tree mortality (Fettig et al. 2007).

2.7.1 Thinning treatments and subsequent bark beetle-caused mortality

Fettig et al. (2012) assessed the effect of thinning prescriptions that specifically targeted stand susceptibility to bark beetle infestations on subsequent levels of bark beetle-caused tree mortality in Jeffrey pine forests in the Tahoe National Forest over a 10-year period. For the duration of the study, only 107 trees were killed by bark-beetles across all treatments. Treatments were implemented using thinning from below prescriptions and were comprised of an untreated control and low density, medium density, and high density thinnings to a targeted residual basal area. The untreated control was the only treatment in which bark beetle-caused tree mortality was recorded for every year measured. In the low density thin treatments, there were no bark beetle-killed pines throughout the 10-year period. Significantly fewer trees (ha/year) were killed in the low density thinning treatments than in the high density thinning treatments or untreated control. Mortality was very low for Jeffrey pine (<0.2% per year), while the majority of mortality was concentrated in white fir (75 trees, 71% total mortality).

Additionally, Egan et al. (2010) examined bark beetle-caused conifer mortality within forested areas of the Warner Mountains located in the Modoc National Forest (CA) that were thinned from 1985 to 1998 prior to a period of high levels of tree mortality from 2001 through 2007 which resulted from drought and bark beetle incidence. These density-thinning prescriptions included pre-commercial, commercial, and insect salvage thinning. Results indicated that density of bark beetle-caused mortality was reduced in pre-commercially-thinned areas within ponderosa and Jeffrey pine plantations and correlated with measures of stand density including trees per area, basal area, and stand density index (SDI). Both the density and percent of bark beetle-caused mortality and percent mortality were significantly less in the pre-commercially-thinned stands compared to the non-thinned stands. There was no detectable difference in percent of bark beetle-caused mortality between commercially thinned and unthinned mixed conifer stands. Density of bark beetle-caused mortality was reduced, although not significantly, between these stands. Findings from this study support thinning ponderosa pine plantations to reduce bark beetle-caused mortality, especially during periods of drought.

Paradoxically, mechanical treatments, including thinning prescriptions, can also inadvertently damage, stress, or weaken residual trees through mechanical injury from equipment, post-treatment vulnerability to increased windfall, or through the accumulation of residual fuels, and thereby have the potential to increase bark beetle activity and subsequent mortality (Wood et al. 1985; Fettig et al. 2006; Fettig et al. 2007; Jenkins et al. 2008). Fettig et al. (2006) assessed ponderosa pine stands in California and Arizona to determine if mechanical fuel treatments influenced the susceptibility of residual trees to bark beetle attack and if chipping and lop-and-scatter treatments and seasonality of treatment had an effect on subsequent bark beetle activity. All treatments consisted of thinning from below of hazardous fuels and were conducted in either spring or late summer. All tree biomass was retained within plots following felling and was either chipped and randomly dispersed or lopped-and-scattered. No significant differences in the amount of bark beetle-caused tree mortality were observed among treatments; however, a significant treatment effect was observed among the percentage of residual trees that were attacked by bark beetles. The mean percentage of trees attacked by bark beetles ranged from 2.0% in the untreated plots to as high as 30.2% in the chipped plots treated in the spring. Furthermore, a significantly higher percentage of *P. ponderosa* were attacked on plots chipped in the spring than those chipped in late summer, and significantly more trees were attacked on plots chipped in the spring than in the untreated control. Results from this study suggests that even though there were no significant differences across treatments in the amount of bark beetle mortality, bark beetle attacks can be exacerbated through chipping of forest thinning residues in *P. ponderosa* stands and can have the potential to lead to increased mortality in the future. The authors reported a three-fold increase in the proportion of residual trees attacked in chipped versus lopped-and-scattered treatments. Also, the timing of treatment can also influence bark beetle attack if conducted during peak periods of adult bark beetle flight activity.

2.7.2 Thinning treatments combined with prescribed fire and subsequent bark beetle-caused mortality

In a mixed-conifer forest in the central Sierra Nevada, Stark et al. (2013) assessed conifer mortality caused by bark beetles in response to prescribed fire and mechanical treatments and found that overall mortality across all treatments was under 7%. The treatments were: a no treatment control; prescribed fire only; mechanical only thinning from below followed by mastication of understory conifers and hardwoods less than 25 cm DBH; and mechanical plus fire using the same mechanical treatment followed by prescribed fire. The greatest overall bark beetle-caused mortality (slightly above 7%) across all treatments occurred in small and medium white firs in treatments that included fire (prescribed fire only and mechanical plus prescribed fire) and were otherwise low for all other tree species. This level of mortality was consistent with the objectives of the study to reduce the density of suppressed, understory white fir. Bark beetle-caused mortality was the lowest in the mechanical only treatments and was either extremely low (under 0.2%) or zero across all tree species. These findings were comparable to other Fire and Fire Surrogate (FFS) studies conducted in the Southern Cascades by Fettig et al. (2010) who also reported overall low bark beetle-caused mortality (~5%) but showed lower findings than a similar study conducted in the Teakettle Experimental Forest by Maloney et al. (2008). Results from these studies indicate that, for the short-term (three years post-treatment), there were fewer risks to the residual forest in the mechanical treatments from bark beetle attack when populations of bark beetles were low (pre-treatment assessments confirmed that bark beetles were at endemic levels since bark beetle-caused mortality was uniformly low or zero across all treatments).

In an interior ponderosa pine forest at Blacks Mountain Experimental Forest in California, Fettig and McKelvey (2014) evaluated the effects of fuel-reduction and forest-restoration treatments on levels of bark beetle-caused mortality. They contrasted mechanical thinning treatments between plots with low structural diversity by removing larger overstory and small understory trees, and plots with high structural diversity by leaving large trees and removing smaller ones. Prescribed burning was conducted on half of each plot treated by the two thinning prescriptions. Results revealed that 5.6% of trees across treatments were killed by bark beetles over the 10-year duration of the study, with most of those trees (87%) being of a smaller diameter (<34.3 cm) while noting that one species of bark beetle, the western pine beetle (*Dendroctonus brevicomis*), did kill many larger diameter pines. They suggested that the two different forest structures exhibited similar resilience to bark beetle infestations and other disturbances, and that the limited mortality following treatments did not appear to interfere with management objectives. Furthermore, gradual treatments conducted prior to prescribed burning might help to reduce mortality of large pines. The authors added that there was variation between their sampling periods, and that longer-term studies are needed to better account for such variation.

2.7.3 Summary

The aforementioned studies reported either overall low mortality or no measurable effect from bark beetles in residual stands post-treatment(s) with the exception of Fettig et. al (2006) who reported an elevated level of bark beetle attacks (not increased mortality), as much as 30.2%, in ponderosa pine plots that were thinned in the spring with all biomass chipped. In all cases, results depended not only on treatment, but also on study site characteristics (topography, aspect, average temperature, etc.), timing and frequency of treatment, species composition and density, and background population levels of bark beetles. None of the studies presented here took place during outbreak or epidemic levels of bark beetle populations, nor did they occur in study sites with widespread bark beetle caused-mortality pre-treatment. Since bark beetle dynamics are unpredictable, there will almost always be uncertainty in managing for bark beetles regardless of treatment. These studies demonstrate that fuel treatments can modify the frequency, intensity, size, and duration of disturbances caused by bark beetles, thereby influencing effectiveness for climate change mitigation.

2.8 Varying Carbon Balance under Different Post Wildfire Treatments

Question: How do the carbon balances, including in-forest black carbon in areas burned by wildfire, vary under different post wildfire treatments (e.g., salvage, reforestation) over time?

2.8.1 Effects of post-fire treatments

Studies of the effects of post-fire forest treatments on carbon have been relatively limited in California, and recent studies, such as Power et al. (2013), focused on short- to mid-term changes to in-forest carbon rather than a fuller accounting that considers harvested materials and long-term dynamics. Regarding soils, Powers et al. (2013) noted that carbon in the mineral soil fraction generally decreases relative to the amount of soil disturbance produced by the management operation (Table 7), but they also cite other studies that show differing responses in other ecosystem types. They studied in-forest carbon stores 10 years following a wildfire in a Sierra Nevada mixed conifer forest across several treatments: a green canopy designation reflected no post-fire intervention in burned areas that experienced very low (<5%) tree mortality; the intensive management treatment occurred in high severity patches that were treated with salvage logging, soil ripping, and tree planting (a treatment that may be more representative of many private timberlands); the no salvage treatment was a stand-replacing wildfire with no intervention; and the salvage and planted treatment involved high severity burned areas that were logged and planted with no soil ripping (which is representative of typical salvage of public lands). They found that total carbon stores and stores in "recalcitrant" forms such as snags and trees were greatest in the no salvage treatment areas; they also found the carbon in mineral soil was lower in the treatment that involved soil ripping.

Table 7: Carbon pools after post-wildfire management (t C/ha, Powers et al. 2013).

	Green canopy	Intensive management	No salvage	Salvaged and planted
Aboveground tree	81	4.1	0	0.4
Aboveground snag	6.5	0.5	82	0
Stump	0.6	11	8.2	2.8
Aboveground understory	1.3	0.2	5.2	5.6
Coarse wood	9.9	19	81	23
Fine wood	1.4	9.5	13	13
Duff	5.5	1.8	5.7	4.6
Mineral soil	100	55	88	88
Total	206	101	283	137
Salvaged		68.8		62.5

Johnson et al. (2005) studied east-side Sierra Nevada Jeffrey pine sites that had experienced stand-replacing fire in 1981. The "shrub" sites experienced stand-replacing wildfire and were then salvage logged. The "forest" sites were burned at low intensity with little mortality of mature trees. The authors compared carbon in the "A" (upper) soil horizon and found that the shrub (burned and salvage logged) plots contained significantly greater carbon than the forest (relatively unburned) plots. Carbon in the "O" (lower) soil horizon was also significantly greater in the shrub sites than in the forest sites (29 kg/ha vs 15 kg/ha). On the other hand, the forest sites contained significantly more carbon in the vegetation pool than the shrub sites (89 kg/ha vs. 10 kg/ha). Carbon density in large woody debris and soil was not significantly different between plots. Ecosystem carbon (excluding roots) was significantly greater in the forest sites (160 kg/ha vs. 112 kg/ha) due to greater vegetation carbon density.

The authors also estimated the relative effect on carbon of volatilization, conversion to ash, salvage logging, and increases in soil, O horizon, and vegetation mass from the time of the fire until sampling (Table 8). Most of the carbon lost from the burned plots was due to salvage logging (15 t C/ha volatilized; 54 t C/ha salvaged). Increases in carbon in the vegetation and O horizon pools more than offset carbon losses due to volatilization and are far short of the losses due to salvage (2 t C/ha from soil; 6 t C/ha from vegetation; 21 t C/ha from O horizon). They also found that post-fire nitrogen gains due to early-successional nitrogen-fixing shrubs (*Ceanothus velutinus*) exceeded nitrogen lost to the fire and to salvage logging combined. Therefore, they concluded that there was potential for the fire to have boosted site productivity, such that if the site eventually reverts to forest, it is likely that net ecosystem carbon could equal or exceed pre-fire levels. However, both this study and a related study (Johnson et al. 2007) noted that there is still a long period of lost carbon storage during which the mature forest must regrow. Furthermore, the Johnson et al. (2005) study did not separate effects of the fire and the salvage, so it does not demonstrate any benefit of salvage to offset the immediate carbon loss.

In summary, the effect of salvage logging on individual carbon pools can be difficult to predict over long time periods, and reforestation dynamics, which are often practically linked to salvage (e.g., managers tend to avoid replanting in areas that have not been salvaged for safety and fuel loading concerns), add even more temporal and spatial complexity. In theory, salvaging and replanting could accelerate carbon recovery in the long-run despite the short-term cost. Indeed, when former forests are at risk of converting to non-forest carbon sequestration, it may be an important objective for post-fire treatments (Hurteau and Brooks 2011). Long-term modeling and experimental studies are needed to evaluate these dynamics.

2.8.2 Black carbon

The term black carbon (BC) refers to pure carbon that results from the incomplete combustion of organic matter during the burning of biomass (Goldberg 1985). Because it is relatively resistant to decomposition, BC represents a long-term carbon pool, as it is eventually deposited in water bodies (e.g., lakes, wetlands, oceans) or incorporated into soils (Schmidt and Noack 2000). The term black carbon is applied to material that remains in the forest (in-forest black carbon), often on the surface or in the soil as “charcoal” or “biochar”, and to material that is emitted into the atmosphere as “atmospheric” or “aerosolized” BC. The impacts of aerosolized BC particles are discussed further in Section 2.11, because they have complex effects on global warming (see Jacobson 2001; McConnell et al. 2007; Sasser et al. 2012; Myhre et al. 2013). The research emphasis on BC aerosols has often focused on fossil fuel combustion, but it has also explored effects of forest fires.

There are several open questions about rates of BC generation and fate, and these are made more complicated by the lack of consistent terminology used between studies. Technically, BC can be limited to graphene/graphite and has been considered just one form of “pyrogenic carbon,” which also includes soot and biomass that has been charred to different degrees (Bird et al. 2015). Many studies, however, simply refer to these forms collectively as BC, despite the fact that they exhibit varying activities and degradation rates in the natural environment; it is therefore not surprising to find relatively wide ranges of BC production and lifespan reported among studies. Regardless, most of these fire-generated materials are reported to have a minimum lifespan as sequestered carbon that is on the order of decades to centuries. "Biochar" is the term often used to describe material produced through the intentional combustion of waste biomass, for the purposes of amending soil quality and sequestering carbon (Lehmann 2007; Woolf et al. 2010). There has been growing interest in pyrolysis technologies that convert low-value biomass from fuel reduction or thinning treatments into more portable biofuels, with charcoal as a by-product that could be returned to forest soils, as a means of mitigating carbon emissions while treating forests (McElligott et al. 2011; Page-Dumroese et al. 2015). Continued research into these technologies is needed to evaluate their influence on greenhouse gas emissions.

2.8.2.1 In-forest black carbon dynamics

Schulze et al. (2000) drew attention to forests and their management in carbon sequestration, highlighting the importance of BC from wildfires. Despite major recent interest in the role of BC in global carbon cycling (e.g., Bond et al. 2013; Bird et al. 2015; Coppola and Druffel 2016; Santín et al. 2016; Surawski et al. 2016), relatively few new studies directly focus on how forest and/or fire management might alter BC production and its subsequent dynamics. In particular, the topic of interest for this report section—how post-fire treatments of salvage logging and reforestation could affect BC—is almost absent from the literature. Hence, included here is a review of the material that is relevant to this question and a synthesis of what is likely to apply in the context of California forests.

In a given wildfire, the percentage of carbon converted to BC is often assumed to be 1 to 5% of C burned (Preston and Schmidt 2006). Some studies have reported substantially higher amounts (e.g., > 25% by Santín et al. 2015), highlighting the importance of standard accounting methods that include different fire-generated carbon components. Although much of the BC produced in wildfires is subsequently transported offsite via erosion processes, some mixes into soils belowground. Estimates as high as 35% of soil organic carbon being due to BC have been reported for certain ecosystems (Forbes et al. 2006), while others report ranges as high as 60% (Preston and Schmidt 2006). The review of DeLuca and Aplet (2008) estimates BC to account for 15-20% of total carbon in temperate conifer forest soils, and a study from the Sierra Nevada in California falls roughly into this range (Mackenzie et al. 2008).

In a more recent study from the Sierra Nevada, Wiechmann et al. (2015) found substantially less BC in forest areas. They found that charcoal carbon represented only 0.29% of total ecosystem carbon (live tree, shrub, snag, coarse woody debris (CWD), fine woody debris (FWD), and soils to 30 cm, with charcoal constituting 0.03 to 0.78 Mg C ha-1 compared to 78 to 287 Mg C ha-1 in live trees.. Methodological differences may contribute to the discrepancies between studies. For Wiechmann et al. (2015), the untreated control had substantially less charcoal carbon than treatment sites (burn-only, understory-thin and burn, and overstory-thin and burn). In another study from the northern Sierra Nevada, Maestrini et al. (2017) found that fires of different severity altered the storage of black carbon, specifically finding that high severity fires depleted black carbon in the forest floor and increased it in standing trees and debris, compared with lower severity fires that added black carbon to the forest floor. They reported that 2-3 years after a wildfire in the northern Sierra Nevada, areas that burned at high severity had 3.5 times greater aboveground black carbon stocks than areas burned at low to moderate severity, yet total carbon stocks in standing trees were 30-23% lower in burned areas than nearby unburned control areas (<2000 m outside of the fire perimeter); however, they do not suggest that sequestration of black carbon in dead wood or soils (or the influence of treatments) is a major factor at the landscape scale.

Effects of black carbon on ecosystem processes remains a subject of considerable scientific uncertainty. For example, one recent study (Bryanin et al. 2018) found that increases in charcoal resulted in more rapid decomposition of fine roots and release of soil carbon following fire in boreal larch-dominated forests in Russia. Those authors summarized research on the topic by noting that the influence of charcoal on organic matter decomposition is highly context-dependent.

2.8.2.2 Changes in black carbon due to post-wildfire salvage logging

The review of DeLuca and Aplet (2008) highlighted that salvage logging (or thinning without prescribed fire) may reduce soil BC content and therefore long-term carbon sequestration by removing the dead and charred trees that might increase soil charcoal. As noted above, numerous publications demonstrate the substantially lower abundance of standing dead trees and downed woody material after salvage logging (e.g., Macdonald et al. 2007; Lindenmayer et al. 2008; Palik and Kastendick 2009; D'Amato et al. 2011), indicating a loss of BC following salvage. When left in place after a fire, such dead trees and logs can also burn in a subsequent fire and produce additional BC (e.g., Donato et al. 2009). In particular, short-interval reburns (≤10-year fire return) of patches can cause a net increase of black carbon on coarse woody debris despite reducing CWD biomass (Ward et al. 2017). Black carbon is a topic of growing research, although it seems difficult to generalize about its significance for evaluating the GHG benefits of various treatment practices. For example, a recent review by Busse et al. (2014) found that there was insufficient information to inform prescriptions for fuel reduction treatments intended to increase charcoal content in soils. Although the amounts of BC lost may be relatively small for any given fire, they do represent a long-term loss of potential carbon sequestration and merit deeper consideration. Much greater research on this question, particularly in the context of California environments, is needed.

2.8.3 Summary

The effect of salvage logging on individual carbon pools is not always predictable, and there is uncertainty around this topic in the published literature-more studies are needed in this area. Soil carbon is generally stable. Salvage harvesting will decrease the dead tree carbon pool but other pools such as surface fuels may increase or decrease depending on the implementation of the salvage operation. Overall, however, total carbon would be expected to decrease in the short-term as a result of salvage logging but may equal or exceed pre-fire/pre-salvage levels in the long-term. Black carbon is a topic of growing research, although it seems difficult to generalize about its significance for evaluating the GHG benefits of various treatment practices.

2.9 Predicting Carbon Loss with Fuel Treatment Parameters

Question: Can fuel treatment parameters (intensity, age, extent) be used to predict post-treatment potential biomass consumption (carbon loss) and emissions by wildfires?

Fuel treatments can reduce fire severity in the treated and adjacent stands considerably (e.g., (Collins et al. 2011, also see chapter 2.4). Empirical studies (e.g., Carlson et al. 2012; Safford et al. 2012) as well as model-based analysis (e.g., Campbell and Agner 2013; Collins et al. 2011, 2013) provide the foundation to link treatment parameters to post-wildfire carbon loss. For the Tahoe Basin, Carlson et al. (2012) found that removing 36% of a site's biomass during treatments resulted in a 22% reduction of total aboveground C storage due to pyrogenic emissions. For four large 2002 fires covering 508,000 ha in the western US, Hurteau et al. (2008) simulated that an 18% biomass removal during treatments reduced pyrogenic emissions by 32%. Several studies (e.g., Safford 2009, 2012; Carlson et al. 2012) discuss the significant changes in carbon fluxes from the live to the dead carbon pools when implementing fuel treatments without quantifying immediate post-wildfire total carbon stock loss, i.e., pyrogenic emissions. In general, treatments that include prescribed burns provide better carbon benefits than treatments that rely solely on thinnings (Hurteau and North 2009; Hurteau et al. 2014).

In summary, carbon consequences can be modeled prior to a specific treatment implementation based on fuel treatment parameters but is difficult to generalize due to the multifactorial nature of treatment as well as biotic and abiotic stand characteristics.

It is important to note that in order to achieve stand characteristics that are conducive to reduced post-wildfire carbon loss, i.e., a moderated wildfire severity, research indicates that treatments have to be i) pervasive and ii) repeated periodically (15 to 20 years; see chapter 2.4). Concerning pervasiveness, relative acreage treated and fuel treatment placement also contribute significantly to the observed change in wildfire behavior (e.g., Krofcheck et al. 2017b). Typical goals are to treat 20-30% of wildfire-prone acreage with mechanical and/or prescribed burning (e.g., North et al. 2009) while more recent research indicates the need to treat a higher percentage of acreage, such as 50-60%, to affect wildfire behavior (e.g., Krofcheck et al. 2017b). It is important to note that this area can include not just treatments, but areas of less burnable vegetation (i.e., meadows), non-flammable cover types such as fields of talus or bodies of water, and areas that have previously been burned by wildfire.

Yet, fuel treatments themselves (i.e., the specific silvicultural management prescription and placement) and their longevity is not the only factor describing their effectiveness to reduce wildfire severity. Another key issue is the probability of fire occurring after treatment implementation (North and Brook 2011). Treatments that are not impacted by wildfire do not change wildfire behavior; hence their effectiveness is determined by the chance event of being hit by a wildfire. The probability of wildfires occurring is influenced by anthropogenic and non-anthropogenic parameters and has been altered significantly in the last century (Mann et al. 2016). Successful fire suppression policies in the last decades have caused reduced annual fire probabilities while also increasing fire severity (Safford and Van de Water 2014; Steel et al. 2015). Since low severity wildfires have been reduced in occurrence, including prescribed burns (Mallek et al. 2013) at a regional level, the chance of a wildfire encountering a treated area can be low (Campbell et al. 2012). In this context, fuel treatments have to be understood as a collective insurance effort where sufficient acreage has to be treated with deliberate placement of the fuel treatments to achieve a landscape-scale reduction in wildfire severity (Krofcheck et al. 2017b). While carbon losses due to treatments are certain when implemented, carbon loss reductions due to reduced fire severity have to be discounted by wildfire probability. An analogy would be the installation of guard rails to prevent severe accidents when straying off specific road segments. Only a fraction of the installed guard rails will ever see use but only through a large-scale installation effort do these measures result in the desired and measurable benefit.

2.9.1 Summary

Forest specific carbon pools and fluxes can be modeled prior to a specific treatment implementation based on fuel treatment parameters but is difficult to generalize due to the multifactorial nature of treatment as well as biotic and abiotic stand characteristics. In general, treatments that include prescribed burns provide better carbon benefits than treatments that rely solely on thinnings. It is important to note that in order to achieve stand characteristics that are conducive to reduced post-wildfire carbon loss, i.e., a moderated wildfire severity, research indicates that treatments have to be i) pervasive and ii) repeated periodically (15 to 20 years). Another key issue is the probability of fire occurring after treatment implementation.

2.10 Potential Tradeoffs of Fuel Treatment Options

Question: Are there other potential effects and tradeoffs with other influences on non-carbon dioxide (CO_2) GHG emissions such as methane (CH_4), nitrous oxide (N_2O), and ozone (O_3)?

Either total carbon or carbon dioxide (CO2) has been the primary focus in published modeling studies that compared outcomes from wildfires versus fuel treatments such as prescribed burning or biomass removal. However, a number of other emissions are important in evaluating effects on climate change as well as air quality pollution such as particulate matter and ozone, which are critically important in California. To fully evaluate the climate change implications of different fuel treatments (including no treatment), it is appropriate to consider non-carbon dioxide greenhouse gas emissions because different mechanisms of biomass reduction (even different kinds of wildfire) may have different potentials to exacerbate global warming. The relative importance of such variation is not clear, in part because of uncertainty in the global warming potential of specific constituents and in the emissions factors for different forms of biomass reduction/burning. Global warming potential is quantified for various constituents to help compare their impacts relative to carbon dioxide (seeCARB 2018) for a description and examples of 100-yr global warming potentials). However, those estimates vary, especially with different time frames, and are subject to change as research advances (Sasser et al. 2012; Myhre et al. 2013). In many cases, the errors associated with estimating actual biomass removed are so great that they may dwarf such chemistry differences when estimating actual global warming impacts. However, those differences may still be important in comparing alternative strategies such as fuel treatments.

Carbon in woody biomass that is burned is left as combustion residue (charcoal and ashes), or released as CO_2, carbon monoxide (CO), methane (CH_4), non-methane hydrocarbons (NMHC, also known as volatile organic compounds or VOCs), oxygenated organics, and particulate carbon (Delmas et al. 1995; Stephens et al. 2007). Scientists have been evaluating the very complex dynamics associated with open biomass burning which include, not only the above mentioned gases and aerosols (including black and brown carbon, tar balls, and reflective particles), but also heat and moisture fluxes, cloud absorption effects, and aerosol effects on clouds (Jacobson 2014). Emissions from biomass are not merely a concern from a climate change perspective, but also from a public health perspective, as many of the emissions from biomass burning are contributing to significant air pollution problems in many communities (Schweizer and Cisneros 2014).

Methane and carbonaceous aerosols (organic aerosols and black carbon) have significant global warming potential although they do not persist in the atmosphere as long as other pollutants such as carbon dioxide. Wildland fires also release carbon monoxide, non-methane organic compounds (NMOC), nitrogen oxides (NO, N2O, NO_2), ammonia (NH_3), and sulphur dioxide

(SO_2) (Urbanski 2014). Carbon monoxide, NMOC, and nitrogen oxides contribute to the formation of ozone, which itself is a complex greenhouse gas when in the troposphere. Carbon monoxide and non-methane organic compounds also have global warming potential as they break down and alter the breakdown of methane. Black carbon also has a particularly potent global warming potential, although it is relatively short-lived, so reductions in those emissions would have potential to have nearer-term benefits (Sasser et al. 2012).

There remains considerable uncertainty in the relative climate-forcing effects of different kinds of biomass burning; however, limiting climate analyses to carbon dioxide effects alone likely underestimates the impacts of open biomass burning (including wildfires) by ignoring emissions of methane, carbon monoxide, and other gases, as well as particles of black and brown carbon based upon both their direct effects and indirect effects (including effects on clouds, snow, and ice), as compared to either decomposition or combustion in biomass-to-energy facilities.

2.10.1 Non-carbon dioxide gases and particles with global warming potential

Because different mechanisms of biomass reduction can influence how different pollutants are released and the resulting climate impacts, it may be important to consider non-carbon dioxide gaseous emissions, especially methane and nitrous oxide in a full accounting framework. For example, although the amount of methane released is quite small compared to carbon dioxide (see Figure 3) and it is shorter-lived than other greenhouse gases, it has 28 times the global warming potential (over 100 years) of CO_2, while nitrous oxide has 265 times greater potential. Some emissions, including carbon monoxide (CO), ozone, and black carbon, are relatively short-lived and have variable impacts depending on where they are emitted; consequently, it is more difficult to specify their global warming potentials.

Understanding the tradeoffs between carbon dioxide and methane in particular could be important in evaluating global warming impacts. For example, Hall (2011), in his master's thesis, concluded that "two thirds of the permanent GHG impact" from pile burning was due to emissions of methane in wet forests of British Columbia. That study defined "permanent" as effects beyond 100 years. However, the study is not directly applicable to forest types in California that are far less wet. For one reason, the physical and chemical effects are likely to differ (as shown by studies that compare emissions from fuels under different moisture conditions as discussed in this section). Perhaps more importantly, the risk of leaving untreated slash in California is likely to be far more hazardous in terms of wildfire effects. Nevertheless, the study demonstrates that different chemical pathways of biomass treatment can impact global warming accounting, particularly if they involve powerful greenhouse gases such as methane.

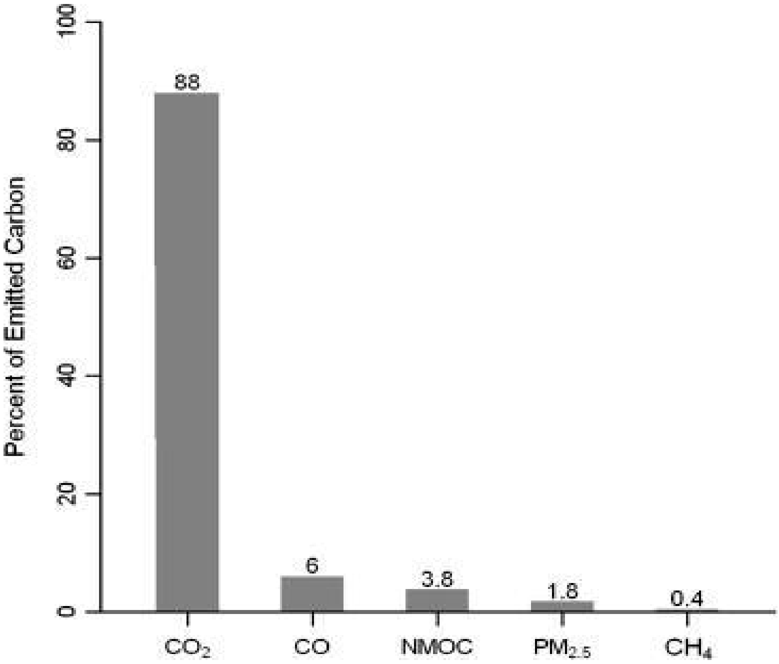

Figure 3: Partitioning of carbon emissions for pine forest understory prescribed fires from Urbanski (2014), based on data from Table 2 of Yokelson et al. (2013); it does not consider some unidentified non-methane organic compounds.

The chemical composition of emissions from different kinds of biomass burning may vary due to several factors, including fuel moisture, which is critical in controlling the carbon and nitrogen partitioning of biomass burning. The availability of oxygen determines the extent to which fuels are completely combusted (forming primarily carbon dioxide and water) versus releasing reduced compounds such as methane and carbon monoxide, which are preferentially emitted through smoldering phases of burning. Chen et al. (2010) explained that carbon dioxide, nitrogen oxides, and nitrogen gas (N_2) are associated with flaming combustion, while carbon monoxide and ammonia are associated with post-flame smoldering. Consequently, variations caused by burning fuels with different moisture, due to season of burning, precipitation events, or intentional wetting of fuels, has potentially important implications for quantifying greenhouse gas emissions. For example, spring burning under moist conditions could lead to increased emissions of particulate matter, carbon monoxide, and other regulated air pollutants while reducing the relative amount of carbon dioxide emissions (Chen et al. 2010). Note that Chen et al. did not measure methane in their study, and nitrous oxide was below their detection limits.

In an analysis of global warming in forest systems, Hurteau et al. (2014) included projections for methane, non-methane organic compounds, and nitrogen oxides in addition to carbon dioxide. However, they assumed that burn severity had different effects on global warming due only to differences in biomass burned rather than the chemical composition of the emissions. However, Liu et al. (2017) and Urbanski (2014) quantify how emissions factors also vary with burn severity. For example, wildfires tend to emit relatively more methane than prescribed fires through greater consumption of fuels that are prone to smoldering combustion, such as stumps and logs (Urbanski 2014).

The impacts from nitrous oxide (N_2O), a product of incomplete combustion, might also be important because of its potency as a greenhouse gas (Cofer et al. 1991). However, Urbanski (2014) reported no difference in emissions factors for nitrous oxide from prescribed burns and wildfires in the Pacific Northwest conifer forests (or with those kinds of fires in southeastern conifer forests). He did report that carbon monoxide emission factors were greater in wildfires from Pacific Northwest conifer forests than in prescribed burns. This result is consistent with greater emission factors for methane, which is similarly a product of incomplete combustion.

2.10.2 Aerosolized black carbon

Black carbon (BC) aerosols can play an important climate-forcing role in the atmosphere (e.g., Jacobson 2001) by altering the albedo of snow and ice (e.g., McConnell et al. 2007), although there remains considerable uncertainty in their net effects (Sasser et al. 2012; Myhre et al. 2013). Given their potential impacts, however, it is important to consider those emissions in the context of forest management (Liu et al. 2014). Aerosolized black carbon from wildfires can have effects on snowpack that are particularly important in regions that are dominated by snow and ice (the cryosphere), such as polar, boreal, and high mountain regions (Khan et al. 2017). High elevation snow areas in the Sierra Nevada are already being impacted by black carbon aerosols from China (Hadley et al. 2010). Large, high severity wildfires (particularly those characterized by pyro-cumulonimbus clouds) are more likely to loft such particles into the upper troposphere or even the stratosphere where they can be transported to remote snow-dominated regions (i.e., the cryosphere) (Khan et al. 2017; Peterson et al. 2015). Consequently, fuel treatment reductions in California that avert such large and high severity fires have potential to mitigate such climate-influencing effects. However, modeling such effects sufficiently to evaluate tradeoffs would be complex given the large scales and uncertainty in deposition patterns.

2.10.3 Considering overall global warming potential

Burning in biomass utilization facilities results in more complete combustion than pile burning, yielding greater carbon dioxide and less carbon monoxide and methane per unit of biomass consumed. In a study in mixed-conifer forest in the Sierra Nevada, Springsteen et al. (2011) estimated that utilization of treatment residuals as fuel in a co-generation (combined heat and electricity) plant, as compared to pile burning, reduced particulate matter (PM) emissions by 98%, nitrogen oxides (NOx) by 54%, non-methane organic compounds by 99%, carbon monoxide (CO) by 97%, and methane by 96%. They estimated a 15% reduction in carbon dioxide by using the residuals for co-generation and thereby displacing non-renewable fossil fuel energy (they assumed natural gas would be displaced in their study). They estimated a 17% reduction in carbon dioxide equivalents (CO_2e) emitted by combining the reduction in carbon dioxide with the reduction in methane emissions; this finding suggests that 15% of the global warming benefit of co-generation compared to pile burning was attributable to avoided methane emissions.

In another study from mixed conifer forests in the Sierra Nevada, Springsteen et al. (2015) found that use of forest wastes from fuel hazard reduction projects at Blodgett Forest Research Station for electricity production reduced PM2.5 (particles with diameters less than 2.5 micrometers), carbon monoxide, non-methane organic compounds, methane, and black carbon by 98% to 99% and nitrogen oxides and carbon dioxide-equivalent greenhouse gases by ~20%. They applied global warming potential factors of 900 for black carbon particles, 28 for methane, and 1.8 for carbon monoxide, which were the second, third, and fourth most important factors after carbon dioxide, and which collectively amounted to approximately half of the avoided climate-forcing emissions.

As a first-order approximation of the relative impacts of different forms of burning, one can apply global warming potential factors (e.g., Springsteen et al. 2015) to the emissions fractions reported by Urbanski (2014) for prescribed fires and wildfires in the Pacific Northwest. Presumably, such a comparison might also include nitrous oxide, which Springsteen et al. (2015) did not, although it did not seem to vary between prescribed fire and wildfire in conifer forests in the study by Urbanski (2014). Applying those figures suggests that wildfires would have greater global warming potential than a prescribed burn, reflecting greater carbon monoxide and methane release, while the prescribed burn would have slightly more global warming potential than pile burning. Further research to integrate such information would help to develop more sophisticated calculators to evaluate such tradeoffs.

The analysis by Springsteen et al. (2015) simply allocated black carbon as 5% of the PM2.5. That assumption is consistent with findings by May et al. (2014), who reported black carbon as 5% of PM1 (particles with diameters less than 1 micrometer) for two broadcast prescribed fires in the Sierra Nevada that burned heavy fuels. Springsteen et al. (2015) also assigned a negative global warming potential for non-black carbon particulates so that the net global warming effect of particulate matter from burning was estimated to be fairly small. However, Jacobson (2014) provided a recent synthesis of the effects of biomass burning which challenged the assumption that non-black carbon aerosols have a net cooling effect (as considered in the calculations by Springsteen et al. (2015). If that effect is not so large, then the relative climate mitigation benefit of burning biomass in a facility could be greater than reported by Springsteen et al. (2015).

While individual studies raise important questions about accounting for the impacts of fuel treatments, considerable uncertainty makes it difficult to generalize the implications for forest management. As Urbanski (2014) noted, the issues of wildfires in temperate forests and residual smoldering combustion are among some of the most significant gaps in knowledge around emissions. Hyde et al. (2012) noted that better estimates of consumption of coarse woody debris in various sizes and decay conditions would allow for more accurate accounting of carbon emissions.

2.10.4 Summary

In summary, differences in emissions from different forms of burning (e.g., pile burning versus broadcast burning versus wildfires in different seasons) results in uncertainty in accounting for global warming effects. Limiting analyses to carbon dioxide alone may understate the impacts of open burning. To the extent that the fate of forest biomass is to be burned, science suggests that the global warming effects can be minimized through controlled combustion in a biomass facility rather than in open burning. In wetter forest environments, decomposition might be a more effective means of mitigating global warming potential than burning, but leaving forest residues such as slash piles in forests is generally considered hazardous because of the potential for exacerbating wildfire severity. Large and intense wildfires appear to be a disproportionately more hazardous way of consuming forest fuels, not only because they consume more carbon and more stable forms of carbon, but also because they can cause emissions to be transported to distant snow and ice areas, where they exacerbate global warming, as well as to populated areas, where they exacerbate air quality problems (Long et al. 2017).

2.11 Extrapolating Fuel Treatment Variables Across California

Question: How do the factors in questions above vary in spatial-ecological terms across California forests?

Both carbon pools and the likelihood of disturbances vary widely between forest types as well as across different geographic regions of California. This variation reflects differences in moisture, soil qualities, disturbance regimes (both natural and human-caused), and other factors (Safford and Stevens 2017). Hudiburg et al. (2009) evaluated potential carbon storage in coniferous forests of northern California. Their findings suggest that forests in the Sierra Nevada are close to their potential (albeit with more carbon in small trees than what would have been present as large trees historically), but forests nearer the coast, particularly in the northwestern part of the state (the Klamath Mountains and Coast Range where redwoods can be dominant), are far below their carbon storage potential. That carbon may be stored in both live trees and dead wood. They noted that carbon storage in dead wood was much lower in the Klamath Mountains than in the Coast Range which is attributable to both more frequent fires and reduced moisture that facilitate decomposition. These patterns suggest that fire regimes and departure indices, as represented in databases such as LANDFIRE fire regime groups, Vegetation Departure Index (http://landfire.cr.usgs.gov/viewer/), and maps (Spies et al. in press; Safford and Van de Water 2014)) provide useful guidance to identify areas where the carbon impacts of forest treatments that remove biomass are most likely to be favorable over the long run. In particular, those areas are expected to have been historically dominated by frequent disturbances and have been altered by management (fire suppression and timber harvest) since the pre-Euro-American settlement era. These areas will include drier forests that are vulnerable to both bark beetle outbreaks and wildfire mortality, but they could also include some moister forests that have experienced significant departure through sudden oak death. In this way, carbon goals can complement broader goals of restoring ecological conditions and resilience to natural disturbances.

2.11.1 Carbon pools for old-growth forest types

“Contemporary Old-Growth Forests” share some stand characteristics (large diameter trees) with old-growth forests found on the landscape prior to 1850, but have been subjected to a similar modified fire regime as second-growth forests over the last century (Stephens 2000). The influence of the modified fire regime distinguishes them from what would be considered old-growth forests on the landscape prior to settlement of the Sierra Nevada in the mid-1800s. Scholl (2008) compared modern (2002) and reconstructed (1899) tree carbon storage at two old-growth mixed conifer locations within Yosemite National Park (Appendix 4). He included carbon from stem wood and bark, live and dead branches, live and dead coarse roots, fine roots, coarse woody debris, and duff but excluded understory vegetation and soil carbon. He found that carbon stocks increased over the period from about 200 t C/ha to roughly 500 t C/ha.

Scholl also documented that the distribution of total tree carbon by age-class and diameter size class was significantly different between 1899 and 2002. By 2002 almost twice the proportion of total carbon was stored in small diameter trees as in 1899. One implication of this finding is that a much larger portion of that stored carbon is now at greater risk of loss to fire, insects, disease, and drought than in the past. On the other hand, larger trees exhibit higher susceptibility to mortality from non-fire causes such as insects and disease (North et al. 2009).

Scholl's results for 2002 tree carbon density (545 t C/ha) are very high—only a Douglas-fir-hemlock stand in the Cascades (557 t C/ha) and a hemlock-spruce stand in Oregon (598 t C/ha) had greater tree carbon density (Smithwick et al. 2002). This could indicate that tree carbon storage is probably near its peak and will decline as older trees begin to die due to competition from infilling small trees. In contrast, Scholl's 1899 reconstructed tree carbon density (242 t C/ha) was more similar to 1990 Sierra Nevada mixed conifer (not old-growth) at 118 t C/ha (Fellows and Goulden 2008) and 1930s Sierra Nevada mixed conifer (wilderness areas) at 87 t C/ha (Fellows and Goulden 2008).

The largest source of increased carbon storage was from stem wood which accumulated about 66 t C/ha of new carbon (roughly a 68% increase at one study site and a 92% increase at the other site). Live tree stem wood was about 31% of total tree carbon in 2002. Litter and duff, on the other hand, increased by about 58 t C/ha in new carbon (roughly an 1886% increase at one site and a 2197% increase at the other).

A relatively small share of total carbon (<10%) was stored in the oldest and youngest trees in 2002. Fire suppression increased carbon stocks by about 39% between 1899 and 2002 due to more small trees and not woody encroachment or growth of existing trees. Although large trees store the greatest amount of carbon per tree, there were relatively few large trees as opposed to small trees.

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APPENDIX A: LIST OF ACRONYMS

Metric tons Carbon/heactare.

Pg=Petagram=10^15 grams.

Tg=teragram=10^12 grams

Fire Severity (low, moderate, high)

Basal Area (BA)

Canopy Cover (CC)

Height to Live Crown Base (HTCB)

Flame Length (FL)

APPENDIX B: LIST OF GEOSPATIAL DATASETS USEFUL FOR WILDFIRE AND CARBON ANALYSIS

The table below includes a list of key geospatial datasets relevant to the literature review, including the data set name, scale, description, and current website. This list is intended to provide report users sources of geospatial data relevant to the overall question of fuel treatments and forest carbon dynamics covered in this assessment.

Dataset Name	Spatial Scale	Description of Dataset	Source Website
LANDFIRE	Landscape	LANDFIRE delivers vegetation, fuel, disturbance, and fire regimes geospatial data products for the entire nation. Methods are based on peer-reviewed science from multiple fields. LANDFIRE products are consistent, comprehensive, and standardized, resulting in multiple applications to fire, fuel, and natural resources.	http://www.landfire.gov/version_comparison.php

Dataset Name	Spatial Scale	Description of Dataset	Source Website
LANDFIRE, Vegetation	Landscape	LF existing vegetation layers describe the following elements: existing vegetation type (EVT), existing vegetation canopy cover (EVC), and existing vegetation height (EVH). These layers are created using predictive landscape models based on extensive field-referenced data, satellite imagery, and biophysical gradient layers using classification and regression trees. LF potential vegetation layers describe the following elements: bio-physical settings (BPS) and environmental site potential (ESP). These layers are created using predictive landscape models based on extensive field-referenced data and biophysical gradient layers using classification and regression trees.	http://www.landfire.gov/vegetation.php
LANDFIRE, Disturbance	Landscape	Disturbance products are developed to help inform updates to LANDFIRE data to reflect change on the landscape caused by management activities and natural disturbance. They are a compilation of data from: Landsat satellite imagery, Burned Area Reflectance Classification (BARC), Rapid Assessment of Vegetation Condition after Wildfire (RAVG), Monitoring Trends in Burn Severity (MTBS), LANDFIRE Refresh events, User contributed data, and Other ancillary data	http://www.landfire.gov/disturbance.php

Dataset Name	Spatial Scale	Description of Dataset	Source Website
LANDFIRE, Fuel	Landscape	LANDFIRE fuel data describes the composition and characteristics of surface and canopy fuel. LANDFIRE fuel products provide consistent fuel data to support fire planning, analysis, and budgeting to evaluate fire management alternatives and supplement strategic and tactical planning for fire operations.	http://www.landfire.gov/fuel.php
LANDFIRE, Topographic	Landscape	Topographic data serves as input to the Landscape (.LCP) file which is used in models to predict wildland fire behavior and effects.	http://www.landfire.gov/topographic.php
The Web-Enabled Landsat Data (WELD) 5-year Land Cover Land Use Change (LCLUC)	Landscape	The Web-Enabled Landsat Data (WELD) 5-year Land Cover Land Use Change (LCLUC) is a composite of 30 meter (m) land use land change product for the contiguous United States (CONUS). The data was generated from five years of consecutive growing season WELD weekly composite inputs from April 15, 2006, to November 17, 2010. WELD data is created using Landsat Thematic Mapper Plus (ETM+) Terrain Corrected data. This product includes data about tree cover loss and bare ground gain, which is composited over the five year period. WELD LCLUC is distributed in Hierarchical Data Format 4 (HDF4). The WELD project is funded by the National Aeronautics and Space Administration (NASA) and is a collaboration between the United States Geological Survey (USGS), Earth Resources Observation and Science (EROS) Center, and the South Dakota State University (SDSU) Geospatial Sciences Center of Excellence (GSCE).	EarthExplorer (http://earthexplorer.usgs.gov/)

Dataset Name	Spatial Scale	Description of Dataset	Source Website
Global Land Survey (GLS)	Landscape	The Global Land Survey (GLS) collection of Landsat imagery is designed to meet a need from scientists to use a carefully coordinated collection of high resolution imagery for global modeling, including for the climate and carbon cycles. GLS replaces GeoCover, which was collected first into three epochs around 1975, 1990 and 2000. The GLS collection improves upon GeoCover by using more accurate elevation data (SRTM) for terrain correction and also by adding another epoch centered around 2005. Imagery from all seven Landsat sensors, plus the Landsat experimental sensor, ALI, are included in the collection.	EarthExplorer (http://earthexplorer.usgs.gov/) or GloVis (http://glovis.usgs.gov/)
Global Land Cover	Landscape	These global land cover layers are the product of a collaboration between USGS and the University of Maryland, Department of Geographical Sciences. Thirty meter resolution raster data layers for circa 2010 tree cover and bare ground and a persistent surface water layer 2000-2012, have been derived from Landsat 7 ETM+ data. The tree cover and bare ground data are per pixel estimates, 1 to 100% (given as integers values 1-100), the water layer is a thematic layer (2 = water). Hansen et. al 2013	http://landcover.usgs.gov/glc/

Dataset Name	Spatial Scale	Description of Dataset	Source Website
Hazardous Fuel Treatment Reduction	Stand	The Forest Service's Natural Resource Manager (NRM) Forest Activity Tracking System (FACTS) is the agency standard for managing information about activities related to fire/fuels, silviculture, and invasive species. FACTS is an activity tracking application for all levels of the Forest Service. This layer represents activities of hazardous fuel treatment reduction that are polygons. All accomplishments toward the unified hazardous fuels reduction target must meet the following definition: "Vegetative manipulation designed to create and maintain resilient and sustainable landscapes, including burning, mechanical treatments, and/or other methods that reduce the quantity or change the arrangement of living or dead fuel so that the intensity, severity, or effects of wildland fire are reduced within acceptable ecological parameters and are consistent with land management plan objectives, or activities that maintain desired fuel conditions. These conditions should be measurable or predictable using fire behavior prediction models or fire effects models."	ESRIgeodatabase: http://data.fs.usda.gov/geodata/edw/edw_resources/fc/S_USA.Activity_HazFuelTrt_PL.gdb.zip Shapefile: http://data.fs.usda.gov/geodata/edw/edw_resources/shp/S_USA.Activity_HazFuelTrt_PL.zip
Timber Harvests	Stand	Depicts the area planned and accomplished acres treated as a part of the timber harvest program of work, funded through the budget allocation process and reported through the FACTS database. Activities are self-reported by Forest Service Units.	ESRIgeodatabase: http://data.fs.usda.gov/geodata/edw/edw_resources/fc/S_USA.Activity_TimberHarvest.gdb.zip Shapefile: http://data.fs.usda.gov/geodata/edw/edw_resources/shp/S_USA.Activity_TimberHarvest.zip

Dataset Name	Spatial Scale	Description of Dataset	Source Website
FRAP Vegetation (FVEG15_1)	Landscape	An accurate depiction of the spatial distribution of habitat types within California is required for a variety of legislatively mandated government functions. The California Department of Forestry and Fire Protection's CALFIRE Fire and Resource Assessment Program (FRAP), in cooperation with California Department of Fish and Wildlife VegCamp program, and through extensive use of USDA Forest Service Region 5 Remote Sensing Laboratory (RSL) data, has compiled the "best available" land cover data available for California into a single comprehensive statewide data set. The data spans a period from approximately 1990 to 2014. Typically, the most current, detailed and consistent data was collected for various regions of the state. Decision rules were developed that controlled which layers were given priority in areas of overlap. Cross-walks were used to compile the various sources into the common classification scheme, the California Wildlife Habitat Relationships (CWHR) system.	http://frap.fire.ca.gov/data/frapgisdata-sw-fveg_download
Existing Vegetation-CALVEG	Landscape	A mapping methodology has been developed to capture vegetation characteristics using automated, systematic procedures that efficiently and cost-effectively map large areas of the state with minimal bias and is supplemented with onsite field visits when appropriate. Map attributes consist of vegetation types using the CALVEG classification system and forest structural characteristics such as tree and shrub canopy cover and tree stem diameters.	http://www.fs.usda.gov/detail/r5/landmanagement/resourcemanagement/?cid=stelprdb5347192

Dataset Name	Spatial Scale	Description of Dataset	Source Website
West Wide Fire Assessment	Landscape	The Council of Western State Foresters and the Western Forestry Leadership Coalition (WFLC) are developing a wildfire risk assessment of all lands for the 17 western states and selected Pacific Islands. This assessment is known as the "West Wide Wildfire Risk Assessment, or "WWA".	https://www.thewflc.org/resources/west-wide-wildfire-risk-assessment-final-report
CalAdapt Climate Tools	Landscape/ Region	Explore charts, maps, and data of observed and projected climate variables for California. The tools show projections for two possible climate futures; one in which emissions peak around 2040 and then decline (RCP 4.5) and another in which emissions continue to rise throughout the 21st century (RCP 8.5).	http://cal-adapt.org/data
Modis Burned Area Product	Landscape	The Burned Area product contains burning and quality information on a per-pixel basis. Produced from both the Terra and Aqua MODIS-derived daily surface reflectance inputs, the algorithm analyzes the daily surface reflectance dynamics to locate rapid changes and uses that information to detect the approximate date of burning, mapping the spatial extent of recent fires only.	https://modis.gsfc.nasa.gov/data/dataprod/mod45.php
Georgetown Climate Center Adaptation Clearinghouse	State/City/ Municipality	The Adaptation Clearinghouse seeks to assist policymakers, resource managers, academics, and others who are working to help communities adapt to climate change. Content in the Adaptation Clearinghouse is focused on the resources that help policymakers at all levels of governments reduce or avoid the impacts of climate change to communities in the United States. The Adaptation Clearinghouse tends to focus on climate change impacts that adversely affect people and our built environment.	http://www.adaptationclearinghouse.org/

Dataset Name	Spatial Scale	Description of Dataset	Source Website
Fire Return Interval Departure	Landscape	This polygon layer consists of information compiled about fire return intervals for major vegetation types on the 18 National Forests in California and adjacent land jurisdictions. Comparisons are made between pre-Euro-american settlement and contemporary fire return intervals (FRIs). Current departures from the pre-Euro-american settlement FRIs are calculated based on mean, median, minimum, and maximum FRI values. This map is a project of the USFS Pacific Southwest Region Ecology Program.	https://www.fs.usda.gov/detail/r5/landmanagement/gis/?cid=STELPRDB5327836
Web Soil Survey (SSURGO)	Landscape	Operated by the USDA Natural Resources Conservation Service (NRCS), this data portal contains spatially-explicit information about soil type and tree productivity site index across the United States and its territories that can be used for: growth and yield modeling when investigating above and belowground carbon sequestration or fuels treatment effectiveness and longevity; identifying limitations affecting recreational or structural development; and water capacity and flooding frequency. Soil data was collected on a geographic scale ranging from 1:12,000 - 1:63,360.	https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx
MTBS: Fire Occurrence, Extent, and Burn Severity Mosaic	Landscape	Monitoring Trends in Burn Severity (MTBS) is an interagency program that offers free geospatial products related to wildfire management in the United States, including Alaska and Hawaii. Users are able to download fire perimeters of all fires, both wildfires and prescribed fires, from 1984 to present that burned 1000 acres or more. Fire severity mosaics derived from 30m Landsat data is also available for those fires.	https://www.mtbs.gov/viewer/index.html

Dataset Name	Spatial Scale	Description of Dataset	Source Website
FIA Database	Landscape	Information about a region's forest structure and composition can be obtained from the USDA Forest Service's Forest Inventory and Analysis program. This tabular data is quantified from annual on-ground vegetation sampling plots with approximate ("fuzzed") survey locations. Data includes overstory and understory species, size, mortality status, and harvest removals, plus coarse woody debris loading.	https://apps.fs.usda.gov/fia/datamart/datamart.html
PRISM Climate Data	Landscape	Oregon State University's Northwest Alliance for Computational Science and Engineering hosts climate data of the conterminous United States. Geospatial climate data is available, summarized monthly or by 30-year "normals" at a resolution of 4km - 800m resolution. This data is central to time series comparisons and can serve as important variables when modeling drivers of contemporary forest structure or conditions under climate change. Note, interpolation between weather stations may be less accurate than localized data collection.	http://prism.oregonstate.edu/
RAWS Weather Data	Landscape	The Western Regional Climate Center hosts Remote Automated Weather Stations (RAWS) data for western United States, including daily and monthly weather summaries and station metadata. Weather reports contain measurements on air temperature, solar radiation, wind speed and direction, fuel moisture, relative humidity, and precipitation. These metrics are useful for understanding fire weather, climatology, air quality management, planning for noxious weed control, and other natural resource management goals.	https://wrcc.dri.edu/

Dataset Name	Spatial Scale	Description of Dataset	Source Website
National Geospatial Data Asset (NGDA) Datasets	Landscape	Other Geospatial Datasets available are county lines, roads/rails, national structure database, wetlands, hydrography (incl. dams), and other information that may impact where/when fuels treatments are conducted.	https://www.fgdc.gov/ngda-reports/NGDA_Datasets.html