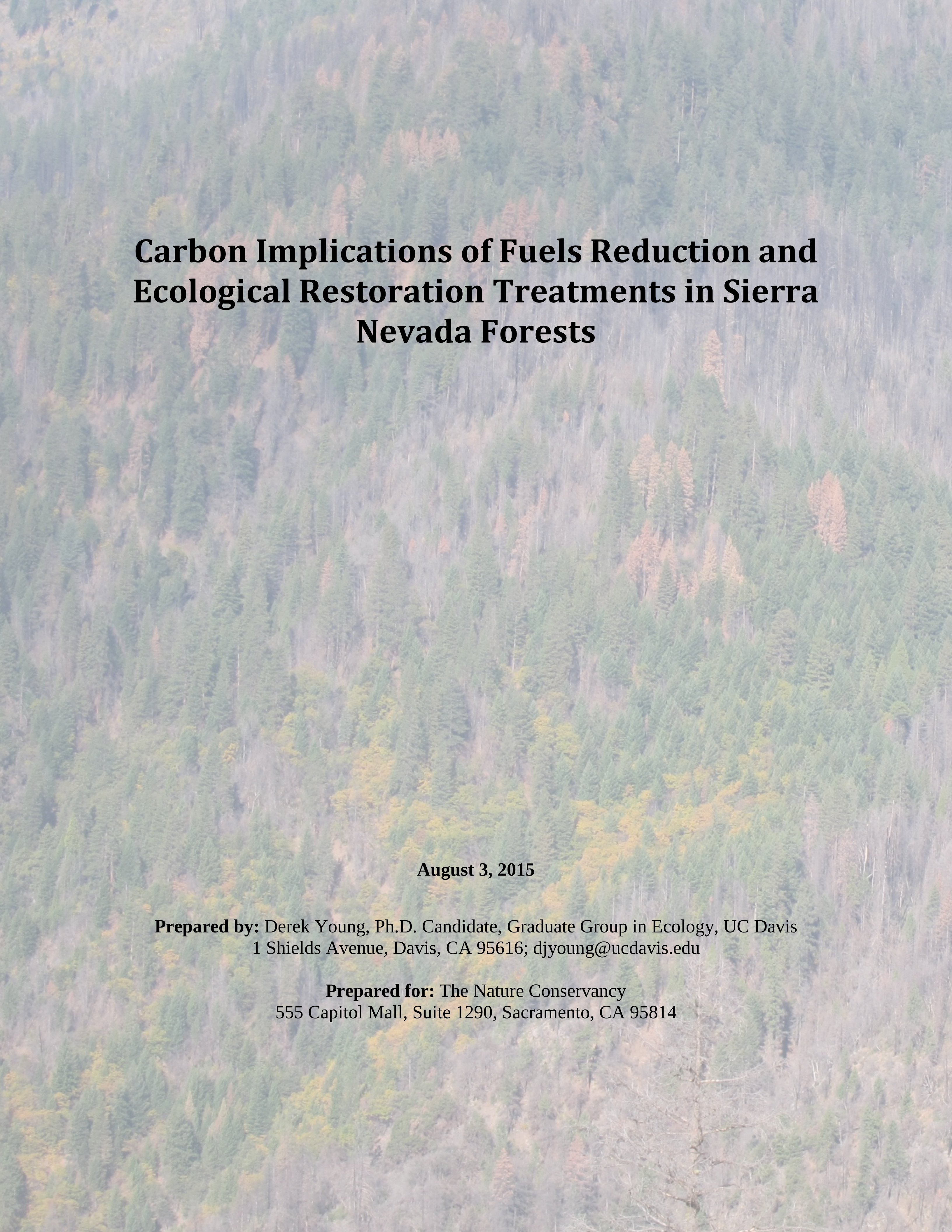

Carbon Implications of Fuels Reduction and Ecological Restoration Treatments in Sierra Nevada Forests

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1. Executive summary

1.1. Introduction

A century of fire suppression has dramatically altered the structure and species composition of many western U.S. forests, particularly by increasing the density of small trees, the abundance of shade-tolerant and fire-intolerant species, and the accumulation of litter and woody debris. When dense, fire-suppressed forests experience wildfire, they often burn at very high severity. To reduce the risk of high-severity wildfire and restore fire-suppressed stands to a more natural state, managers may employ mechanical thinning, prescribed fire, and/or strategically-managed wildfire. Scientists and managers have begun to express interest in the potential for these forest restoration and fuels reduction treatments to result in an increase in terrestrial carbon storage by increasing growth rates and moderating wildfire behavior. Increasing carbon storage reduces atmospheric concentrations of greenhouse gases, and any resulting benefit for climate change mitigation may help justify public and private investments to increase the pace and scale of forest treatments.

When wildfire occurs, treated stands burn less severely—and release less carbon—than comparable untreated stands. However, treatment itself involves substantial removals of carbon, leaving it unclear whether treatment results in a net release or net sequestration of carbon over time–relative to a no-treatment scenario–given the possibility of wildfire. Due in part to this ambiguity, carbon accounting of forest treatments in the context of wildfire has been a very active field of research during the last seven years. Because of differences in the scenarios evaluated and the assumptions made, the numerous studies to date have drawn divergent conclusions regarding the potential for fuels treatments to yield a net increase in terrestrial carbon storage. In this document, I review the evidence that has accumulated to date and apply it to evaluate the potential for prescribed fire and mechanical thinning projects in Sierra Nevada ponderosa pine, Jeffrey pine, and mixed-conifer forests to increase terrestrial carbon storage.

1.2. Biological and analytical factors

The conclusions drawn regarding the carbon implications of forest management depend on many factors. The most influential factors include:

- Probability of treatment-wildfire interaction: The probability that a given forest treatment project will have the opportunity to reduce wildfire-related carbon emissions depends on the probability that the treated area experiences a wildfire during the effective lifetime of the treatment. This probability depends on the annual probability of wildfire (on average currently 0.4-0.6% for the focal forest types) and the number of years during which the treatment retains its effectiveness in moderating wildfire behavior (approximately 20 years). The current average probability that a given treatment project will interact with wildfire is thus approximately 8-12%. These numbers imply that among all treated areas (which entail carbon releases due to treatment), on average only 8-12% will also confer a carbon benefit by moderating carbon emissions due to wildfire.
- Post-wildfire carbon dynamics: Carbon accounting conclusions can depend substantially on

the rate of decay of (and carbon release from) trees killed in the wildfire; it can also depend on the rate of forest regrowth (and associated carbon sequestration) following the fire. In some cases, more severely-burned forests take substantially longer to recover their pre-fire carbon stocks; in other cases, they recover nearly as quickly as forests experiencing low disturbance severity.

- Fate of thinned forest material: When thinned forest material is used to generate energy (as a substitute for fossil fuels) or to manufacture long-lasting wood products, the calculated carbon emissions of the treatment project can be reduced by the amount of carbon emissions avoided. Due to limitations on the proportion of thinned C that can be stored in long-lived wood products and the amount of fossil fuel C emissions that can be offset by bioenergy, these alternative uses can reduce treatment emissions by a maximum of approximately 20% on average.
- Consideration of the "treatment shadow:" Fuels treatments can moderate wildfire emissions outside the immediate treated area (e.g., by slowing wildfire spread and reducing severity); in an ideal scenario, treating only 20% of a given landscape can be sufficient to moderate wildfire behavior across the entire landscape. Accounting for this effect can substantially increase the calculated benefits of a treatment project. The magnitude of the effect remains very difficult to accurately quantify.
- Treatment approach (one-time project or repeated treatment program): Because repeated disturbance can increase the proportion of carbon stored in large, fire-resistant trees, repeated treatment programs, evaluated over many cycles of treatment, may have a greater probability of increasing net terrestrial carbon storage than one-time treatment projects.

1.3. Conclusions

- There is no strong evidence to suggest that one-time forest treatment projects can be expected to result in increased terrestrial carbon storage under prevailing contemporary conditions in Sierra Nevada ponderosa pine, Jeffrey pine, and mixed-conifer forests. In many cases, treatments appear to lead to a net loss of carbon to the atmosphere.
- Under some scenarios, treatment programs that involve ongoing, repeated application of treatments that are strategically located across a landscape may yield a net increase in terrestrial carbon storage after approximately 100 years or more of repeated treatment. Even in these scenarios, however, treatment may result in a net loss of carbon relative to a no-management scenario for many decades. The range of conditions that may lead to increased carbon storage in the long term, and the prevalence of such conditions throughout the Sierra Nevada, remain to be clearly identified.
- The limited potential for forest treatment projects to increase net terrestrial carbon storage stems largely from the low probability of treatment-wildfire interaction. This low probability implies that for every unit of treated area that reduces wildfire emissions, a much greater area of treatment, which entails carbon release, does not contribute to reduced emissions during wildfire.
- The majority of the differences in conclusions among studies can be attributed to differences in assumptions regarding the probability of wildfire. Studies that assume more realistic contemporary wildfire probabilities tend to conclude that treatments are less likely to yield net storage of carbon. However, even some studies that assume all treated areas burn (an

unrealistic best-case scenario) find that treatment results in a net release of carbon to the atmosphere.

- Additional factors, such as the magnitude of the treatment shadow effect and the end-use of thinned forest material, can affect the calculated carbon implications of treatment programs, but they appear to be of insufficient magnitude to result in classification of treatment projects as net sinks of carbon. Nonetheless, substantial uncertainty in these and other factors leaves open the possibility that in some unique scenarios in the Sierra Nevada that have yet to be clearly identified, even one-time treatment projects may result in a net increase in terrestrial carbon storage. For example, areas with a high probability of wildfire in which ignition locations are highly predictable may be uniquely conducive to treatment projects that yield a net increase in carbon storage.
- Changes in stand conditions and wildfire regimes resulting from climate change and changing management priorities may increase, to at least some degree, the potential for forest treatments to result in increased carbon storage. However, there is substantial uncertainty in the magnitude of these effects.
- Although treating forests and introducing more frequent disturbance (in the form of thinning, prescribed fire, and/or managed wildfire) may result in a net release of carbon, it can lead carbon stocks to be less sensitive to wildfire (e.g., because the stand is comprised of fewer, larger, more fire-resistant trees) and therefore more stable over time. Forests that experience more infrequent disturbance (and therefore accumulate greater fuel loads between disturbances) can undergo larger swings from very high to very low carbon storage states.
- In summary, management intended to restore fire-suppressed forests and reduce the risk of high-severity wildfire is unlikely to increase net terrestrial carbon storage and may in fact result in a net release of carbon to the atmosphere. The approach most likely to result in an increase in terrestrial carbon storage is one in which sites that are strategically located across a landscape are treated repeatedly as necessary over time. This approach may lead to increased carbon storage after many decades of repeated treatment, but in the intervening period it may result in a release of carbon to the atmosphere compared to a no-management scenario. The range of conditions under which a repeated treatment program may yield net positive carbon storage in the long term—and the prevalence of such conditions throughout the Sierra Nevada—have not yet been clearly identified.

2. Introduction

Western U.S. ponderosa pine, Jeffrey pine, and mixed-conifer forests are adapted to a fire regime characterized by fires occurring at a high frequency but low severity (Taylor and Skinner 2003, Rhodes and Baker 2008, Beaty and Taylor 2008, 2009, North et al. 2012, Mallek et al. 2013). However, a century of fire suppression has dramatically altered the structure and species composition of these forests, particularly by increasing the density of small trees and the abundance of shade-tolerant and fire-intolerant species. When dense, fire-suppressed forests experience wildfire, they often burn at high severity (Mallek et al. 2013). High-severity wildfire is not a disturbance to which western dry forests are adapted, and it can threaten human safety and property. Concerns about ecological integrity and fire damage have spurred substantial interest in reversing the densification that has occurred over the past century. Such management often takes the form of "fuels reduction treatments," which specifically seek to remove the small trees, woody debris, and other fuels that can lead to high-severity wildfire. Some treatments, referred to as "restoration treatments," have the additional goal of moving forest structure, species composition, and, ultimately, disturbance regime toward pre- fire suppression conditions. Treatments, which may be implemented using mechanical thinning and/or prescribed fire, can be expensive to execute and are currently only conducted over a small fraction of fire-suppressed area (North et al. 2012). There is increasing interest in the potential for forest treatments to result in an increase in terrestrial carbon (C) storage through their effects in moderating wildfire behavior. Increasing C storage reduces atmospheric concentrations of greenhouse gases (GHGs), and any resulting benefit for climate change mitigation may help justify public and private investments to increase the pace and scale of forest treatments.

It has been well documented that when wildfire occurs, treated stands burn less severely—and release less C—than comparable untreated stands (e.g., Hurteau et al. 2008, Finkral and Evans 2008, Hurteau and North 2009, Reinhardt and Holsinger 2010, North and Hurteau 2011, Carlson et al. 2012; Fig. 1), particularly if the treatment projects do not leave behind substantial "activity fuels" (e.g., masticated material or limbs from felled trees; Stephens and Moghaddas 2005, Safford et al. 2009). However, treatment involves substantial removals of C, leaving it unclear whether treatments result in a net release or net sequestration of C over time–relative to a no-treatment scenario–given the possibility of wildfire. Theoretically, the benefit of treatment in reducing C loss during wildfire may outweigh the C losses due to the treatment itself (e.g., Hurteau et al. 2008); on the other hand, treatment may cause greater C emissions during implementation than it prevents during wildfire (e.g., Reinhardt and Holsinger 2010, North and Hurteau 2011). Due in part to this ambiguity, C accounting of restoration and fuels treatments in the context of wildfire has been a very active field of research during the last seven years.

In this document, I present a review of the literature relevant to evaluating whether applying thinning or prescribed fire treatments in fire-prone forests of the Sierra Nevada of California may result in a net increase in terrestrial C storage. I first present a number of important biological and analytical factors that should be considered when modeling and interpreting the potential C benefits of forest treatments. I then review existing studies that quantify the effects of thinning and prescribed fire on net C storage in the context of wildfire (summarized in Table A1.1). For each study reviewed, I critically examine the assumptions, approach, and conclusions in an effort to reconcile differing results and draw general conclusions regarding the C implications of forest treatments under contemporary management scenarios. I discuss studies in groups based on their approaches to accounting for processes such as probability of wildfire and post-wildfire dynamics. Within each group, after summarizing each study, I explore how realized C outcomes under probable management scenarios may vary from the results reported in the studies based on the assumptions made. Finally, I combine all of this information into comprehensive synthesis of the existing evidence. This review is intended to draw conclusions applicable to yellow pine and mixed-conifer forests of the Sierra Nevada, but I draw on all studies from western U.S. yellow pine and mixed-conifer forests adapted to a high-frequency, low-severity fire regime. An objective of thinning and prescribed fire projects may be to prepare stands for eventual re-introduction of a high-frequency, low-severity wildfire regime (e.g., through increased use of managed wildfire). While restoring a high-frequency, low-severity fire regime is an important component of forest restoration overall—with potential implications for C dynamics (Earles et al. 2014)—this review is focused specifically on the C implications of prescribed fire and mechanical thinning projects in the context of a contemporary wildfire regime.

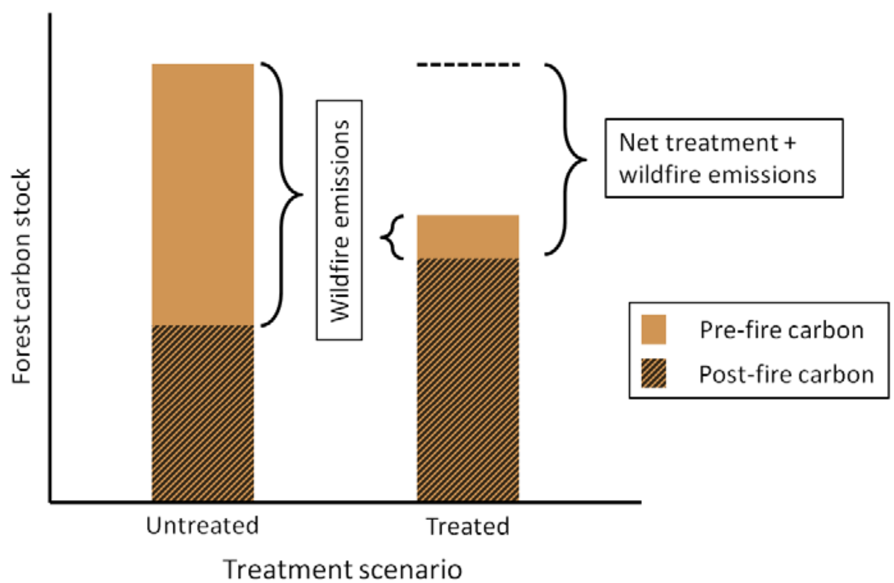

Figure 1: Effect of one-time treatment and wildfire on forest C stock. The difference between pre-fire C (solid bars) and post-fire C (hatched bars) represents wildfire emissions. The difference between pre-fire C in the untreated scenario and post-fire C in the treated scenario represents net treatment plus wildfire emissions. In some situations (such as that depicted here), treated stands store more C than untreated stands, assuming a wildfire occurs.

3. Summary of current forest conditions and natural C dynamics

Sierra Nevada yellow pine and mixed-conifer forests are adapted to a high-frequency, low-severity wildfire regime (Taylor and Skinner 2003, Rhodes and Baker 2008, Beaty and Taylor 2008, 2009, North et al. 2012, Mallek et al. 2013). However, a century of fire suppression has excluded the majority of natural fires from these forests and has created forests in which the tree species composition and structure largely do not resemble historical conditions (McKelvey et al. 1996). Due to fire exclusion, Sierra Nevada forests contain a much greater abundance of shade-tolerant, fire-intolerant species (e.g., white fir and Douglas-fir) relative to the historically dominant, fire-tolerant species (primarily pines). Due to the infrequency of fires that would naturally clear woody debris, litter, and small tress from the understory, the average forest today contains a much greater proportion of younger, smaller trees and has greater accumulation of litter and woody debris (McKelvey et al. 1996). When wildfire occurs, these surface fuels and "ladder fuels" (small trees) can burn intensely and carry fire into the canopy of large trees, causing high mortality. Fire suppression thus has had the effect of causing fires to be generally more severe and destructive when they do occur. On top of the threats due to fire suppression, increasing drought intensity in California appears to be leading to increasing mortality (Van Mantgem and Stephenson 2007) and increasing frequency of high-severity wildfire (Westerling et al. 2011).

High-severity wildfire can cause substantial reductions in landscape C storage. An analysis of terrestrial C storage in California found that statewide C storage decreased between 2001 and 2010, and the majority of the C losses were due to wildfire. Following high-severity wildfire and other stand-replacing disturbances, forests can take decades to recover the C that they previously stored. A chronosequence study in central Oregon ponderosa pine forests found that intermediate-aged stands (i.e., 70-100 years old) accumulated C at the fastest rates, while both young and old stands had relatively low rates of C accumulation (Law et al. 2003). Twenty years following disturbance, stands had accumulated approximately 46% of the C stored by 250 year-old stands; storage increased to 61% after 70 years of regrowth. Although some theories suggest that old-growth forests may reach a C equilibrium in which net C exchange is roughly zero (Odum 1969), empirical work demonstrates that most old-growth forests are actually C sinks (Harmon et al. 2004, Luyssaert et al. 2008).

The net C dynamics in post-disturbance stands depend on the balance of C lost due to decaying dead wood and the C stored due to regeneration and growth. When adult tree mortality is relatively low and regeneration is sufficiently rapid, stands may become C sinks quickly following disturbance (Reinhardt and Holsinger 2010); when mortality is high and regeneration is poor, stands may take longer to become C sinks (Dore et al. 2012). Further, the frequency and intensity of disturbance can affect both the stability of C stores over time and long-term average C storage. Keith et al. (2010) present the relevance of evaluating the "carbon carrying capacity" of an ecosystem; this metric represents the long-term C storage under a natural disturbance regime. Western dry forests that experience frequent, low-severity disturbance (e.g., a historical disturbance regime) generally store, on average, less C than forests that experience an infrequent, high-severity disturbance regime reflecting contemporary conditions (Campbell et al. 2011, Earles et al. 2014). However, contemporary low-frequency, high-severity fire regimes result in much greater fluctuation in C stocks over time (Earles et al. 2014), and thus greater long-term average C storage comes along with substantial uncertainty in C at any given point in time.

4. Biological and analytical considerations in evaluating the C implications of forest treatments

Almost all analyses of the C balance of fuels treatment projects involve some amount of modeling, and the conclusions can depend heavily on the assumptions the models make. Common variables for which models must make assumptions include:

- Probability of wildfire occurrence within the project area
- Post-wildfire forest dynamics (regeneration, growth, mortality, decomposition)
- Fate of C in thinned biomass (lost to atmosphere, substitution for fossil fuels, conversion to long-lived wood products)
- Effect of treatment on nearby untreated areas (treatment shadow effect)
- Treatment approach (one-time or ongoing)

In the following sections, I explore each of these variables and the influence they may have on the C consequences of forest treatments.

4.1. Wildfire regime and treatment longevity

The assumed wildfire regime is an important variable influencing study conclusions (Fig. 2). The majority of studies reviewed in this report include a scenario evaluating the effect of the entire treatment area experiencing one wildfire soon after treatment (Hurteau et al. 2008, Finkral and Evans 2008, Hurteau and North 2009, Reinhardt and Holsinger 2010, North and Hurteau 2011, Carlson et al. 2012, Vaillant et al. 2013b). That is, they ask the following question: what is the effect of the forest treatment on net C balance, *given that a wildfire burns the entire treatment area*? The approach of these studies limits the applicability of their results to a contemporary management context. In reality, many treated areas will not experience wildfire during the effective lifetime of the treatments (Rhodes and Baker 2008), and these treatments will thus entail C costs (removal of C due to treatment) without the benefit of moderating wildfire behavior. Evaluating the effect of treatments assuming that a wildfire occurs would lead one to conclude that treatments are more effective in yielding net C storage than treatments would be in reality.

Contemporary fire suppression-influenced fire rotations in the Sierra Nevada average approximately 173 years for yellow pine and dry mixed-conifer forests and 241 years for moist mixed-conifer forests (calculated using data from Mallek et al. 2013). Fire rotation for a given focal area is defined as the amount of time that would be required for a wildfire to burn a total area equal in size to the focal area. The rotations above represent averages for the entire distribution of each forest type within the Sierra Nevada and Southern Cascades, and they reflect the meanfig. 2 time between fires averaged across all points within the same area (Mallek et al. 2013). Fire rotations for specific sub-regions inevitably differ from these region-wide averages; for example, Saah et al. (2012) estimate a mean fire rotation of 263 years for an area of mixed-conifer forest on the west slope of the northern Sierra Nevada.

In addition to long fire rotations, the probability of treatment-wildfire interaction is limited by the lifespan of treatments. Fuels treatments generally only remain effective at moderating wildfire behavior and emissions for a maximum of 20 years (Vaillant et al. 2013a, Yocom 2013). Given average fuel treatment longevity and contemporary fire rotation, the probability that the average fuel treatment will interact with wildfire during its effective lifetime is approximately 4-12% (Table 1). Independent estimates corroborate these values: Campbell et al. (2011) estimate that treatments in western U.S. semiarid forests have a 1-20% chance of interacting with wildfire, and Rhodes and Baker (2008) estimate that treatments in California ponderosa pine forests have a 9% chance of experiencing wildfire during the effective lifetime of the treatments. The low probability of treatment-wildfire interaction implies that many treated areas will never experience wildfire while treatments remain effective. Treated areas that do not burn during the treatment's effective lifetime would incur a C cost (treatment removals) without generating C benefits (reduction in wildfire emissions).

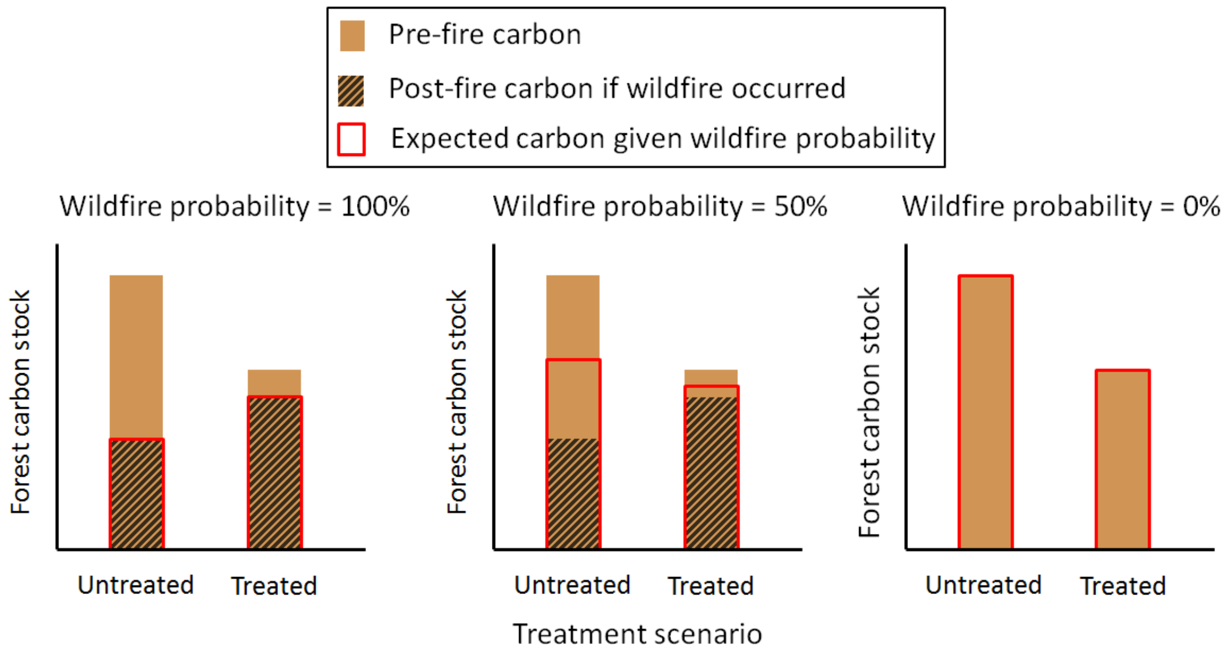

Figure 2: Influence of one-time treatment and wildfire on forest C stock given different wildfire probabilities. If wildfire is certain to occur soon after treatment (hatched bars), treated stands may store more C following wildfire than untreated stands; exceptions exist—see text. If wildfire does not occur following treatment (solid bars), treated stands will store less C than untreated stands due to removal of C during treatment. The expected C storage (red outline) depends on the assumed probability that a treated stand will interact with wildfire. For example, assuming a wildfire probability of 50% (center panel) may result in greater expected C storage in untreated stands than in treated stands, even if the reverse is true when wildfire is guaranteed (left panel).

The fire rotation at any specific location within the Sierra Nevada is likely to deviate from the overall average, and treatment longevity also varies depending on site characteristics and treatment prescription. For example, though most evidence suggests treatments remain effective for a maximum of about 20 years (Vaillant et al. 2013a), modeling by Hurteau and North (2009) of a region of in the central Sierra Nevada suggests that thinning may mitigate the emissions of a wildfire occurring 50 years following treatment. Locating treatments in areas with uniquely high wildfire probability—and/or in areas where treatments will remain effective for a uniquely long period of time—is therefore one potential approach for maximizing the net C benefits of treatment, or at least for minimizing the net C costs.

Average annual area burned, particularly at high severity, has been increasing over time during the last several decades, likely due partially to climate change and partially to management changes and fuels accumulation (Westerling et al. 2006, 2011, Littell et al. 2009, Miller and Safford 2012). Continued decreases in fire rotation will increase the probability that treatments will interact with wildfire and in turn potentially increase the likelihood that treatments will result in net storage of C. However, other uncertainties associated with climate change (e.g. potential decreases in fuel production and forest growth rates; Diggins et al. 2010) make it difficult to predict whether climate change, overall, will increase or decrease any potential net benefit of fuels treatments. Although multiple studies have evaluated the effect of fuels treatments on C storage under multiple wildfire scenarios (e.g., Saah et al. 2012, Winford and Gaither 2012, Loudermilk et al. 2014), no studies to date have quantified the C implications of forest treatments in the context of wildfire under future climate scenarios.

Table 1: Influence of fire rotation and treatment longevity on the probability of treatment-wildfire interaction.

Fire rotation (years)	**Treatment longevity (years)**	**Probability of treatment-wildfire interaction**
150	10	7%
200	10	5%
250	10	4%
150	20	13%
200	20	10%
250	20	8%
150	50	33%
200	50	25%
250	50	20%

4.2. Post-wildfire dynamics

Studies also differ substantially in whether—and if so, how—they account for post-wildfire C dynamics. Treated and untreated stands, particularly following wildfire, may exhibit divergent patterns in regeneration, growth, mortality, and/or decomposition in ways that affect net C storage. For example, untreated stands generally experience greater wildfire-induced mortality than treated stands (North and Hurteau 2011), and this can lead to increased decomposition and release of stored C to the atmosphere in untreated-burned stands than in treated-burned stands. On the other hand, wildfire may trigger substantial seedling recruitment and, by reducing competition among trees, promote greater primary productivity (C sequestration) in the adult trees that remain. Conclusions regarding treatment effectiveness in sequestering C can be highly dependent on mortality and seedling recruitment rates (Carlson et al. 2012). The amount of time a burned stand takes to become a C sink depends substantially on the survival of large trees. If most large trees are killed by wildfire, the site may constitute a substantial C source for many years as those trees release C; had they remained alive, those trees would have continued to sequester C and may have led the site to resume functioning as a net C sink immediately following wildfire.

When all sources of C flux are considered, severely burned dry forests may remain C sources for at least 4-15 years following disturbance, while stands experiencing more moderate disturbance can quickly become C sinks or exhibit roughly net neutral C exchange (Meigs et al. 2009, Dore et al. 2012). In some cases, however, regeneration and growth may quickly catch up to decomposition such that even untreated stands become C sinks after about 11 years following wildfire (Reinhardt and Holsinger 2010). Studies that evaluate forest treatment effects on C storage both soon after wildfire and >10 years following wildfire (Hurteau and North 2009, Reinhardt and Holsinger 2010, Osborne 2011, Carlson et al. 2012) generally suggest that treatments are more effective in producing net C storage when post-wildfire dynamics are incorporated (Table A1.1).

The effectiveness of treatments in yielding any net positive C storage may be even stronger if wildfire leads to a long-term conversion in vegetation community (e.g. high-C forest to low-C shrubland) and if the probability of such a conversion is affected by treatment. However, management activities may reduce any difference in post-wildfire C dynamics between treated and untreated stands. For example, managers may plant seedlings in at least a portion of severely-burned area. Increasing seedling density in the most severely burned (often, untreated) areas may increase the primary productivity in untreated-burned stands such that it more closely resembles the primary productivity in treated-burned stands (Carlson et al. 2012).

4.3. Fate of thinned forest material

The outcomes of C balance analyses also depend on the assumed fate of thinned forest material. Harvested live and dead forest material may be used to generate energy as a substitute for fossil fuels or to manufacture long-lasting wood products. Such uses of thinned material may not emit as much C as the alternative of piling and burning the thinned material on-site, and some forest C studies account for this effect (Finkral and Evans 2008, Mitchell et al. 2009, Goslee et al. 2010a, 2010b, Ager et al. 2010, Saah et al. 2012, Winford and Gaither 2012, Campbell and Ager 2013). The potential reduction in C emissions that can be obtained by using thinned material to produce long-lived wood products depends on many factors, including the longevity of the product, the amount of C that would be emitted through the use of an alternate product, and the proportion of thinned biomass that can be converted into wood products. Furthermore, the amount of carbon from a harvested tree that ends up in long-lasting wood products varies among forest types and local mills. One study in an old-growth Sierra Nevada mixed-conifer forest estimated that 60% of the C in thinned logs (representing 6-20% of the total ecosystem C, depending on thinning intensity) ended up in dimensional lumber, a potential long-term store (North et al. 2009). Given the size of the trees at this site, this is probably higher than would be realized by most forest treatments. The amount of time that carbon remains stored in harvested wood varies substantially, though the average half-life of harvested wood (across all wood product types) in the western U.S. is approximately 35 years (Earles et al. 2012).

When thinned biomass is instead used to generate energy as an alternative to burning it in piles on site, a project can discount its emissions by any quantity of fossil fuel emissions avoided. However, burning woody biomass to generate energy releases about twice as much C per unit of energy generated as do fossil fuels (Mitchell et al. 2012). Therefore, compared to a no-management scenario, thinning forest material to generate bioenergy may result in a net release of C. This would be the case if thinning does not trigger increased C sequestration to such an extent as to compensate for the greater emissions per unit of energy produced using biomass relative to fossil fuels. Though using thinned forest material to generate bioenergy is unlikely, on its own, to make treatments C-neutral, it can reduce C emissions compared to burning thinned material in open piles.

The reduction in C emissions that can be achieved by using thinned material to generate bioenergy rather than burning it in piles is relatively small. An analysis by the Placer County Air Pollution Control District concluded that in the Sierra Nevada, sending thinned biomass to a bioenergy plant rather than burning it in a pile on site would reduce CO_2-equivalent emissions from thinning by 17% (Springsteen et al. 2011). Other analyses suggest that using thinned material for bioenergy production and manufacture of long-lived wood products may offset up to 15% of the treatment removals (Finkral and Evans 2008, Ager et al. 2010, Saah et al. 2012). Nonetheless, there is still some uncertainty surrounding the exact amount by which end-use may help to offset treatment emissions. For example, studies that evaluate the potential for thinned biomass to substitute for fossil fuels do not consider the C emissions associated with extraction and processing of the fossil fuel. Accounting for the full life-cycle emissions of fossil fuel extraction would increase the potential for fossil fuels to offset C emissions, though the magnitude of this effect is unknown.

Accounting for black carbon, one chemical component of wildfire emissions, may increase the calculated benefits of bioenergy generation. Although its residence time in the atmosphere is short, black carbon contributes more to climate forcing than carbon dioxide by several orders of magnitude. Black carbon is removed by scrubbers in bioenergy generators whereas during open pile burning it is released to the atmosphere. By including black carbon in calculations of climate forcing reductions achieved through use of biomass energy, the Placer County Air Pollution Control District calculated that sending thinned biomass to a bioenergy plant rather than piling and burning it can reduce CO_2-equivalent emissions due to thinning by 20%; when not accounting for black carbon, this reduction would be approximately 13% (Bruce Springsteen, Placer County Air Pollution Control District, *unpublished analysis*). Accounting for black carbon emissions in treatment projects that involve prescribed fire or piling and burning mechanically-thinned biomass may also have an effect on net C balance calculations, as active flaming fires (which may be more common during wildfires) appear to release greater amounts of black carbon than smoldering fires (which may be more common during prescribed fires or pile-burns) (Reid et al. 2005). However, no work to date has directly compared the black carbon emissions of wildfires, prescribed fires, and/or pile burns.

4.4. Evaluation of the treatment shadow

Many studies evaluating the C balance of fuels treatment projects assume that fuels treatments only affect wildfire behavior within the stands that are treated. However, a large body of research demonstrates that fuels treatments can also moderate fire behavior in nearby untreated areas (Finney et al. 2007, Ager et al. 2007, Schmidt et al. 2008, Syphard et al. 2011). Perhaps most importantly, treatments can slow fire spread and facilitate suppression efforts, thus reducing the probability that any given point beyond the immediate ignition area will burn. The influence of treatments on wildfire behavior outside of the treatment area is known as the "treatment shadow effect." Existing modeling work suggests that treating only 20% of a given landscape can substantially moderate wildfire behavior across the larger landscape, particularly if the treatments are located in areas where they will have the greatest influence on wildfire probability, severity, and/or rate of spread (Finney et al. 2007, Ager et al. 2007, Osborne 2011). However, the magnitude of the treatment shadow effect remains very difficult to accurately quantify, and it is likely highly sensitive to stand structural characteristics, fuel types, fuel moisture, and other factors. In addition, seeking to increase the C benefits of a given treatment program by locating treatments so as to maximize the treatment shadow effect may be inconsistent with the goals of forest restoration if it has the effect of reducing the forest area that experiences disturbance (wildfire and/or treatment). If, on the other hand, treatments have the effect of moderating wildfire severity (but not size) outside treatment areas, then treatments with large treatment shadows may be very consistent with the goals of restoring low- to moderate-severity disturbance to forests.

4.5. Treatment approach (one-time project or ongoing program)

There are at least two temporal approaches that can be used when evaluating the C implications of treatment. The majority of analyses quantify C balance on a *one-time project* basis (Hurteau et al. 2008, Finkral and Evans 2008, Goslee et al. 2010a, 2010b, Reinhardt and Holsinger 2010, Ager et al. 2010, North and Hurteau 2011, Osborne 2011, Carlson et al. 2012, Saah et al. 2012, Winford and Gaither 2012, Vaillant et al. 2013b). That is, they evaluate the C implications of a one-time thinning event or a one-time application of prescribed fire. However, the C costs and benefits of one-time treatment projects in the context of wildfire are not permanent; they decrease over time as the treatment loses effectiveness, and benefits are only generated if the stand burns during the treatment's effective lifetime.

An alternative approach is to evaluate the C implications of a *repeated treatment program* over a longer time period (Mitchell et al. 2009, Campbell and Ager 2013, Loudermilk et al. 2014). Such a program may simply involve repeated thinning at semi-regular intervals, or it may involve thinning a stand and then re-incorporating high-frequency fire disturbance through repeated prescribed burning. Analytical approaches that evaluate repeated treatment programs focus not on the C implications of individual treatments but rather evaluate long-term C storage given repeated disturbance and continued wildfire risk. Ultimately, if historical disturbance processes are successfully restored, wildfire may become a useful tool for maintaining forest structure and C storage as opposed to a disturbance to be avoided. Indeed, a given wildfire produces fewer C emissions in stands that experience frequent disturbance than those that experience infrequent disturbance (Campbell et al. 2011). Introducing repeated disturbance may help to shift forest structure toward fewer, larger, more fire-resistant trees. As a result, stands with frequent disturbance generally have a more constant, predictable C trajectory, while those that experience infrequent disturbance may enter either much higher or much lower C storage states than frequently-disturbed stands (Earles et al. 2014). Although stands under restored fire regimes may store more or less C than stands experiencing infrequent wildfire, this report is focused specifically on the C implications of active management projects (i.e., thinning and prescribed fire), which may or may not be intended to prepare a stand for eventual reintroduction of frequent wildfire.

5. Critical review of relevant literature

Focusing specifically on western U.S. forests adapted to a high-frequency, low-severity fire regime, I present a critical review of all existing studies I am aware of that have quantified the C implications of prescribed fire and thinning treatments in the context of wildfire. I identified relevant studies by searching Google Scholar and Web of Science using variants of the following search phrase: "forest wildfire (fuel treatment/thinning/management/prescribed fire) (carbon/greenhouse gas) (emission/pool/flux/sink/source/storage)" and exploring citations of and by the resulting papers. I narrowed the results to studies that quantify the net effect of prescribed fire and/or thinning treatments on C storage in the context of wildfire in yellow pine and/or mixed-conifer forests. The resulting set of studies is summarized in Table A1.1.

When studies involve analysis of multiple forest types, I focus specifically on the analyses of the forest types most representative of Sierra Nevada yellow pine and mixed-conifer forests. I note whenever assumptions regarding fire regime, post-wildfire C dynamics, fate of C in thinned biomass, treatment type, and other factors may affect the conclusions, and I discuss the applicability of such assumptions to contemporary management projects.

5.1. One-time treatment projects

The first set of studies I review addresses the C implications of one-time treatment projects as opposed to repeated treatment programs. This is the approach used in determining whether a single application of a treatment may generate C benefits in the short or long term.

5.1.1. One-time treatments in which all treated areas burn in wildfire

The majority of studies evaluating C implications of one-time fuels treatments in the context of wildfire assume that a wildfire occurs soon after treatment. These studies implicitly or explicitly ask the following question: what is the effect of the fuels treatment on net C balance, *given that a wildfire occurs and interacts with the treatment*? This approach represents the most optimistic scenario in which all fuels treatments have the opportunity to moderate wildfire behavior before they lose their effectiveness.

5.1.1.1. Short-term post-fire C dynamics given one-time treatments in which all treated areas burn in wildfire

I focus first on studies that evaluate the C implications of a single treatment soon after wildfire. One such study concludes that treatment has a net effect of sequestering C. Hurteau et al. (2008) estimate the total live tree C remaining in areas that were severely burned by four large wildfires that occurred in 2002. They compare this estimate to their estimate of the live-tree C that would have remained had the burned areas been thinned prior to wildfire. According to their calculations, treating these severely-burned areas prior to the wildfires would have resulted in fewer net live tree C emissions than their no-thinning scenario.

Even among studies that assume the entire treated area burns, most draw ambiguous conclusions or conclude that fuels treatments result in net emissions of C (Table A1.1). For example, Finkral and Evans (2008) simulated a wildfire in a treated stand and in a modeled reconstruction of the stand before treatment and concluded that treatment results in net positive C sequestration only when all merchantable material removed during thinning is considered C storage; the scenario accounts for C emissions resulting from the energy used in processing thinned material, but it does not incorporate milling inefficiencies or the fact that commercial wood products will ultimately decay and release C. In an alternative scenario in which all removed biomass is used for home heating to replace oil at a 1:1 substitution by energy (as opposed to 1:1 by carbon; see Section 4.3), treatment results in a net loss of C given wildfire interaction with treatment.

Vaillant et al. (2013b) applied a similar approach; they surveyed stands pre- and post-treatment and simulated growth in the treated and untreated stands for eight years. They simulated a wildfire in years 1, 2, or 8 following treatment (in separate simulations for each wildfire year) and found that post-wildfire C stores were higher in untreated stands regardless of the year in which the wildfire occurred. Because the treatment was a prescribed fire, all C removed during treatment constituted emissions; there was no opportunity to use forest material to generate bioenergy or manufacture wood products.

In an alternative approach, North and Hurteau (2011) surveyed pairs of plots throughout California that had been burned by wildfire; one plot in each pair had received a fuels treatment prior to burning while the other had not. The plots were located in areas of very high-severity wildfire; the average mortality rate in untreated stands was 97%. The investigators reconstructed pre-wildfire and pre-treatment stand conditions and concluded that treatment results in slightly greater net C release than a no-management scenario given wildfire. However, they note that fire-induced mortality was much greater in untreated stands than in treated stands, and they suggest that over time, the C released by decaying wood may lead untreated, wildfire-burned stands to produce greater net C emissions. The analysis employed by this study assumed that all thinned C was lost to the atmosphere; it did not evaluate the potential to offset treatment emissions by using thinned material for bioenergy generation or manufacture of long-lived wood products.

Section synthesis: The studies in this section evaluate a relatively simple scenario: they compare C stocks in treated and untreated stands, after a wildfire occurs. However, in reality, many treated areas will not experience wildfire during the effective lifetime of the treatments (Section 4.1), and thus the C accounting conclusions of the studies in this section do not reflect the expected net C impact of contemporary forest treatment projects. In a management context, the methodological approaches of these studies would lead to an overestimate of net C storage, as they do not incorporate (a) the fact that many treated areas will not burn during the effective lifetime of the treatment and (b) the fact that wildfires do not burn at uniformly high severity across all untreated stands. In this regard, real-world forest management projects would be much less effective in yielding net C storage than suggested by the studies in this section. The fact that some studies find that treatments cause net emissions of C despite these optimistic assumptions is notable.

On the other hand, some assumptions made by these studies may lead to conclusions suggesting that treatments are less effective as net C sinks than they would be in reality. For example, using thinned material to generate bioenergy or to manufacture wood products may reduce the C costs of treatment, though the magnitude of this effect, if present, is likely small, and uncertainties surrounding the C consequences of end-use preclude a conclusive assessment of the potential for such uses to affect the net C balance of treatments (Section 4.3). Additionally, the studies in this section focus specifically on C stocks present soon after wildfire, whereas the C balance of real-world management projects will depend on the C dynamics (e.g., decay, growth, and seedling establishment) during some period of time following wildfire. Post-wildfire C dynamics may or may not substantially affect the C balance of treatment projects (Section 4.2).

5.1.1.2. Long-term post-fire C dynamics given one-time treatments in which all treated areas burn in wildfire

Two studies have evaluated growth and decomposition in treated and untreated stands following wildfire. Reinhardt and Holsinger (2010) used stand data collected from northern Rocky Mountain ponderosa pine forests to parameterize forest growth simulations that included treatment in year 5 (or no management) and a wildfire in year 10. They simulated growth, mortality, and decomposition for 75 years following wildfire and found that untreated stands contained greater C stocks than treated stands during the entire simulation period. Both treated and untreated stands became C sinks within 12 years following wildfire, suggesting that gross primary productivity (from growth and regeneration) increases sufficiently to overwhelm C losses due to decomposition of trees killed by wildfire. Post-fire net primary productivity was very similar in both treated and untreated stands, so the initial difference in C stores following wildfire between treatments and controls persisted for many years.

Carlson et al. (2012) simulate growth in treated and untreated stands following wildfire and, in contrast to the conclusions of Reinhardt and Holsinger (2010), find that treated stands return to a baseline pre-treatment C stock 10-35 years sooner than untreated stands, despite the fact that immediately post-wildfire, treated stands contained less C than untreated stands.

Section synthesis: The difference in conclusions between Reinhardt and Holsinger (2010) and Carlson et al. (2012) regarding long-term C dynamics potentially stem from differences in pre-treatment stand conditions and model assumptions regarding post-fire mortality, regeneration, and growth. Nonetheless, both studies evaluate a scenario in which all treated areas experience wildfire soon after treatment. Under contemporary management scenarios, only a fraction of treated area will experience wildfire during its effective lifetime (Section 4.1), and in this regard the net C storage benefits would therefore be much smaller (or the costs larger). Although the studies in this section seek to account for another source of uncertainty—the effect of post-wildfire C dynamics resulting from post-wildfire mortality, decomposition, regeneration, and growth—other assumptions, particularly the probability of treatment-wildfire interaction—impact the C balance conclusions of these studies. Evaluating the influence assumptions regarding post-wildfire C dynamics on study outcomes will need to be achieved in parallel with other C budget components in order to apply these study results to contemporary scenarios.

5.1.2. One-time treatments given an explicit wildfire probability

All of the studies described above evaluate a best-case scenario for fuels treatment effectiveness as net C sinks: they assume that all areas treated will experience wildfire during the effective lifetime of the treatments. However, the probability that any given treatment will interact with wildfire during its effective lifetime is low, and the probability of treatment-wildfire interaction can dramatically affect the classification of treatments as net sinks or net sources of C (Section 4.1; Fig. 2). To account for the fact that most treated areas will not experience wildfire during the lifetime of the treatments, several studies have evaluated the net effect of treatment on C balance given an explicit probability of wildfire.

5.1.2.1. One-time treatments given an explicit wildfire probability and given no influence of treatments on fire outside of treated areas

Two studies that incorporate an explicit wildfire probability focus on the effect of treatments specifically within treated areas. Goslee et al. (2010a, 2010b) surveyed stands pre- and post-treatment to estimate treatment emissions, and they accounted for treatment emissions that were offset by use of thinned material for bioenergy production and wood products. They simulated the effect of fire on treated and untreated stands and then simulated growth and decay for 10 years following wildfire. They assumed a one-time wildfire probability of 0.60% to 0.64%, which they accounted for in their 10-year C balance calculations by calculating a weighted average of wildfire C balance vs. no wildfire C balance as follows:

C emissions due to treatment = (C emissions given treatment and wildfire * probability of wildfire) + (C emissions given treatment and no wildfire * probability of no wildfire)

The studies concluded that treatment has a net negative effect on forest C storage. Notably, even stands that did burn contained less C if they had been thinned prior to burning than if they had not been thinned (Table A1.2). Although the models include post-fire mortality and growth, the reports do not state whether post-fire regeneration is included in the simulations.

Rather than assuming a one-time chance of fire, Winford and Gaither (2012) model C balance assuming a given annual wildfire probability every year over 50 years, concluding that after 50 years under a contemporary fire regime, treatment will result in a net loss of C relative to no management. They surveyed stands before and after treatment and quantified the C lost through thinning by comparing the treated and untreated stands. They assumed that thinned biomass replaces fossil fuels at a 1:1 by energy—as opposed to 1:1 by carbon–substitution, thus acknowledging that burning biomass releases more C per unit of energy generated than does fossil fuel (Section 4.3). The investigators quantified potential wildfire emissions by averaging the simulated emissions of a fire occurring after 5, 10, and 20 years of simulated growth, and they multiplied this number by the expected annual wildfire probability to calculate annual expected wildfire C emissions in treated and untreated stands. They estimated a fixed annual post-fire C sequestration rate due to growth by averaging annual C sequestration over 15 years of simulated growth. Finally, they used the estimated annual primary productivity and wildfire emissions to project stand C stocks over 50 years. Although the investigators conclude that treatment results in a net loss of C over 50 years under a contemporary fire regime, they find that given a fire rotation period of 31 years or less, treatment results in a net storage of C.

Section synthesis: The conclusions of Goslee et al. (2011 a,b) and Winford and Gaither (2012) imply that under a wide range of realistic contemporary wildfire probabilities, treatment will not result in a net storage of C. Although Goslee et al. (2011 a,b) evaluate a scenario that implies a very low probability of treatment-wildfire interaction, the conclusion that treatment results in a net loss of C holds regardless of the assumed wildfire probability (Table A1.2). The reports by Goslee et al. do not state whether post-fire regeneration is included in the simulations. If it is not, then the conclusions may overestimate the benefit of treatments: untreated stands, which generally experience greater mortality during wildfire, depend heavily on regeneration to recover pre-treatment C stocks (Carlson et al. 2012), though this effect may be small ten years after wildfire as evaluated by Goslee et al. (2011 a,b). Additionally, increased shrub productivity following disturbance may partially compensate for decreased tree productivity (Campbell et al. 2009), and models that focus specifically on tree-based C would miss this effect.

Like Goslee et al., Winford and Gaither (2012) suggest that under contemporary conditions, treatment will result in a net loss of C, though they suggest that treatment may result in a net storage of C if the fire return interval is within the range of historic variability; that is, 31 years or less. However, some of the modeling decisions depart from expected fire patterns. For example, the model does not allow pyrogenic emissions to vary based on fire rotation period. In reality, wildfire C emissions may be lower given shorter fire rotation periods because fewer fuels accumulate between fires. In this regard, the model may estimate a greater net C benefit of treatment under short fire rotation periods than would be expected in reality. On the other hand, the model does not incorporate the effects of wildfire on mortality, decomposition, regeneration, and growth; these dynamics are parameterized using unburned stands. Not accounting for the effects of wildfire on post-wildfire C dynamics may lead one to conclude that fuels treatments are less effective as net C sinks then they would be in reality, though it could also have the opposite effect (Section 4.2). Additionally, the analyses by Goslee et al. (2011 a,b) and Winford and Gaither (2012) do not evaluate the potential benefit of fuels treatment in moderating wildfire emissions in nearby untreated areas. Accounting for this benefit—and strategically locating treatments in areas where they would have the maximum possible effect in moderating landscape C emissions—would decrease the net C cost of treatment.

5.1.2.2. One-time treatments given an explicit wildfire probability and given an influence of treatments on fire in untreated areas

All of the studies discussed above assume that forest treatments only affect wildfire behavior within stands that are treated. However, a large body of research demonstrates that treatments can also moderate fire behavior in nearby untreated areas (e.g., Finney et al. 2007, Schmidt et al. 2008, Syphard et al. 2011). Studies that do not acknowledge this phenomenon may thus underestimate the C storage effect of fuels treatments. Among studies that examine the C implications of a one-time treatment, four account for the treatment shadow—that is, the potential reductions in fire emissions in untreated areas due to nearby treatments.

Buckley et al. (2014) compared modeled C stocks following wildfire in a no-treatment scenario and a fuels treatment scenario in which only a portion of the landscape was treated. They modeled C emissions due to wildfire based on assumed combustion factors (the proportion of pre-wildfire stand C that is released due to wildfire), using both low-range and high-range estimates of this proportion from the literatures. The analysis also incorporated the effect of treatments in reducing both the size and severity of wildfires. The resulting decrease in wildfire-induced C emissions was considered to represent the C benefit of treatment, and the C cost of treatment was calculated as the total C removed by treatments that fell within the (post-treatment) fire perimeters. This accounting approach does not incorporate the C releases that occurred due to treatments outside the fire perimeters, even though those treatments influenced wildfire C emissions by reducing wildfire size and severity. This analytical approach thus only incorporates about 30% of the treatment-induced C emissions and effectively assumes a 100% probability of wildfire across the C accounting landscape. The placement of fuels treatments was not designed specifically to optimize mitigation of wildfire emissions, though mitigation of emissions was one consideration of the committee that designed the treatments. Additionally, the analysis does not incorporate any potential reductions in C emissions achievable by using thinned material for bioenergy generation or manufacture of wood products. The authors conclude that when assuming low-range combustion factors, treatment generally results in a net loss of C, but when assuming high-range combustion factors, treatment can yield net C storage.

In contrast to the approach of Buckley et al. (2014), the analysis by Ager et al. (2010) makes very conservative assumptions regarding the probability that treated areas will experience wildfire. Ager et al. (2010) parameterized a forest growth model using stand conditions within a 68,474 ha watershed dominated by ponderosa pine in southeastern Oregon. They simulated fuels treatments in a portion of the study area and then simulated forest C stocks in both treatment and no-management scenarios. They then calculated wildfire probability by simulating fire progressions following 30,000 random ignitions in both the treatment and no-management scenarios. They calculated burn probability as the number of times a pixel burned divided by 30,000 ignitions; thus, the calculated number represents the probability of burning given one ignition within the study area. To calculate the effect of treatment given the calculated wildfire probability, they computed a weighted average as follows:

C stocks following treatment = (C stocks given treatment and wildfire * probability of wildfire) + (C stocks given treatment and no wildfire * probability of no wildfire).

They performed the same calculations for the no-management scenario. Despite accounting for treatment effects on nearby untreated areas, the analysis concluded that treatments produce a net loss of C. The study highlights the importance of considering the effect of treatments within a broader landscape, as the majority of the benefits of treatment in reducing wildfire emissions were accrued outside the treatment area.

Saah et al. (2012) demonstrate the importance of the assumed fire rotation period by performing a similar simulation as Ager et al. (2010) but with three different probabilities of wildfire. They assumed a continuous, annual probability of wildfire following treatment rather than a single year of fire probability. They simulated treatment in 25% of the study area using a USFS-recommended mix of prescriptions. At each 5-year forest growth simulation time step, they simulated potential C emissions from a wildfire burning the entire landscape, and they then discounted the potential wildfire emissions savings by the assumed probability of a wildfire actually occurring within each simulation time step. They used fire spread models to quantify the proportion of burned area avoided due to treatment and then multiplied this number by expected wildfire C emissions to calculate wildfire emissions avoided due to treatment in each time step. They conclude that C savings due to treatment are only possible under an assumed pre-historical fire regime representing a 15-year fire rotation. When they assume a contemporary fire rotation of 200 years (and even an intermediate rotation of 50 years), they conclude that treatment results in a net loss of C, even when assuming that thinned biomass will substitute for fossil fuels and generate long-lived wood products. However, the model does not account for post-wildfire C dynamics due to decomposition of trees killed by wildfire or changes in recruitment and growth.

Osborne (2011) applied a landscape-based approach that potentially improves on that of Ager et al. (2010) and Saah et al. (2012) by accounting for post-wildfire C dynamics due to regeneration, mortality, and decomposition. Osborne (2011) simulated 10,000 ignitions and counted the number of times each pixel was simulated to have burned. He then simulated treatments over 10%, 20%, or 30% of the landscape with highest burn probability. Finally, he simulated a wildfire occurring 5 years post-treatment in 33.86% of the untreated landscape—and a smaller proportion of the treated landscape—with highest burn probability. He used the same burn probability threshold to assign stands to wildfire vs. no wildfire in the treatment and no treatment scenarios, but because treatments reduced mean wildfire probability across the landscape, a smaller area burned in the treatment scenarios. He used a forest growth simulator to model regeneration, growth, and decomposition over 50 years following treatment. He concluded that given treatment of 20% of the study area, in both the short and long term, prescribed fire treatments resulted in net C storage and thinning treatments resulted in net C loss relative to the no-treatment scenario. However, given treatments covering 10% or 30% of the study area, neither prescribed fire nor thinning produced net C storage. These findings highlight the strong importance of treatment type, scale, and configuration in affecting C balance. However, the modeling approach makes several assumptions that may limit the applicability of the results to contemporary management scenarios. For one, the model assigns treatments to the exact pixels which, according to the model, would have the greatest wildfire probability in the absence of treatment. In reality, while managers sometimes use potential wildfire behavior as a variable in prioritizing areas for fuels reduction treatments, they often must select treatment areas with imperfect information regarding wildfire behavior or probability in the absence of treatment. Though models such as the one developed by Osborne (2011) may help to inform efficient placement of treatment, the real-world effects of treatment will differ from those predicted by the model, and managers may be unable achieve treatment placement that is as efficient as the placement evaluated in this study. Additionally, Osborne (2011) effectively assumes that 33.86% of the untreated landscape would burn during the effective lifetime of the treatments. This proportion is substantially greater than the average for the region—which has an estimated fire rotation of 283 years (Taylor and Skinner 2003)—as well as for Sierra Nevada yellow pine and mixed-conifer forests (see Section 4.1), though fire rotations in specific sub-regions will differ from regional averages. The assumption of an unusually high probability of wildfire may lead to conclusions that are unrepresentative of the expected effects of contemporary management in an average site. Nonetheless, the results of Osborne (2011) do suggest that given optimal treatment placement—particularly in areas with unusually short fire rotations—the potential for treatments to act as net C sinks may be greater than if treatments are not placed optimally.

Section synthesis: The studies in this section all account for the potential for fuels treatments to moderate wildfire emissions in untreated areas, and some of these studies conclude that treating stands may result in net C storage. However, all of these studies make substantial assumptions that may limit the applicability of their results to contemporary, realistic management scenarios. By focusing the C calculations exclusively on emissions of treatments that fell within the wildfire perimeters, the analysis by Buckley et al. (2014) does not account for a large portion (approximately 60%) of the total treatment C emissions, all of which arose from treating areas that did not interact with wildfire. Incorporating all treatment emissions leads to the conclusion that treatment results in a net loss of C, regardless of the emissions factor assumed.

The study by Buckley et al. (2014) also does not incorporate several factors that may help to reduce the C cost of treatment, such as potential reductions in emissions achievable by using thinned forest material for bioenergy generation, and it does not evaluate post-wildfire C dynamics. Finally, treatments were not placed with the sole purpose of optimizing mitigation of wildfire C emissions; optimizing placement of treatments may increase net C storage, or at least decrease net C release.

Like the analysis by Buckley et al. (2014), the calculations of Osborne (2011) imply an assumed probability of treatment-wildfire interaction that may be much greater than expected for most Sierra Nevada yellow pine and mixed-conifer forests (Section 4.1). In contrast, the assumption of ignition probability made by Ager et al. (2010) may lead to conclusions suggesting that treatments result in greater net emissions of C than they would in reality; Ager et al. assumed a single wildfire ignition within the 68,474 ha study area, whereas in reality a region of this size may experience more than one ignition during the effective lifetime of the treatments. Saah et al. (2012) avoid problems associated with selection of a single wildfire probability by evaluating the sensitivity of the conclusions to fire rotation. They find that even assuming an unusually short 50-year fire rotation, treatment results in net C release. However, the study does not account for post-wildfire C dynamics. If post-wildfire C flux is substantially different in treated vs. untreated stands, this simplification could substantially affect the applicability of the modeling results to contemporary management outcomes (Section 4.2). It is possible that treatment would have a relatively small influence on post-wildfire C dynamics (Reinhardt and Holsinger 2010), and if so, the conclusions of Saah et al. may represent relatively strong evidence that under conditions representative of one part of the Sierra Nevada, thinning stands would cause a net release of C.

Treatment placement can also influence the C implications of forest treatments, and neither Saah et al. (2012) nor Ager et al. (2010) place treatments specifically so as to maximize the net C benefits (i.e., to maximize the treatment shadow effect). If real-world management projects specifically prioritize net C storage and are able to identify the appropriate treatment locations to achieve it, they may draw more optimistic conclusions regarding the potential for treatments to achieve net C storage. The work by Osborne (2011) suggests that in areas with unusually short fire rotations, optimally placed treatments may yield net C storage.

5.2. Repeated treatment programs

All of the analyses reviewed to this point have evaluated the C implications of a one-time treatment. An alternative approach is to evaluate the C implications of a program of repeated treatment or disturbance over a longer time period. This approach focuses not on the C implications of individual treatments but rather evaluates long-term C stores given repeated treatment and continued wildfire risk. Repeatedly treating strategically located areas may be an effective way to maintain a consistently low probability of high-severity wildfire. An additional objective of repeated treatment programs may be to restore a historical disturbance process to a stand (e.g., through regular use of prescribed fire or managed wildfire), in which case wildfire may become a tool to maintain the forest as opposed to an unnatural disturbance to be mitigated. However, given the focus of this review is on the C implications of contemporary forest management, I focus in this section specifically on the C implications of repeated prescribed fire and/or mechanical thinning projects in the context of a contemporary wildfire regime.

5.2.1. Repeated treatment programs given no influence of treatments on fire in untreated areas

Two studies that adopt a repeated-treatment approach assume that treatments do not affect wildfire behavior outside treated stands. Mitchell et al. (2009) simulate treatment in stands representative of East Cascades ponderosa pine forests. They model factorial combinations of treatment prescriptions (salvage logging, understory removal, prescribed fire, and understory removal plus prescribed fire), four treatment frequencies (5 years, 10 years, 25 years, and no treatment), and two mean fire rotation periods intended to represent pre-historical fire regimes (8 years and 16 years) over 800 years. Across all combinations, the effect of treatment on net C balance is either near-zero or negative. The authors do not conduct an analysis of how using thinned biomass for bioenergy production may affect long-term C balance in the East Cascades system. However, they note that if the emissions associated with biomass processing and transportation are less than those avoided due to replacement of fossil fuels, then after a very long time period, fuels treatments may ultimately lead to net C storage.

Hurteau and North (2009) apply a somewhat similar C accounting framework to evaluate the effect of a one-time thinning event followed by prescribed fire repeated every 20 years. They model C stocks in treated and untreated stands given a single wildfire occurring in the middle of their 100-year simulation period. The simulations suggest that treatment has a net positive effect on end-of-simulation C balance only in a “no thin plus prescribed fire” scenario. Given wildfire, the no-treatment scenario stores equal or greater C than all other treatment scenarios (two types of one-time thinning prescriptions, with and without prescribed burning). Though introducing prescribed fire in some overstocked, fire-suppressed stands without first thinning them may result in high mortality and high C emissions, this study suggests that doing so under suitable conditions—and repeating the treatment at a regular interval—may produce positive net long-term C storage. However, because the analytical approach assumes one wildfire occurring during a 100-year period, it implies a substantially greater probability of treatment-wildfire interaction than would be expected in most Sierra Nevada yellow pine or mixed-conifer forests, which on average burn once every 173 to 241 years (Section 4.1).

Section synthesis: The two studies in this section draw opposite conclusions regarding the potential for repeated treatment programs to yield net positive C storage. The results of Hurteau and North (2009) may not closely reflect the expected outcomes of contemporary management, as the analysis assumes one wildfire occurs during the 100-year simulation period. Contemporary fire rotations in most of the Sierra Nevada are substantially longer than 100 years, and therefore on average untreated stands may not suffer such substantial reductions in C as the study suggests. Incorporating C emissions from treatments that do not burn would decrease any net benefit of treatment. Like the modeling by Hurteau and North (2009), the analysis by Mitchell et al. (2009) incorporates a wildfire probability substantially greater than the contemporary average. However, the latter analysis finds that treatment has a net negative or near-neutral effect on C. Assuming a longer fire rotation that is more representative of contemporary rotations would further increase the C costs of treatment, as it would incorporate the fact that a proportion of treated areas would remain unburned during the effective lifetime of the treatments.

In contrast to the assumptions regarding fire rotation, other analytical approaches of the studies in this section may lead the conclusions to suggest that treatments are less effective in yielding net C storage than they would be in reality. For example, using thinned material to generate bioenergy or long-lived wood products (assuming the treatment is thinning rather than burning) may decrease the C costs of treatment. Similarly, if the studies considered the effect of treatments in moderating wildfire in nearby untreated areas, they would attribute a greater net C benefit to treatments.

5.2.2. Repeated treatment programs given an influence of treatments on fire in untreated areas

Finally, two studies evaluate repeated treatment programs and consider the potential influence of treatments on wildfire behavior outside of treated areas. Campbell and Ager (2013) created process models representing C dynamics over time due to forest growth, decomposition, fuels treatment effectiveness and longevity (including effects in both treated and untreated areas), wildfire, and harvesting of merchantable timber for long-lived wood products. Although these models required substantial assumptions, the authors performed a sensitivity analysis over a 16-fold range of values for each parameter. The model assumed one wildfire ignition every 20 years within the 2000 ha study area. Under all parameter assumptions evaluated in the sensitivity analysis, treatment always reduced the total system C storage. The authors attribute this effect largely to the fact that the majority of the treated area does not burn.

An analysis by Loudermilk et al. (2014) may represent the most comprehensive and realistic approach to date in accounting for the effects of fuels treatments on C storage across a landscape. The investigators parameterize a spatially-explicit ecosystem model, LANDIS-II, to represent contemporary conditions in the Lake Tahoe Basin using empirical forest survey data. They simulate forest thinning each year on a 15-year rotation—a rate consistent with current management—and a 30-year rotation, prioritizing treatments in areas with the highest wildfire probability. Each year, they simulate random wildfires with sizes, locations, and frequency parameterized to represent the contemporary wildfire regime. They conclude that after 100 years of repeated treatment and wildfire risk, implementing fuels treatments on a 30-year rotation (but not a 15-year rotation) results in slightly greater (though not significantly so) landscape C storage than a no-management scenario. Throughout most of the 100-year simulation period, however, the treatment scenarios store less C than the no-treatment scenario. Although the authors do not propose an explanation for this result, one possible explanation is that continued treatment over a century results in stands with large, fire-resistant trees that store more C per hectare relative to stands that experience less frequent but more severe disturbance. Indeed, the simulated treatment scenarios result in a much greater proportion of fire-resistant pines relative to fire-sensitive white fir than the no-treatment scenario. These observations suggest that fuels treatments must be conducted repeatedly at regular intervals for their benefit to be realized after 100 years. If treatment is discontinued, stands may become dominated by shade-tolerant, fire-sensitive trees and accumulate substantial ladder fuels, creating the potential for wildfire to trigger a transition back to a low C-storage system.

Section synthesis: The two studies in this section draw somewhat divergent conclusions regarding the net C balance of fuels treatments, likely stemming from differences in modeling assumptions. The assumptions made by Campbell and Ager (2013) may result in an estimate of area burned that is much lower than contemporary expectations; at the mid-range estimate, about 3% of the landscape burns every 20 years. This translates to a mean fire rotation of approximately 670 years, which is very long for the study area in the East Cascades and for

Sierra Nevada yellow-pine and mixed-conifer forests. The analysis thus may not allow treatments as much opportunity to mitigate wildfire C emissions (and thus generate C benefits) as they would have under a contemporary Sierra Nevada management scenario in which fire rotations average 173-241 years (Section 4.1). Additionally, it appears that in the analysis, the sensitivity of each parameter is evaluated assuming the middle estimate of all other parameters. Because mid-range estimates imply a fire rotation period substantially longer than the contemporary mean rotation period, the analysis may not allow for a fair evaluation of the influence of important parameters in affecting treatment effectiveness in the context of wildfire. The analysis also spreads treatment equally over the landscape rather than preferentially assigning treatment to high fuel-load plots, as occurs in current on-the-ground fuels management. These modeling decisions may lead to results that suggest treatments are less effective in yielding net C storage than they would be in reality.

Assuming fire rotations that are more realistic for the Sierra Nevada, the analysis by Loudermilk et al. (2014) finds that repeated treatments may result in net C storage after 100 years. However, the analysis may reflect a best-case scenario for treatment effectiveness for several reasons. First, the model applies treatments to the very sites which, according to the model, are at greatest risk of wildfire, given they are accessible. In reality, although managers do often prioritize treatment in the stands with the greatest risk of high-severity wildfire, this is not their only criterion, and real-world fire risk is not as predictable as modeled fire risk.

In addition, fuels treatments may be uniquely effective in the Lake Tahoe Basin, where the majority of wildfire ignitions occur in a relatively small fraction of the landscape. Thus, a relatively small number of fuels treatments prioritized around likely ignition sources can make a large difference in the impacts of wildfire on the landscape. In regions where ignition locations are more dispersed, treatments would need to be applied over a larger area—with commensurate C costs—to be similarly effective in influencing fire behavior.

Finally, because any positive net C storage due to treatment appears to be very small, many additional factors—even those with a small C impact—could influence the determination of treatments as net sources or sinks of C after 100 years. These include end-use of thinned biomass, selection of treatment method (thinning or prescribed fire), and the amount of C emitted by machinery during treatment implementation.

6. Synthesis and conclusions

6.1. One-time treatment projects

Currently, no empirical or modeling evidence supports the hypothesis that under predominant contemporary conditions, one-time fuels treatments can be expected to yield net C storage. However, no single study or group of studies has evaluated every potential combination of conditions or dynamics that are found within the ponderosa pine and mixed-conifer forest types in the Sierra Nevada. Conditions in the Sierra Nevada are highly spatially variable; it is possible that some areas possess multiple unique characteristics which, when combined, would allow treatments to yield net storage of C. For example, some areas may have an unusually short fire rotation, an unusually large potential for treatments to moderate wildfire outside of treated areas, and an unusually long effective treatment lifetime. Such a scenario may be similar to the one evaluated by Osborne (2011), which concluded that when treatments are distributed optimally, the treatment program may yield net C storage. It is notable, however, that another study that evaluated a range of fire rotations and treatment application strategies—and which incorporated the treatment shadow effect—drew opposite conclusions regarding the C impact of treatment (Saah et al. 2012).

Recent comprehensive reviews of the C implications of forest management in the context of wildfire (Campbell et al. 2011, Restaino and Peterson 2013) suggest that treatments have a low probability of increasing terrestrial C storage and may be more likely to cause net C emissions. These reviews highlight numerous reasons for which fuels treatments are unlikely to result in net C storage, particularly the fact that most treatments—which entail C emissions—will not experience wildfire during their effective lifetimes. Although there exist two reviews suggesting forest treatments cannot be expected to result in net C storage, there exist no comprehensive reviews or syntheses concluding the opposite.

Many studies evaluate the C implications of treatment given a single assumed probability of treatment-wildfire interaction. To explore how conclusions may change given different probabilities of treatment-wildfire interaction—and given variation in other factors such as post-wildfire C dynamics—I have extracted data on C storage under different management and disturbance scenarios from all studies for which this is possible (Table A1.2). Based on the proportion of stand C that remains following treatment only, wildfire only, and treatment plus wildfire, I have calculated the minimum probability of treatment-wildfire interaction at which treatment yields net storage of C (methods presented in Appendix 3). Additionally, because most studies do not incorporate the potential for end-use of thinned material to offset some of the treatment emissions, I included a scenario to explore the influence of assuming that 20% of all treatment emissions are offset (likely a high estimate; Section 4.3). I only evaluate the effect of this offset for scenarios that involve at least some amount of mechanical thinning, as treatments that are conducted exclusively via prescribed fire do not yield any forest material. The data summarized in Table A1.2 demonstrate that in some situations, treated-burned stands actually contain less C than untreated-burned stands. In such scenarios, treatment results in net C loss regardless of the assumed probability of treatment-wildfire interaction. In many other scenarios, the effect of treatment in moderating wildfire emissions is so small relative to the C removals due to treatment that even when treated areas are guaranteed to experience wildfire, treatment would not result in net C storage.

Several scenarios presented in Table A1.2 suggest that given a sufficiently high probability of treatment-wildfire interaction, treatment may yield net C storage. For example, when using the data of North and Hurteau (2011) and assuming that all fire-killed trees release all their C and that this loss is not compensated at all by regeneration—an unlikely scenario (Section 4.2)—the probability of treatment-wildfire interaction would need to be unusually high (31-39% or greater) for treatments to yield net C storage. When assuming that C remains in dead trees (or that any decomposition of dead trees is compensated by regeneration—a more likely scenario (Section 4.2)—treatment would result in net C loss even if wildfire were guaranteed to occur. Although incorporating a treatment shadow effect may decrease the net C costs of this scenario, a landscape-level analysis would also need to acknowledge that not all untreated areas burn at high severity and therefore not all treatments would substantially moderate wildfire behavior even if they did burn.

A different scenario, the repeated application of prescribed fire modeled by Hurteau and North (2009)—particularly when evaluated at 50 years following wildfire to allow post-fire C dynamics to play out—would yield net C benefits given a probability of treatment-wildfire interaction of 46% or greater. Though this probability is far outside the range of average contemporary expectations (Section 4.1), there may be some unique sites where this value is representative. In addition, the analysis does not incorporate all potential benefits of treatments, particularly the potential for the treatments to generate a treatment shadow. The impact that incorporating a treatment shadow might have on the break-even treatment-wildfire interaction probability is uncertain.

The analysis of Buckley et al. (2014) does incorporate a treatment shadow effect, and the proportional effects of treatment and wildfire on C stocks (Table A1.2) suggest that the probability of treatment-wildfire interaction would need to be very high in order for the treatments to yield net C storage (a finding corroborated by Osborne 2011; Section 5.1.2.2). Buckley et al. (2014) do not evaluate post-fire C dynamics, so to explore the sensitivity of the C balance conclusions to post-fire dynamics, I included two scenarios in which all trees killed by wildfire were considered to release all their carbon. Despite the fact that this represents an unlikely extreme scenario (Section 4.2), it would still require an unusually high probability of treatment-wildfire interaction, even assuming high-range emissions factors, for treatments to be justified from a C standpoint. Although additional modifications to the scenario (e.g. more strategic placement of treatments) may further decrease the net C costs of treatment, it is unclear whether the effect of such factors would be large enough to lead to the conclusion that treatments increase net C storage given a reasonable contemporary probability of wildfire. This and numerous other sources of uncertainty, combined with the substantial variation in forest conditions across the landscape of the Sierra Nevada, leave open the possibility that some unique treatment projects may result in net storage of C.

6.2. Repeated treatment programs

Repeated treatment programs that are maintained over a sufficiently long time period may be more likely than one-time treatment programs to yield positive net C storage. However, the conditions that allow treatments to yield net C storage may be quite specific and relatively rare. Net positive C storage may be most likely when the thinning program is conducted in a landscape with relatively predictable ignition locations and when managers can accurately identify the areas at greatest risk of C loss—for example, areas of high fuel load adjacent to areas that experience frequent ignitions—and prioritize those areas for treatment. These conditions are met by the scenario evaluated by Loudermilk et al. (2014). This modeling approach incorporates the effects of treatments in moderating wildfire behavior in nearby untreated areas, and it also incorporates post-wildfire C dynamics due to growth and decay. Another analysis of a repeated treatment program (Hurteau and North 2009) also finds repeated treatments may increase net C storage. Although the conclusions of this study may have been different had the study evaluated C dynamics over a full fire rotation cycle and/or evaluated the effect of the treatment shadow (see Section 5.2.1), the results corroborate those of Loudermilk et al. (2014), at least under a scenario in which wildfire is unusually frequent. The findings of Loudermilk et al. (2014) and Hurteau and North (2009) contrast with those of Campbell and Ager (2013), which suggest that under a wide range of conditions, treatment results in net C loss.

The scenario evaluated by Loudermilk et al. (2014) may represent a best-case scenario for fuels treatment to increase terrestrial C storage. The study focuses on the Lake Tahoe Basin, which, as described in Section 5.2.2, may be uniquely suited to yield positive net C benefits through optimized placement of treatment. Despite the unique situation of the Lake Tahoe Basin, during the first century of the C simulations, treatment resulted in a net C loss, implying that treatment may not favor C storage in the short- to mid-term, even given optimal treatment placement. It may not be until after approximately 100 years of continued thinning that treatment would result in net storage of C. However, Loudermilk et al. (2014) did not evaluate the sensitivity of their conclusions to all possible variables (e.g., treatment type—thinning or prescribed fire—or end-use of thinned material), and it is possible that under different management and wood-utilization scenarios, their analyses would have suggested that treatments are more (or less) effective at yielding net C storage.

It is important to note that if it were possible for a repeated treatment program to generate any long-term C benefit, the benefit would be one-time in nature. It would be generated over time through implementation and maintenance of the treatment *program* rather than accumulating repeatedly with each successive treatment. Therefore, it would not be possible to assign a specific incremental C benefit to an individual treatment event. The benefit would be one-time in nature because the ongoing treatment program would ultimately have the effect of shifting the forest to a higher-carbon state. This shift in C would occur just once despite the repeated nature of the fuels treatments. Importantly, if the treatment program were discontinued and the system's C stores returned to their pre-treatment levels, any C benefits originally gained through implementation of the treatment program would be lost (reversed). Regardless of whether repeated fuels treatments increase or decrease net long-term C storage, the increase in disturbance frequency would likely have the effect of increasing the stability of C storage in the system over time and reducing the risk of sudden loss of large amounts of C (Earles et al. 2014).

There is one potential exception to the one-time nature of the C benefit of ongoing treatment programs. If thinned biomass were used to generate bioenergy (to replace fossil fuels) rather than piled and burned (or removed using prescribed fire) and thinning resulted in increased C sequestration in the stand to a sufficient degree so as to compensate for the fact that bioenergy releases more C per unit of energy generated than do fossil fuels, then each treatment event within the ongoing treatment program may yield an additional incremental C benefit. This benefit would accumulate over time on top of any stand-level changes in C stocks due to treatment.

6.3. Geographic and ecological scope of assessment

Although this report is intended to evaluate the C implications of fuels treatments in yellow-pine and mixed-conifer forests in the Sierra Nevada Mountains of California, it draws evidence from studies across western U.S. yellow pine and mixed-conifer forests that historically experienced a high-frequency, low-severity fire regime. Many of the system-specific factors that influence the conclusions of C accounting studies (e.g., fire regime, the response of wildfire to weather and stand conditions, current stand structure and C stocks, and net primary productivity) are more consistent throughout the range of this forest type than they are among different forest types (Hudiburg et al. 2009, Sommers et al. 2011, Liu et al. 2012). Some studies that have evaluated the sensitivity of C accounting conclusions to one or more of these variables have demonstrated strikingly low sensitivity of conclusions across a range of assumptions that encompass realistic values for the Sierra Nevada (Saah et al. 2012, Winford and Gaither 2012, Loudermilk et al. 2014). In contrast, Carlson et al. (2012) demonstrate strong sensitivity of C balance conclusions to assumed fire-induced mortality and seedling recruitment rates. Carbon balance studies focused specifically on the Sierra Nevada (Hurteau and North 2009, North and

Hurteau 2011, Carlson et al. 2012, Saah et al. 2012, Winford and Gaither 2012, Loudermilk et al. 2014) do not appear to draw conclusions that differ systematically from those focused on other Western U.S. yellow pine and mixed-conifer forests.

6.4. Fate of thinned forest material

Not all studies reviewed in this report account for the potential to reduce treatment-induced C emissions by using thinned biomass to generate energy or to manufacture wood products. Although accounting for such uses has the potential to reduce the calculated net C emissions of treatment, avoided emissions through bioenergy production and manufacture of long-lived wood products account for only a small proportion (<20%) of the C removals due to treatment (Finkral and Evans 2008, Ager et al. 2010, Campbell et al. 2011, Springsteen et al. 2011, Saah et al. 2012). The potential for bioenergy generation to reduce the net emissions of a thinning project is limited by the fact that woody materials release much more C per unit of energy generated than do fossil fuels (Mitchell et al. 2012). Additionally, any C stored in wood products will eventually be released as the wood products decay (Section 4.3). Even among studies that assume some proportion of thinned biomass is used for wood products or bioenergy, most conclude that treatment results in a net release of C (Goslee et al. 2010a, 2010b, Ager et al. 2010, Saah et al. 2012, Winford and Gaither 2012). The one study that concludes otherwise (Finkral and Evans 2008) evaluates a scenario that is unrepresentative of contemporary dynamics, particularly in that it assumes that all treated areas burn. Accounting for reductions in black carbon emissions by burning thinned biomass in a bioenergy facility rather than in open piles would result in a greater estimate of reduction in CO_2-equivalent emissions, but likely only by approximately 30% of the original (modest) bioenergy savings (Bruce Springsteen, Placer County Air Pollution Control District, *unpublished analysis*).

The analyses that have been conducted to date thus provide no strong evidence that using thinned material for bioenergy production or wood product manufacture can, by, itself, affect the determination of contemporary one-time forest treatment projects as net sinks or sources of C. However, when evaluating repeated treatment projects, the modest benefits of bioenergy generation, if they exist, may shift conclusions regarding net C storage effects of treatments from negative to positive. After many cycles of forest thinning, the gradually accumulating C savings due to bioenergy production may overwhelm the C losses due to forest thinning (Mitchell et al. 2009). However, this benefit may take an impractically long time to accrue, if it does at all. Numerous factors would need to align to favor the accumulation of bioenergy benefits. For example, thinning would have to trigger increased C sequestration in the stand to a sufficient degree to offset the greater amounts of C released per unit of energy produced using biofuels vs. fossil fuels (Mitchell et al. 2012).

There is still some uncertainty surrounding the exact amount by which end-use may help to offset treatment emissions. For example, studies that evaluate the potential for thinned biomass to substitute for fossil fuels do not consider the C emissions associated with extraction and processing of the fossil fuel. Accounting for the full life-cycle emissions of fossil fuel extraction would increase the potential for fossil fuels to offset C emissions, though the magnitude of this effect is unknown and should be the subject of future inquiry.

6.5. Influence of fire rotation period

The conclusions of C accounting studies are highly dependent on the assumed fire rotation period. When treated areas have a high probability of interacting with wildfire during their effective lifetimes, the treatments (which entail C releases) are more likely to also result in increased C storage due to avoided wildfire emissions (Fig. 2). For example, Winford and Gaither (2012) found that fuels treatments resulted in a net storage of C when the assumed fire rotation period was less than 31 years, but not when it was greater than 31 years, and Saah et al. (2012) found that among their 15-year, 50-year, and 200-year fire rotation period scenarios, treatment only resulted in net positive C storage in the 15-year scenario. Among the remaining studies of one-time fuels treatment projects, the only studies implying that treatments have a net positive effect on C storage are those that assume an effective fire rotation period substantially shorter than contemporary average fire rotations in Sierra Nevada mixed-conifer and yellow pine forests. Such results leave open the possibility that in unique areas with unusually short fire rotations—or in future scenarios in which fires become more frequent and more difficult to suppress—treatments may result in net C storage, given that other factors are also conducive.

6.6. Inclusion of treatment shadow effect

Because treatments can have the effect of moderating wildfire behavior outside treated areas, studies that do not incorporate the treatment shadow effect (Hurteau et al. 2008, Finkral and Evans 2008, Hurteau and North 2009, Mitchell et al. 2009, Goslee et al. 2010a, 2010b, Wiedinmyer and Hurteau 2010, Reinhardt and Holsinger 2010, North and Hurteau 2011, Carlson et al. 2012, Winford and Gaither 2012, Vaillant et al. 2013b) may draw conclusions that suggest treatments are less effective in yielding net C storage than they would be in reality. Three studies that do account for the treatment shadow effect (Ager et al. 2010, Saah et al. 2012, Campbell and Ager 2013) find that treatments result in net C loss. Another study that incorporates the treatment shadow effect (Osborne 2011) finds potentially net positive effects of treatments on C storage, but this study makes other assumptions that may make its results unrepresentative of expected contemporary Sierra Nevada management outcomes (see Section 5.1.2.2). The analyses performed to date thus provide no strong evidence that accounting for the treatment shadow effect can, by itself, lead to the conclusion that one-time treatment projects result in net storage of C. On the other hand, when evaluating treatments in a repeated-treatment context (Section 4.5), accounting for the treatment shadow effect has the potential to lead to the conclusion that treatments can result in net C storage. A study that accounts for the treatment shadow effect in a repeated-treatment context (Loudermilk et al. 2014) finds that repeated treatment may yield net C storage after a century. This study suggests that under suitable conditions (which may be relatively rare in the Sierra Nevada), considering the treatment shadow effect, combined with other factors, may lead to the conclusion that repeated treatment programs may yield net C storage. However, the magnitude of the treatment shadow effect remains very difficult to accurately quantify, and it is likely highly sensitive to stand structural characteristics, fuel types, fuel moisture, and other factors. The results of studies that include an evaluation of the treatment shadow effect must be interpreted with this in mind.

Finally, utilizing the treatment shadow effect to maximize the C benefits of a given treatment program may or may not be consistent with the goals of forest restoration. If treatment has the effect of reducing the forest area that experiences disturbance (wildfire and/or treatment), it may contribute to increased densification of stands outside the treatment area. If, on the other hand, treatments have the effect of reducing wildfire severity (but not size) outside treatment areas, then treatments with large treatment shadows may be very consistent with the goals of restoring low- to moderate-severity disturbance to forests.

6.7. Climate change effects

The effects of fuels treatments on net C storage are likely to shift as climate changes, particularly due to expected climate change-induced increases in annual area burned (and thus decreases in fire rotation). Climate change may affect wildfire behavior in both treated and untreated areas by influencing fire weather, fuel production, fuel moisture, and other factors. Using a climate envelope approach, Spracklen et al. (2009) predict a 54% increase in annual area burned by 2050 across the western U.S., though they do not provide predictions specific to the Sierra Nevada. Westerling et al. (2011) predict a multiple increase in annual area burned in mid-elevation west-slope Sierra Nevada forests by 2085. However, such predictions may be overestimates for a number of reasons, including the fact that increasing drought intensity may result in reduced fuel production and availability (Diggins et al. 2010). Accounting for such dynamics, Loudermilk et al. (2013) predict a 43% increase in mean annual area burned by 2080 under high-range climate change predictions for the Lake Tahoe Basin. Miller and Safford (2012) show that annual area burned at high severity has already increased in California during the past two decades. Nonetheless, fuels treatments appear most effective at moderating wildfire behavior when wildfires burn at intermediate severity (Lydersen et al. 2014); if a greater proportion of fires burn at very high severity in the future, fuels treatments may become less effective in moderating wildfire behavior, unless their application is adjusted to compensate for increased fire severity. Further, an additional source of uncertainty is the effort that land management agencies will put into fire response; increased suppression effort, for example, may moderate any effects of climate change on wildfire probability. On the other hand, if management priorities shift to include greater use of managed wildfire, fire rotation would decrease and the probability that treatments would have the opportunity to moderate wildfire emissions may increase.

In addition to climate change effects on fire regime, increasing drought intensity due to climate change may cause greater mortality of adult trees (Van Mantgem and Stephenson 2007). Thinning may help to ameliorate some drought stress (Kerhoulas et al. 2013), and this effect may help to offset the C releases due to treatment. Further, the interaction of wildfire and climate change may result in state changes (Lenihan et al. 2007) and shifts in ecosystem carbon carrying capacity, and how this interaction may be influenced by forest treatments is unknown. Due to the numerous sources of uncertainty, it is very difficult to predict how climate change may influence the effectiveness of future treatments in yielding net C storage. Nonetheless, under increasing drought stress, forests comprised of fewer, larger trees and which experience disturbance more frequently (such as those that might result from repeated treatment and/or reintroduction of frequent fire) maintain substantially more consistent C stocks over time relative to dense, fire-suppressed forests (Earles et al. 2014). Forest treatments may thus result in C storage that is more stable over time, regardless of whether it is on average greater or less than C storage in a no-management scenario.

Despite the uncertainties and caveats, it appears reasonable to conclude that climate change will increase, to at least some degree, the opportunity for fuels treatments to moderate wildfire behavior in the Sierra Nevada. Such dynamics would increase the net C benefits of fuels treatments, or at least reduce the net C costs. The evidence accumulated to date suggests that in many cases, the probability of treatment-wildfire interaction would need to increase by a large amount for one-time treatments to result in net storage of C (Table A1.2). In some unique cases, however, a relatively small increase in wildfire probability may be sufficient. Whether increases of sufficient magnitude will be realized through climate change and/or changing management priorities, and whether any effects on the C balance of treatments will be offset by changes in other factors such as the effectiveness of treatments in moderating wildfire emissions, remains to be explored.

If repeated, landscape-scale treatment programs can potentially produce a net increase in C storage under a contemporary climate scenario, an increase in wildfire probability due to climate change may strengthen the C storage effect. Loudermilk et al. (2014), for example, evaluate the impact of assuming a contemporary fire rotation period compared to assuming a doubling of ignitions relative to contemporary patterns (a "high fire" scenario) given an ongoing, landscape-scale treatment program, and they conclude that the treatment break-even point (the year in which C storage due to treatment becomes positive) occurs 30 years sooner (2080 vs. 2110) in the high-fire scenario vs. the contemporary scenario. Nonetheless, due to the additional sources of uncertainty in the effects of climate change—for example, on fuel production and on the effectiveness of treatments in moderating wildfire emissions—it remains difficult to make strong predictions of the overall effect of climate change on the C implications of fuels treatments.

6.8. Overall conclusions

Despite the large body of research that has accumulated to date, there does not yet exist any strong evidence that one-time fuels treatment projects in Sierra Nevada yellow pine or mixed-conifer forests can be expected to yield net positive C storage under prevailing contemporary conditions. Although variation in any one project attribute that can influence outcomes (e.g., wildfire probability, use of thinned biomass, or ability to place treatments so as to maximize the treatment shadow effect) may not affect the ultimate conclusions, it is possible that some unique sites and treatment projects possess a sufficient number of conducive attributes such that treatment may yield net C storage. Factors associated with climate change, including the potential for increased wildfire frequency and drought mortality, particularly in unthinned stands, may increase the potential for treatments to result in net C storage. However, further research is needed to determine the extent of these effects.

In contrast to one-time treatments, there is a possibility that repeated, landscape-scale treatment programs can result in modest positive net C storage in the long term (i.e., 100 years or longer). The net C storage potentially achievable through such programs may be somewhat greater if thinned biomass were used for bioenergy generation (assuming the scenario is conducive to it; Section 4.3) and if annual wildfire probability were to increase. Although some studies suggest that repeated treatment programs may lead to increased C storage (Hurteau and North 2009, Loudermilk et al. 2014), they may evaluate scenarios in which treatments are uniquely suited to yield positive net C benefits through fuels treatments (see Section 5.2). Thus, repeated treatment programs may result in modest net C storage in the long term, but potentially only under very specific circumstances that have yet to be clearly identified. Although the potential for repeated treatment to result in increased C storage in the long term may be limited, repeated treatment does confer a C benefit in the sense that treated forests are likely to maintain more consistent, stable C stocks over time. Future modeling and empirical studies can help to identify any specific circumstances under which treatment may increase C stocks—in addition to stabilizing them—and to evaluate the prevalence of these conditions throughout the Sierra Nevada.

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Appendix 1. Summary tables

Table A1.1: Summary of studies evaluating the net C implications of forest thinning and prescribed fire treatments in the context of wildfire

Study	Type of treatment	Average probability of wildfire over study area during a year with wildfire risk	Number of years with wildfire risk	Treatment one-time or repeated	Post-wildfire C dynamics included	End-use of thinned biomass evaluated	Considers treatment shadow effect	Treatment effect on net sequestration of C (short-term)[1]	Treatment effect on net sequestration of C (long-term)[2]
Ager et al. 2010	Thin + burn	N/A[3]	1	One-time	No	Wood products	Yes	Negative	
Buckley et al. 2014	Thin	100%	1	One-time	No		Yes	Negative or positive[4]	
Campbell and Ager 2013	Thin	< 0.01% to approximately 0.13%	80	Repeated	Yes	Wood products	Yes		Negative
Carlson et al. 2012	Thin, burn	100%	1	One-time	No and Yes		No	Negative	Positive[5]
Finkral and Evans 2008	Thin	100%	1	One-time	No	Fossil fuel substitution and wood products	No	Negative or positive[6]	
Goslee et al. 2011 a,b	Thin	0.60% and 0.64%	1	One-time	Yes	Fossil fuel substitution and wood products	No	Negative	
Hurteau and North 2009	Thin, burn, thin + burn	100%	1	One-time and repeated	No and Yes		No	Negative or positive[7]	Negative or positive[7]
Hurteau et al. 2008	Thin	100%	1	One-time	No		No	Positive	
Loudermilk et al. 2014	Thin	N/A[8]	100	Repeated	Yes		Yes	Negative	Positive[9]
Mitchell et al. 2009	Thin, burn, thin + burn	6.25% to 12.5%	800	Repeated	Yes	Fossil fuel substitution	No		Near-zero or negative[10]
North and Hurteau 2011	Thin, burn, thin + burn	100%	1	One-time	NR		No	Negative	
Osborne 2011	Thin, burn, thin + burn	33.86%[11]	1	One-time	Yes		Yes	Negative or positive[12]	Negative or positive[12]

Table A1.1 (continued)

Study	Type of treatment	Average probability of wildfire over study area during a year with wildfire risk	Number of years with wildfire risk	Treatment one-time or repeated	Post-wildfire C dynamics included	End-use of thinned biomass evaluated	Considers treatment shadow effect	Treatment effect on net sequestration of C (short-term)	Treatment effect on net sequestration of C (long-term)
Reinhardt and Holsinger 2010	Thin, burn	100%	1	One-time	No and Yes		No	Negative	Negative
Saah et al. 2012	Thin, burn	0.50%, 2.00%, and 6.67%	40	One-time	No	Fossil fuel substitution and wood products	Yes	Negative[13]	Negative
Vaillant et al. 2013	Burn	100%	1	One-time	No		No	Negative	
Winford and Gaither 2012	Thin	0.4% to 7.0%	50	One-time	No	Fossil fuel substitution	No	Negative	Negative or positive[14]

[1] C balance evaluated 0-10 years following execution of treatment or initiation of simulation
[2] C balance evaluated >10 years following execution of treatment or initiation of simulation
[3] Assumes one average ignition within 45,193 ha of forested study area
[4] Conclusion depends on on assumed emission factors (proportion of forest C that is released during wildfire); the higher estimates result in a net positive estimate of treatment effect on net C sequestration, while the lower estimates result in a net negative effect of treatment on net C sequestration.
[5] Long-term C stores of treated and untreated stands are not reported, but number of years needed to recover pre-treatment C is lower in treated stands
[6] Conclusions depend on whether thinned biomass is used for bioenergy (negative) or wood products with assumed infinite lifespan (positive)
[7] The burn treatment resulted in greater C storage than no treatment; the thin and thin + burn treatments resulted in less C storage than no treatment. (From Fig. 1 A-F)
[8] Assumes 3 to 6 ignitions per year within 85,000 of forested study area
[9] Effect of treatment becomes positive after 80 to 100 years of uninterrupted, repeated treatment
[10] Near-zero for thin; negative for prescribed fire
[11] Represents probability in no-treatment scenario; probability is reduced by treatment
[12] Positive for spatially-optimized prescribed fire; negative for spatially-optimized thin + burn.
[13] Treatment results in a net release of C unless assuming pre-historic fire return interval, in which case treatment results in a net short-term (but not long-term) sequestration of C
[14] Assuming a fire rotation of 31 years or less, treatment results in net emissions of C until approximately 50 years post-treatment, at which point it results in net sequestration of C. With longer fire rotations, treatment results in net emissions of C for time periods well beyond 50 years post-treatment.

Table A1.2: Carbon storage given treated, burned, and treated-burned scenarios from all studies that provide such data, and the calculated probability of treatment-wildfire interaction above which treatment would yield net C storage. A description of the calculations performed to compute this probability is provided in Appendix 2.

	Proportion of untreated, unburned stand C remaining following:			**Minimum probability of treatment-wildfire interaction required to yield expectation of net C storage**			
Source	**Treat-ment**	**Wildfire**	**Treat-ment then wildfire**	**Assuming no offset of treatment emissions**	**Assuming 20% of thinning emissions are offset by end-use**	**Treat-ment type**	**Scenario evaluated (when multiple scenarios are evaluated per study)**
Buckley et al. 2014[1]	0.86	0.52	0.60	63%	51%	Thin	High-range emissions factors; fire-killed trees do not release C
	0.86	0.35	0.57	38%	31%	Thin	High-range emissions factors; fire-killed trees release all C
	0.86	0.71	0.69	NP	90%	Thin	Low-range emissions factors; fire-killed trees do not release C
	0.86	0.53	0.67	52%	41%	Thin	Low-range emissions factors; fire-killed trees release all C
Carlson et al. 2012[2]	0.62	0.58	0.50	NP	NP	Thin	
Finkral and Evans 2008[2]	0.75	0.83	0.62	NP	NP	Thin	
Goslee et al. 2011a,b[2]	0.70	0.83	0.60	NP	NP	Thin	"Berry Timber" scenario
	0.91	0.80	0.73	NP	NP	Thin	"Davis" scenario
	0.81	0.85	0.66	NP	NP	Thin	"Bull" scenario
	0.64	0.85	0.48	NP	NP	Thin	"Hot Rocks-Collins" scenario
Hurteau and North 2009[3]	0.73	0.76	0.61	NP	NP	Thin	Values represent C storage at 10 years following wildfire
	0.83	0.73	0.73	NP	83%	Thin	Values represent C storage at 50 years following wildfire
	0.84	0.76	0.84	67%		Burn	Values represent C storage at 10 years following wildfire
	0.88	0.73	0.88	46%		Burn	Values represent C storage at 50 years following wildfire
North and Hurteau 2011[4]	0.81	0.75	0.70	NP	NP	Mix	Fire-killed trees do not release C
	0.81	0.28	0.57	39%	31%	Mix	Fire-killed trees release all C
Reinhardt and Holsinger 2010[5]	0.60	0.71	0.47	NP	NP	Thin	Thinning treatment
	0.88	0.71	0.71	99%		Burn	Prescribed fire treatment
Vaillant et al. 2013b[2]	0.88	0.83	0.78	NP		Burn	Wildfire occurs 1 year following treatment
	0.86	0.83	0.76	NP		Burn	Wildfire occurs 8 years following treatment

NP: Not possible; treatment yields net C loss even at 100% probability of treatment-wildfire interaction

[1] Values represent C immediately post-wildfire within the modeled fire perimeters, summed across all five fires modeled in the report; treatment removals only include C removed within post-treatment fire perimeters.

[2] Values represent C immediately post-wildfire; fire-killed trees do not release C.

[3] Values incorporate post-wildfire C dynamics.

[4] Values represent C within several years of wildfire; removal only counts live-tree C removals because total C removal was not evaluated in the paper; the values presented thus underestimate C loss due to treatment.

[5] Values include post-fire C dynamics through approx. 11 years post-fire, the time point at which fire had the greatest negative effect on C stock.

Appendix 2. Prospects for future evaluation of the C implications of fuels treatments

Although future modeling of one-time treatment projects may help to identify any unique situations in which treatments may yield net C storage, it appears the greatest potential for future C accounting work lies in modeling the C implications of repeated treatment programs implemented on a landscape (i.e., programs that allocate treatments as needed to specific sites across a landscape in order to maximize treatment effectiveness across the landscape). The modest one-time net C storage potentially achievable though such programs may be small relative to the need to maintain the treatment program in perpetuity (Loudermilk et al. 2014), but additional modeling can help to determine the range of situations (if any) in which treatments may achieve meaningful net C storage in the long term.

The most powerful approach for modeling treatment effects is likely to apply a spatially-explicit landscape ecosystem model. For example, Loudermilk et al. (2014) use the LANDIS-II model (Scheller et al. 2007) with the Dynamic Fire and Fuels and Century Succession extensions. This model keeps track of forest conditions (including C pools); models the effects of both wildfire and fuels treatments on forest conditions; and simulates continuous growth, mortality, and decomposition based on those conditions. Such models account for post-wildfire C dynamics (due to decomposition and growth) and incorporate the effects of fuels treatments on fire behavior in untreated areas. Especially when conducting long-term (≥ 100 years) simulations, it is very important to use a model that dynamically incorporates feedback among forest conditions, growth, decomposition, and wildfire. Numerous C modeling studies to date have employed methods that do not account for such feedbacks (e.g., they assume that each wildfire results in similar C emissions regardless of the fire rotation period, that fuels treatments last indefinitely, or that primary production does not change following wildfire or treatment; Section 5). The Forest Vegetation Simulator (FVS), combined with spatially-explicit fuel and fire behavior platforms such as FlamMap, Farsite, and ArcFuels, may represent an alternative modeling platform, but it may be a poor choice because it does not include a component for simulating seedling recruitment based on current stand conditions in the Sierra Nevada; recruitment must be hard-coded by the analyst and any dynamic response of recruitment to stand conditions must be specified on a project-by-project basis. Due to the high sensitivity of forest C dynamics to seedling recruitment rates (Carlson et al. 2012), it is important to use a model that realistically accounts for recruitment effects on C dynamics.

The model landscape should be parameterized based on stand data representative of the landscape of interest. Because of inevitable uncertainty regarding actual conditions, a strong modeling approach will include numerous "alternative" landscapes that are likely to encompass the true conditions. If analysts wish to simulate dynamics representative of a broader region (e.g., the Sierra Nevada), they could simulate many alternative landscapes that encompass the variation throughout the region. Such modeling work could also help to determine whether treatment programs can result in a net increase in C storage when the initial C releases due to *initiation* of the program are included or whether C storage only results from *continuation* of existing treatment programs (see Section 5.2.2). To do so, the analyst could compare the results of simulations beginning with (a) a highly overstocked forest landscape and (b) a landscape with lower stocking levels that reflect conditions given an existing treatment program.

In order to draw robust conclusions suitable for informing forest management, it is very important to validate the accuracy of the model's predictions by comparing them against empirical datasets. Loudermilk et al. (2013) evaluated the accuracy of LANDIS-II in simulating growth of yellow pine stands, but it will be important to evaluate its predictions in mixed-conifer stands as well as its representation of wildfire effects and how those effects are influenced by stand conditions. Further, the analysis should include an assessment of the sensitivity of the results to the model assumptions. Parameters over which sensitivity should be assessed include the fire rotation period, fire ignition locations, the proportion of the landscape that is treated each year, the approach for assigning treatments to particular stands, the climate during the simulation period, and important mechanistic relationships within the model itself, including parameters that determine how wildfire interacts with stands. A sensitivity analysis will help to (a) determine whether any uncertainties may introduce a substantial bias in the conclusions, (b) characterize the range of conditions and scenarios under which fuels treatments may result in a net storage of C, and (c) identify the management prescription that maximizes net C storage.

Appendix 3. Methodology for quantitative comparison of C balance studies

Eight of the C balance studies included in this review present data that allow calculation of the proportion of forest carbon that remains following treatment, following wildfire, and following treatment plus wildfire. I extracted these values from the published papers and included additional scenarios (e.g., to explore the impact of assuming that all fire-killed trees released all of their stored C) when the published data allowed; these values are presented in Table A1.2. I used these values to calculate the minimum probability of treatment-wildfire interaction that would be required for treatment to yield expected net C storage. Below I present the calculations I performed to calculate this "break-even" probability. The calculations use the following symbols:

C_{NTNF}: Amount of C prior to treatment and wildfire

C_{F} : Amount of C remaining following wildfire

C_{T} : Amount of C remaining following treatment

C_{TF} : Amount of C remaining following treatment and then wildfire

P_{F} : Probability of treatment interacting with wildfire during the treatment's effective lifetime

C_{ET} : Amount of C expected to remain following treatment given a specified treatment-wildfire interaction probability

C_{ENT} : Amount of C expected to remain given no treatment and given a specified treatment-wildfire interaction probability

First, I defined C_{ENT} based on the expected probability of wildfire. It represents a weighted average of the C in the untreated, burned scenario and the C in the untreated, unburned scenario, weighted based on the probability of wildfire:

$$C_{ENT} = P_F * C_F + (1 - P_F) * C_{NTNF}$$

Next, I defined C_{ET} based on the expected probability of wildfire. It represents a weighted average of the C in the treated, burned scenario and the C in the treated, unburned scenario, weighted based on the probability of wildfire:

$$C_{ET} = P_F * C_{TF} + (1 - P_F) * C_T$$

Next, because I sought to identify the probability of wildfire at which the expected C storage given treatment equals the expected C storage given no treatment, I set C_{ENT} and C_{ET} equal and solved for P_F:

$$C_{ENT} = C_{ET}$$

$$P_F * C_F + (1 – P_F) * C_{NTNF} = P_F * C_{TF} + (1 – P_F) * C_T$$

$$P_F = (C_{NFNT} – C_T) / (C_{FT} + C_{NFNT} – C_T – C_F)$$

I used this last equation to calculate the probability of treatment-wildfire interaction at which treatment stores as much C as no treatment (Table A1.2). Any probability greater than this "break-even" probability would lead treatment to store more C than no treatment, on average.

To evaluate an additional scenario in which 20% of treatment emissions are offset based on the end-use of thinned material, I increased C_T and C_{TF} as follows:

$$C_T' = C_T + 0.2 * (C_{NFNT} - C_T)$$

$$C_{TF}' : C_{TF} + 0.2 * (C_{NFNT} - C_T)$$

where C_T' and C_{TF}' represent the C stored by the treatment and treatment-wildfire scenarios, respectively, assuming 20% of treatment removals are stored rather than released, and where (C_{NFNT} - C_T) represents the amount of C removed due to treatment. I then used the new values for C_T and C_{TF} in the equation for P_F above.