CONSULTANT REPORT

Landscape fuel treatment effects on wildfire hazard, California spotted owl habitat, and forest carbon

Task 5 in the Forest Biomass Utilization Project

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ABSTRACT

Forest managers are challenged with meeting numerous demands that include carbon (C) sequestration and wildlife habitat. We used a probabilistic framework of wildfire occurrence to 1) estimate the potential for fuel treatments to reduce fire risk and hazard across the landscape and within protected California spotted owl (*Strix occidentalis occidentalis*) habitat and 2) evaluate the greenhouse gas consequences of treatments. Silvicultural and burning treatments were simulated on 20% of a central Sierra Nevada landscape in three scenarios that varied in the land area eligible for treatment. Treatment prescriptions varied with topography, vegetation characteristics, and ownership. Additional simulations allowed us to consider the influence of wildfire size on estimated emissions. While treatments outside of owl activity centers reduced the probability of burning and potential fire intensity within owl habitat and across the landscape, directly treating activity centers produced more substantial reductions in fire hazard within activity centers. Treatments also reduced estimated wildfire emissions of C by 23-47 percent. Due to significant emissions associated with treatment activities, the treatment scenarios were associated with the highest greenhouse gas emissions, even when emissions arising from bioenergy production and use were excluded from emissions accounting. Further, for wildfires of moderate size (714-2,133 ha), the C contained in live tree biomass was reduced even when accounting for avoided wildfire emissions resulting from treatments. When large wildfires (8,070-10,757 ha) were simulated, the treatment scenario retained more live-tree-based C than the no treatment scenario. Our approach, which estimated landscape C immediately following wildfire, did not account for long-term C dynamics, such as emissions associated with post-wildfire decay and C sequestration by future forest growth. We also note that the potential benefits of fuels management activities are not limited to avoided C emissions and include reducing the risk of uncharacteristically severe wildfire across the landscape and within protected habitat as well as supporting local natural resource-based economies.

Keywords: Carbon sequestration, wildfire, treatments, California spotted owl

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EXECUTIVE SUMMARY

California forest managers seek to balance a complex set of sometimes-competing objectives including providing wildlife habitat, avoiding catastrophic disturbance, and supporting local economies. In recent years, maintaining and increasing the capacity of forests to store carbon (C) has been added to these considerations due to concern over the effects of rising atmospheric greenhouse gas concentrations on the earth's climate. In California and across the western U.S., meeting all demands is complicated by the increasing area burned and severity of wildfires occurring in concert with climate change.

A high-visibility example of competing objectives in forest management is that of California spotted owl (*Strix occidentalis occidentalis)* conservation. Management of owl habitat is complicated by uncertainty over the consequences of management activities for habitat suitability. By moderating the intensity and size of future wildfires, coordinated landscape-scale treatments offer a potential compromise – treating fuels outside of sensitive habitat may reduce wildfire risk and hazard within it. Fire modeling studies have shown that treating a portion of the landscape can alter fire behavior within and outside of treated areas, and that strategically locating fuel treatments across the landscape has the potential to reduce fire hazard throughout.

We used a probabilistic framework of wildfire risk to evaluate the ability of landscape treatments to alter wildfire risk and hazard across a northern Sierra Nevada landscape and within California spotted owl protected activity centers. We estimated treatment effects on the likelihood of burning and on wildfire intensity by simulating many wildfires in treated and untreated landscapes. Simulated treatments varied at the stand level according to ownership, vegetation type, and topography. Using multiple treatment scenarios, we considered how restrictions on the land area available for treatment influence treatment effectiveness. In addition, we evaluated the greenhouse gas consequences of treatment.

Key Findings:

- Landscape treatments reduced simulated wildfire size and intensity. The treatments greatly reduced the likelihood that sensitive California spotted owl habitat would be burned by wildfire, even when the habitat was not treated. However, directly treating the protected activity centers more effectively reduced wildfire intensity within the habitat as measured by estimated flame lengths.

- Increasing the land area potentially available for treatment (i.e., protected habitat, private ownership) had a moderate effect on estimated wildfire risk and hazard. This is likely due both to similar treatment patterns across scenarios and treatment prescriptions that varied according to stand characteristics. For example, less restrictive treatment scenarios permitted modest treatments within sensitive species habitat. In turn, these treatments would be expected to have a modest influence on wildfire behavior.

- Landscape fuel treatments reduced estimated wildfire emissions of C by 23-47 percent.

- Prescribed fire was a large source of emissions in this study, as all simulated treatments included some form of burning (broadcast or pile). Wildfire size was an important factor in the greenhouse gas consequences of treatment. Only when large wildfires (~10,000 hectares) were simulated did the reduced wildfire emissions conferred by fuel treatments compensate for emissions from prescribed burning. The large fire scenario was based on a 2014 fire that burned more than a quarter of the study area.

- Treatments protected more of the carbon contained in live trees, but again, only for large wildfire simulations. Otherwise, the loss of live-tree carbon from forest thinning, prescribed burning, and wildfire (through emission, removal, or conversion to necromass) in the treatment scenarios exceeded the loss from wildfire in the no treatment scenarios.

- Our approach is a snapshot assessment of the carbon consequences of treatments and a simulated wildfire; a full accounting would include long-term wildfire risk, future sequestration of carbon and post-wildfire emissions, and emissions associated with the maintenance of treated stands.

Conclusions

Due to the significant emissions associated with treatment, mainly from prescribed fire, and the low likelihood that wildfire will encounter a given treatment area, greenhouse gas accounting favored the no treatment scenarios. While treatment favorability improved with simulation of larger wildfires, the no treatment scenario still produced fewer emissions than the corresponding treatment scenario. Given the potential for large wildfire in the region demonstrated by the 2013 Rim Fire and the 2014 King Fire, and the increasing frequency of large wildfires and area burned in California expected from climate modeling studies, we suggest that future studies of fuel treatment-wildfire-C relationships should incorporate the potential for large wildfires at a frequency greater than those observed over the last 20-30 years.

Here, we show that landscape fuel treatments can alter simulated fire hazard across the landscape both within and outside of treated stands, and have the potential to affect the likelihood of burning and fire intensity within protected California spotted owl habitat. Modest simulated treatments within activity centers significantly reduced potential fire intensity relative to both the no treatment landscape and a treatment scenario that did not permit direct treatment of owl habitat, supporting the argument that active management may be desirable to protect habitat in the long term. Treatments also produced woody biomass and timber feedstocks that would offset the economic costs of treatments, benefit the local economy, and could potentially be used in bioenergy production to offset emissions from fossil fuels.

INTRODUCTION

California forest managers seek to balance a complex set of sometimes-competing objectives including providing wildlife habitat, avoiding catastrophic disturbance, and supporting local economies. In recent years, maintaining and increasing the capacity of forests to store carbon (C) has been added to these considerations due to concern over the effects of rising atmospheric greenhouse gas concentrations on the earth's climate. In California and across the western U.S., meeting all demands is complicated by the increasing area burned and severity of wildfires occurring in concert with climate change (McKenzie et al., 2004; Stephens, 2005; Westerling et al., 2006; Miller et al., 2009)

A high-visibility example of competing objectives in forest management is that of California spotted owl (*Strix occidentalis occidentalis)* conservation. The northern (*S. occidentalis caurina*) and Mexican (*S. occidentalis lucida*) spotted owl subspecies have been listed as Threatened under the Endangered Species Act. Management directives for the California subspecies focus on identifying and protecting activity centers (PACs): sites that include 300 acres (121 ha) of the best-quality habitat near nesting/roosting habitat (Verner et al., 1992). Given the multi-storied, dense canopy forest characteristics of nesting and roosting sites, the potential vulnerability of PACs to high-severity fire is a challenge to owl conservation (Collins et al., 2010). While low-moderate severity wildfire within nesting/roosting habitat may not negatively impact owls in the short term (Bond et al., 2002), longer-term effects of high-severity wildfire can include significant habitat loss due to direct and indirect tree mortality (Gaines et al., 1997). However, due to uncertainty concerning the effects of fuels reduction activities, management options for reducing wildfire hazard within PACs are restricted to light prescribed burning, although some thinning is permitted in the wildland-urban interface (USDA Forest Service, 2004).

There is concern that such constraints on management activities limit the effectiveness of landscape-scale treatments intended to reduce the threat of uncharacteristically severe wildfire (Collins et al., 2010). Fire modeling studies have shown that treating a portion of the landscape can alter simulated fire behavior within and outside of treated areas, and that strategically locating fuel treatments across the landscape has the potential to maximize treatment benefits while minimizing area treated (Finney et al., 2007; Schmidt et al., 2008). Restrictions on fuel treatment location and severity limit real-world application of treatment optimization methods. Even so, there may be significant opportunity for active management outside of high-quality owl habitat on fire-prone landscapes (Ager et al., 2007; Prather et al., 2008; Gaines et al., 2010). Given their demonstrated ability to alter wildfire behavior and effects (Martinson and Omi, 2002; Pollet and Omi, 2002; Ritchie et al., 2007; Fulé et al., 2012), fuel treatments that address accumulated fuels and reduce stand density (e.g., prescribed burning, forest thinning, mastication) are commonly applied in dry western forests where wildfires were once frequent. It is less certain how treatments influence C stocks, and how to maximize C storage in frequent-fire systems. Treatments initially release C to the atmosphere through harvest operations, burning, and biomass transport. In the absence of disturbance, untreated forests may sequester the most C (Hurteau and North, 2009; Stephens et al., 2009; Hurteau et al., 2011). However, high-severity wildfires can rapidly convert C sinks to sources, and burned forests may continue to be sources for beyond a decade (Dore et al., 2008; Dore et al., 2012). Treatments can reduce wildfire emissions (Finkral and Evans, 2008; Hurteau and North, 2009; North et al., 2009a;

Hurteau and North, 2010; Reinhardt and Holsinger, 2010; Wiedinmyer and Hurteau, 2010; North and Hurteau, 2011) and may retain more live-tree C post-fire (Hurteau and North, 2009; North and Hurteau, 2011; Stephens et al., 2012). The circumstances under which treatments might lead to a net gain in C have not yet been resolved, however. Some studies have shown that C emissions associated with treatment may overwhelm avoided wildfire emissions (Ager et al., 2010), but these findings are largely driven by the depressed fire probabilities resulting from highly effective fire suppression efforts (Marlon et al., 2012; Stephens et al., 2012). Fire activity is predicted to increase considerably over the next several decades (Westerling et al., 2011), which would likely change the balance of C emissions in treatments vs. wildfire. The C effects of treatments also depend on the fate of removed materials (Finkral and Evans, 2008).

Recently, as a result of concern over the C costs of fossil fuel use and the threat of wildfire, interest in harvesting historically low-value woody biomass has increased (Evans and Finkral, 2009). Utilizing forest biomass for energy production can help to reduce the cost of fuel treatments, support local economies, offset fossil fuel use, and reduce the C and smoke emissions associated with fuel treatments (Reinhardt et al., 2008). Concerns remain over the sustainability of biomass removals, funding, and the availability of markets (Evans and Finkral, 2009).

The focus of our research was to 1) evaluate whether withholding some land area from treatment influences potential wildfire hazard across the landscape and within California spotted owl habitat, 2) estimate the C balance of treatments, and 3) quantify the biomass harvested in treatments. We simulated fuels reduction treatments and wildfire in a northern Sierra Nevada study area that encompassed 61 spotted owl protected activity centers. In order to evaluate the C balance of the treatment scenarios, we quantified the C contained in the forest biomass harvested in each treatment scenario and that emitted during prescribed fire treatments and wildfires, as well as the C remaining within onsite pools. We confined our analysis to the immediate changes in C stocks and emissions, but recognize that a full accounting of treatment effects would also include long-term C dynamics (e.g., Dore et al., 2008).

METHODS

Study area

The study area was defined by a long-term demographic study site for the California spotted owl (*Strix occidentalis occidentalis*). The 55,398-ha area contains 61 owl Protected Activity Centers (PACs). The study area is located ca. 20 km west of Lake Tahoe in the central Sierra Nevada, with elevation ranging from 300 to 2400 m. The climate is Mediterranean, with warm, dry summers and cool, wet winters. Vegetation at lower elevations in the study area is montane mixed conifer. The forest type is dominated by ponderosa pine (*P. ponderosa* Dougl.), Douglas-fir (*Pseudotsuga menziesii* var. *menziesii* (Mirb.), sugar pine (*Pinus lambertiana* Dougl.), incense-cedar (*Calocedrus decurrens* [Torr.] Florin.), white fir (*Abies concolor* (Gord. and Glend.)), Franco), and California black oak (*Quercus kelloggii* Newb.). California red fir (*Abies magnifica* var. *magnifica* Andr. Murray) dominates above ~2,000 m (Barbour and Minnich, 2000).

One-third of the study area is privately held in a generally checkerboard pattern of ownership (Fig. 1). The remaining 37,120 hectares are managed by the Tahoe and Eldorado National Forests. Young forests dominate private land in the study area due to a history of logging, while mature forests are relatively abundant on public land (Laymon, 1988; Bias and Gutiérrez, 1992).

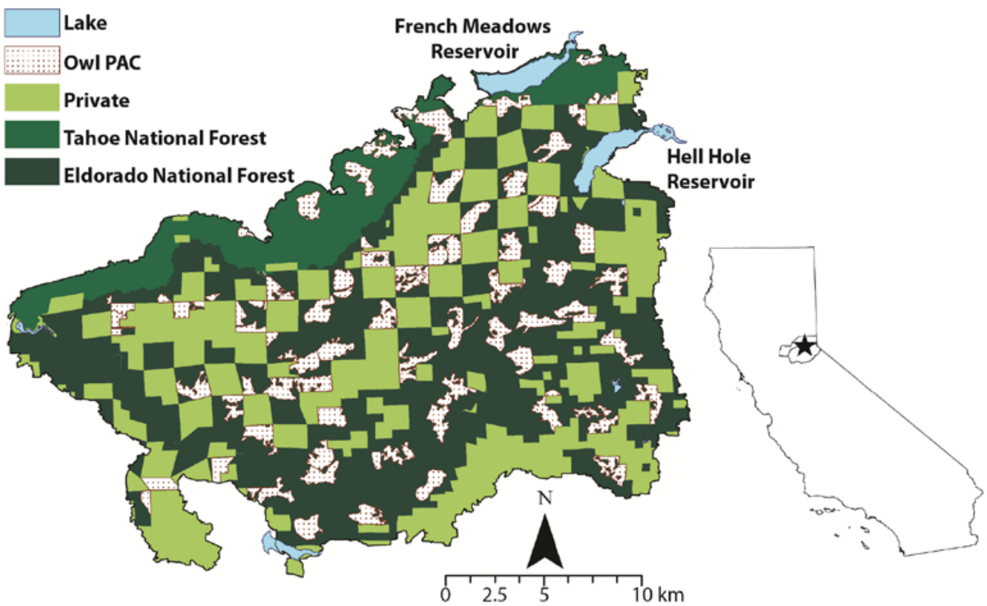

Figure 1. Study area in Tahoe and Eldorado counties, central Sierra Nevada, California. Land ownership and owl protected activity center (PAC) locations.

Vegetation and Fuels Data

The vegetation classification map developed in Chatfield (2005) forms the basis of our study area. Using aerial photographs combined with field accuracy assessment, Chatfield (2005) digitized eight land cover classes consistent with the California Wildlife Habitat Relationships (CWHR) (Mayer and Laudenslayer, 1988) system. A description of the cover classes is provided in Table 1. From the resulting cover class map, we delineated polygons to represent stands of similar vegetation composition and structure (n=4470) based on aerial photographs and topography (Fig. 2).

Table 1: Description of Chatfield (2005) cover classes.

Cover Class	Description
1	Hardwood forest (> 10% hardwood canopy closure and <10% conifer canopy closure).
2	Clearcut or shrub/small tree (<6 in [15.3 cm] dbh)
3	Pole (6-10.9 in [15.3-28 cm] dbh) forest
4	Medium (11-23.9 in [28-61 cm] dbh) conifer/mixed-conifer forest with low to medium canopy closure (30-69%).
5	Medium (11-23.9 in [28-61 cm] dbh) conifer/mixed-conifer forest with high canopy closure (≥70%).
6	Mature (≥24 in [61 cm] dbh) conifer/mixed-conifer forest with low to medium canopy closure (30-69%)
7	Mature (≥24 in [61 cm] dbh) conifer/mixed-conifer forest with high canopy closure (≥70%)
8	Water

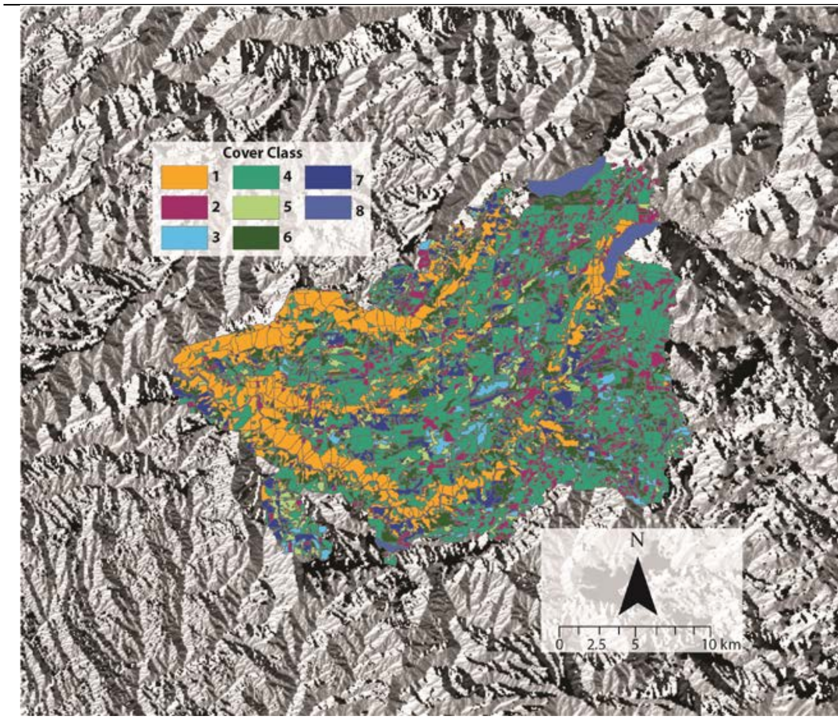

Figure 2. Land cover classes (Chatfield, 2005) within the core study area, stand polygons, and 10-km-minimum bounding rectangle for fire spread modeling. See Table 1 for description of classes.

Stands were populated with vegetation data collected in 2007 in 382 sampling plots located within 10 km of the study area's northern boundary (see Collins et al. (2011) for a detailed description of data collection). Chatfield cover classes were assigned to each sampling plot based on species composition, canopy cover, and tree diameter distribution. Stands were then populated with data from plots of the same cover class. We used a Most Similar Neighbor procedure (Crookston et al., 2002) to select five nearest neighbor plots for each stand using the Random Forest method with the R package yaimpute (version 1.0-22) (Crookston and Finley, 2008). Variables used in identifying nearest neighbors were topographic relative moisture index, eastness, northness, slope, and elevation. In order to increase variability in stand conditions, three of the five plots initially selected to represent each stand were chosen randomly to contribute data to the stand. Each plot contributed data to an average of 35.5 stands (range: 1-437).

The methodology in which surface fuels are represented for fire modeling has important implications for findings related to expected fire behavior and effects. Fuel models are representations of fuelbed properties such as the distribution of fuel between particle size classes, heat content, and dead fuel moisture of extinction for use in the Rothermel (1972) surface fire spread model. As representations, fuel models artificially constrain the variation in surface fuel conditions. In order to represent a range of pre-treatment fuel conditions for fire modeling, we overrode FVS-FFE fuel model assignments and selected two fuel models for each stand. Fuel models representing the low end of the range were assigned following the selection logic of Collins et al. (2011); high-end models were selected to amplify surface fire behavior relative to the low-end models (Table 2) (Collins et al., 2013).

Table 2. Fuel models (Scott and Burgan, 2005) assigned to untreated stands for fire modeling. Two models were applied to each stand to represent a range of fuelbed conditions. The stand structure thresholds were defined and low-range fuel models selected as in Collins et al. (2011).

Stand Structure	Fuel Model	
	---Low---	---High---
Basal area <31.5 m^2/ha, canopy cover <50%	SH3 (143)	SH4 (144)
Basal area <31.5 m^2/ha, canopy cover ≥50%	TU2 (162)	TU3 (163)
Basal area ≥31.5 m^2/ha, tree density ≥1111.5 trees ha^{-1}	TU5 (165)	SH6 (146)
Basal area ≥31.5 m^2/ha, tree density <1111.5 trees ha^{-1}, dominant tree height <41.8 m	TL9(189)	SB2 (202)
Basal area ≥31.5 m^2/ha, tree density <1111.5 trees ha^{-1}, dominant tree height ≥41.8 m	SB2(202)	SB3 (203)

Study area data were processed in the western Sierra variant of FVS to obtain the data layers required for fire behavior modeling. In addition, Landfire vegetation, surface fuel, and topographic data layers (www.landfire.gov) were obtained for an area adjacent to the study area boundary defined by a 10-km minimum bounding rectangle (Figure 2). We merged study area and Landfire data layers to build 90 x 90 m resolution landscape files for fire behavior modeling in Randig, described below. This allowed wildfires originating outside of the study area to be included in our analysis.

Wildfire, Fuel Treatments, and Carbon Loss Modeling

We used ArcFuels (Ager et al., 2006) to streamline fuel treatment planning and analysis of effects. ArcFuels is a library of ArcGIS macros that facilitates communication among the array of models and other programs commonly used in fuel treatment planning at the landscape scale (vegetation growth and yield simulators, fire behavior models, ArcGIS, and desktop software). Our process involved:

1) Fire behavior modeling (Randig, Finney, 2006) to identify stands with high fire hazard
2) Prioritizing stands for treatment using the Landscape Treatment Designer (Ager et al., 2012).
3) Modeling fuel treatments in FVS and the Fire and Fuels Extension (FFE) to FVS (FVS-FFE, Dixon, 2002; Reinhardt and Crookston, 2003)
4) Fire behavior modeling for the post-treatment and untreated landscapes
5) Developing C loss functions from simulated burning with FVS-FFE

Wildfire simulations

Wildfire growth simulations were performed in Randig, a command-line version of FlamMap (Finney, 2006). Randig uses the minimum travel time algorithm (Finney, 2002) to simulate fire growth during discrete burn periods under constant weather conditions. Simulations were conducted at 90-m resolution for computational efficiency. We simulated 80,000 randomly located ignitions with a 5-hr burn period for all scenarios, including no treatment. The burn period was selected to produce fire sizes that approximated area burned in spread events of historic large wildfires near the study area. With the exception of a recent extreme wildfire, the 2014 King Fire, large daily spread events in previous wildfires in the northern Sierra Nevada have burned >2,000 ha (Dailey et al., 2008; Safford, 2008); average fire sizes from our simulations ranged from 715-2,133 ha. (The exceptional growth observed in the King Fire is addressed in a subsequent subsection.) The combination of ignition number and burn period was sufficient to ensure that 99% of pixels in burnable fuel types experienced fire at least once (average: 64-1891).

Randig outputs were used both in prioritizing stands for treatment and in evaluating the effects of treatment. We performed Randig runs for each fuel model range (low and high) within each scenario (no treatment, S1, S2, and S3) using landscape files representing the year immediately following treatment, 2009. Simulations were also completed for the 2007 pre-treatment landscape for use in treatment prioritization, for a total of 10 modeling runs.

To evaluate the effect of treatments on fire risk and fire hazard, we assessed changes in burn probability and conditional flame length between the treatment scenarios and the untreated landscape. It is important to note that the burn probabilities estimated in this study are not empirical estimates of the likelihood of wildfire occurrence (e.g., Preisler et al., 2004; Brillinger et al., 2006; Parisien et al., 2012). Rather, burn probability is defined here as the likelihood that a pixel will burn given a single ignition in the study area and assuming the simulation conditions described. From the simulation of many fires, Randig calculates a pixel-level distribution of flame lengths in 20 0.5-m classes between 0.5 and 10 meters. Conditional flame length (CFL), the probability-weighted flame length given that a fire occurs (Ager et al., 2010), was calculated by combining burn probability estimates with flame length distributions summarized at the stand level:

$$\text{CFL} = \sum_{i=1}^{20} \left(\frac{\text{BP}_i}{\text{BP}}\right) F_i$$

where BP is burn probability, BPi is the probability of burning at the ith flame length class and Fi is the midpoint flame length of the ith flame length class.

To estimate the effect of treatment on fire risk and hazard, we first computed average pixel-level BP and CFL for treated and untreated stands in each scenario. Then, we calculated average BP and CFL for the same stands within the no treatment landscape. The effect of each treatment scenario was estimated as the proportional change in each fire metric between the untreated and treated landscapes.

We obtained weather and fuel moisture inputs for wildfire modeling from the Bald Mountain and Hell Hole weather stations, based on recommendations from local USDA Forest Service fire and fuel managers. We used 95th percentile weather conditions from the June 1-September 30 period (1989-2013). This period represents the typical fire season for the study area, encompassing 85% of wildfires and 93% of the area burned within a 100-mi. (161-km) radius of the study area between 1984 and 2012 (Monitoring Trends in Burn Severity database, Eidenshink et al., 2007).

Weather and fuel moisture inputs for wildfire simulations are provided in Table 3. These conditions are similar to those occurring during recent large wildfires in and near the study area (e.g., 2008 American River Complex, 2001 Star Fire, 2013 American Fire). In addition to using Randig to model fire spread and intensity, we used FVS-FFE to project effects of prescribed and wildfires with FVS-FFE (described below). Wind inputs varied somewhat between fire models: FVS-FFE requires only a single wind speed, while multiple wind scenarios were applied in Randig fire simulations. Wind speeds, azimuths, and relative proportions for Randig simulations followed Collins et al. (2011).

Table 3. Weather conditions for prescribed and wildfires simulated with FVS-FFE. Wildfire temperature and fuel moistures are 95th percentile conditions for the typical fire season in the study area (June 1-September 30). Wildfire modeling in Randig utilized the fuel moistures and temperature specified here but incorporated multiple wind speeds (see Collins et al., 2011). Prescribed fire conditions are based on recommendations from local fire management specialists.

Weather parameter	Prescribed fire	Wildfire
Temperature (°C)	21	33
Wind speed (km h^{-1} (mi h^{-1}))	13 (8.1)	29 (18, FVS)
		27-31(16.8-19.3, Randig)
Fuel moisture (%)		

1 h	10	2
10 h	11	3
100 h	12	4
1000 h	15	6
Duff	75	20
Live woody	90	70
Live herbaceous	120	30

Spatial Optimization of Fuel Treatments

Stands were selected for treatment based on modeled pre-treatment wildfire hazard and stand structure using the LTD (Ager et al., 2012), which allows multiple objectives to be combined in the spatial prioritization of fuel treatments. Three treatment scenarios varied in the land designations eligible for treatment:

Scenario 1: Public land, excluding spotted owl habitat
Scenario 2: Public land, including spotted owl habitat
Scenario 3: All lands: public and private ownerships

Objectives were consistent across treatment scenarios but differed in the land area available for treatment. For all LTD runs, we directed the model to maximize a total score that comprised numeric stand structure and fire hazard rankings (Table 4). The stand structure ranking (0, 1, 2) was based on cover class category: cover classes most conducive to thinning were ranked highest. Fire hazard ranking (0, 2, 3) was assigned according to stand-level CFL as calculated from flame length probability files generated in Randig simulations for the 2007 pre-treatment landscape.

To isolate the effect of varying land designations in the area available for treatment, total area treated was held constant between scenarios (20% of the core study area). In order to exclude small, spatially isolated treatment areas that would be impractical from a management standpoint, we required a minimum treatment area of 12.1 ha (30 ac). To achieve this, the treatment prioritization process was iterative. In each step, we eliminated all stands selected by LTD for treatment that were not contiguous with a ≥12.1-ha treatment area. We then calculated the treatment area remaining. This process was repeated until total treatment area summed to the target area (~11080 ha).

Table 4. Fire hazard and cover class priority ratings used in treatment prioritization with LTD. Conditional flame length (CFL) is the probability weighted flame length given a fire occurs and assuming the burning conditions described in the text. CFL was calculated for each stand as the average of low and high fuel model range estimates from Randig runs. Cover class descriptions are provided in Table 1.

Category	Priority Rating
Conditional Flame Length (m)	Hazard Rating
0 – <3.5	0
3.5 – <5.1	2
≥5.1	3
Cover Class	Structure Class Rating
1	1
2	0
3	0
4	2
5	2
6	1
7	1

We simulated fuel treatments using FVS-FFE. Stands selected for treatment were assigned one of 13 treatment prescriptions depending on topography, vegetation cover class, ownership, and overlap with owl PACs (Table 5). In an effort to promote landscape-scale heterogeneity, basal area targets for commercial thinning on public land varied with topography (aspect and slope position: canyon/drainage bottom, mid-slope, and ridge)(North et al., 2009b; North, 2012). All thinning treatments were simulated as thin-from-below harvests. We assumed that trees ≥10 in. (25.4 cm) dbh would be harvested for wood products (FVS VOLUME keyword) and that the biomass contained in smaller trees and in the tops and branches of larger trees would be utilized as feedstocks for bioenergy conversion. Therefore, all thinning (except hand-thinning) treatments were simulated as whole tree harvests (FVS keyword YARDLOSS). Treatments preferentially retained fire-resistant species, with relative retention preference as follows: black oak>ponderosa pine>sugar pine>Douglas-fir>incense-cedar>red fire>white fir.

Prescribed fires were simulated in the year following thinning (2009). Broadcast burning was applied except within owl PACs, on private land, and on steep slopes (>35%), where follow-up burning was limited to pile burning. To capture a more realistic range of post-treatment surface fuel conditions stands selected for treatment were randomly assigned to one of three post-treatment fuel models for each fuel model range: TL1 (181), TL3 (183), or TL5 (185) (low range); TL3 (183), TL5 (185), or SB1 (201) (high range)(Scott and Burgan, 2005). Weather conditions for prescribed fire modeling were based on recommendations from a local fire management specialist (Brian Ebert, Personal Communication, August 2014).

Table 5. Treatment prescriptions applied to stands selected for treatment in each scenario. Retention targets for large and understory trees, thinning method, upper diameter limits for commercial harvests, and prescribed fire type varied between prescriptions. Stand descriptions are ownership (public or private) and overlap with owl PACs (PAC) or non-PAC (NP). Cover classes are Chatfield (2005) classes; see Table 1 for cover class descriptions. Understory thinning methods are whole-tree harvest (WT) or handthin (HT). All thinning treatments are thin from below. "--" indicates no treatment in that stand/thin combination.

Stand description	Cover class	Slope (%)	Topographic position	Understory thin (<10 in dbh)		Commercial thin (>10 in dbh)		Burn type
				Method	Density target: trees acre^{-1} (trees ha^{-1})	Upper dbh limit: in (cm)	Basal area target: ft^2 acre^{-1} (m^2 ha^{-1})	
Public, NP	1,4-7	≤35	N- and E-facing slopes, canyons, drainage bottoms	WT	20 (49)	30 (76.2)	160 (36.7)	broadcast
Public, NP	1,4-7	≤35	S- and W-facing slopes, ridges	WT	20 (49)	30 (76.2)	100 (23.0)	broadcast
Public, NP	1,4-7	>35-50	All	HT	20 (49)	--	--	pile burn
Public, NP	2	≤35	All	--	--	--	--	broadcast
Public, NP	2	>35-50	All	--	--	--	--	pile burn
Public, NP	3	≤35	All	WT	120 (297)	--	--	broadcast
Public, NP	3	>35-50	All	HT	120 (297)	--	--	pile burn
Public, PAC	1,4-7	≤50	All	HT	20 (49)	--	--	pile burn
Public, PAC	2	≤50	All	--	--	--	--	pile burn
Public, PAC	3	≤50	All	HT	120 (297)	--	--	pile burn
Private	1,4-7	≤50	All	WT	20 (49)	none	100 (23.0)	pile burn
Private	2	≤50	All	--	--	--	--	pile burn
Private	3	≤50	All	WT	120 (297)	--	--	pile burn

Biomass and Carbon Effects of Treatment

We tracked the C emitted from burning, removed during harvesting, and contained in live and dead biomass with FVS-FFE carbon reports (Reinhardt and Crookston, 2003; Hoover and Rebain, 2008). FVS converts biomass to units of C using a multiplier of 0.5 for all live and dead C pools (Penman et al., 2003) except duff and litter pools, for which a multiplier of 0.37 is applied (Smith and Heath, 2002). Stand C is partitioned into a number of pools including aboveground live tree, standing dead tree, herb and shrub, litter and duff, woody surface fuel, and belowground live and dead tree root C. FVS-FFE also reports the C emitted during burning and tracks the fate of C contained in harvested biomass including that stored in wood products, utilized in energy production, and emitted (Rebain et al., 2009). Treatment effects were assessed by comparing expected biomass C and emissions between the treated and untreated landscapes.

We developed C loss functions for each FVS treelist by simulating burning with FVS-FFE at a range of flame lengths (SIMFIRE and FLAMEADJ keywords) (Ager et al., 2010; Cathcart et al., 2010). The flame length values supplied to FLAMEADJ were the 20 midpoints of the 0.5 m flame length classes (0.5-10 m) found in Randig flame length probability output files. As noted by Ager et al. (2010) and Cathcart et al. (2010), it is not currently possible to precisely match fire behaviors between Randig and FVS. The flame lengths reported in Randig outputs are the total of surface fire and, if initiated, crown fire. In contrast, the flame lengths supplied to FVS-FFE via the FLAMEADJ keyword are treated as surface fire flame lengths, and when FLAMEADJ is parameterized with only a predefined flame length, the model does not use the input flame length in crown fire simulations. To estimate fire effects in FVS-FFE, we parameterized FLAMEADJ with percent crowning (PC) and scorch height in addition to flame length (FL). Scorch height and critical flame length for crown fire initiation (FLCRIT) were based on Van Wagner (1977). We estimated PC using a downward concave function where PC = 32% when flame length = FLCRIT and PC = 100% when flame length is ≥30% of stand top height (the average height of the 40 largest trees by diameter)(A.A. Ager, personal communication).

The derived C loss functions were combined with the probabilistic estimates of surface fire behavior produced in Randig simulations to estimate the "expected C" contained in biomass. We estimated expected C in each pixel in the postfire landscape as follows:

$$\mathrm{E[C]}_j = \sum_{i=0}^{20} \left[\mathrm{BP}_{ij} \cdot \mathrm{C}_{ij}\right]$$

Where $\mathrm{E[C]}_j$ is the expected biomass C in pixel *j* in mass per unit area,
BP_{ij} is the probability of burning at the *i*th flame length class for pixel *j*,
C_{ij} is the C remaining in pixel *j* post-wildfire, given burning at the *i*th flame length class

We similarly applied C loss functions and probabilistic estimates of wildfire behavior to estimate wildfire emissions of C. However, because our simulated wildfires burned both the core and buffer regions of our study area while emissions were estimated only for the core region, the use of expected emissions would not have permitted a full accounting of the emissions arising from a wildfire (being limited to those produced within the core study area).

Instead, we used conditional expected wildfire emissions to approximate the emissions from a wildfire burning entirely within the core study area. Conditional expected emissions are those produced for an area given that the area is burned. Conditional emissions were estimated for each pixel as follows:

$$\mathrm{C[WC]}_j = \sum_{i=1}^{20} \left[\frac{\mathrm{BP}_{ij}}{\mathrm{BP}_j} \cdot \mathrm{WC}_{ij} \right]$$

Where $\mathrm{C[WC]}_j$ is the C emitted by wildfire from pixel *j* in mass per unit area,
BP*j* is the probability that pixel *j* is burned,
BP*ij* is the probability of burning at the *i*th flame length class, and
WC*ij* is the C emitted from pixel *j* when burned at the *i*th flame length class

To obtain average wildfire emissions for each scenario, average pixel-level wildfire emissions were multiplied by average wildfire area burned.

Large Fire Revision

During the course of the study, a very large fire encountered our study area. The King Fire began on 13 September 2014 in El Dorado County and burned 39,544.67 hectares -- more than an order of magnitude greater than our modeled wildfires -- including >25% of the study area. Given the potential for very large wildfires in this region as demonstrated by the King Fire, we completed additional wildfire modeling to estimate the C effects of treatment given the occurrence of a very large fire. Randig modeling was repeated for the no treatment and S3 scenarios using the high-range fuel models and a revised burn period, number of simulated ignitions, wind speed, and wind directions. Burn period was increased from 5 to 12 hours; number of ignitions was reduced by half to 40,000. Wind directions and relative probabilities (Table 6) were those recorded at Hell Hole RAWS between 0400 and 1900 hours on 17 September, the day of the largest spread event. We used the probable one-minute maximum wind speed as calculated from the maximum gust recorded on that day: 33 km h^{-1} (20.5 mph), based on maximum gust of 54.7 km h^{-1} (34 mph) (Crosby and Chandler, 1966). These settings produced average fire sizes of NT = 10,756.87 ha (no treatment scenario) and 8,070.41 ha (S3). Average fire size was limited by the size of our buffered study area: longer burn periods resulted in an increasing number of simulated wildfires that burned to the study area boundary.

Table 6. Wind directions and relative probabilities for very large wildfire modeling.

Azimuth	Probability
270	.56
180	.19
135	.13

225	.12

Greenhouse Gas Balance of Treatments

To evaluate the short-term greenhouse gas (GHG) balance of fuel treatments, we combined emissions from wildfire and prescribed burning (if applicable) for each scenario with estimated emissions from lumber and biofuel production and biofuel combustion. While a full life cycle assessment of bioenergy production from forest biomass was beyond the scope of this report, we used values published in this document and elsewhere to estimate emissions arising from forest operations, transportation of forest biomass and merchantable material, milling, and biofuel (biodiesel) production, transport, and combustion (Table 7). Such an analysis necessarily relies on numerous assumptions. We attempted to be conservative in estimating the GHG benefits of harvesting and biofuel conversion and combustion. When a range of values was provided, we applied the least favorable with respect to GHG benefits. To roughly bracket the GHG consequences of landscape treatments, we estimated the full GHG costs for each scenario as well as the GHG costs when bioenergy is considered to displace fossil fuels.

Table 7. Summary of conversion factors applied in GHG accounting.

Variable	Assumption	Source and Notes
Forest operations and wood production of planed softwood lumber	112.3 kg CO_2e/m^3	Puettman et al., 2012. Survey of wood product manufacturing in the Pacific Northwest. Incorporates an average 113-km (70-mi) one-way haul distance for merchantable timber.
Emissions for recovery and transport of small-diameter forest biomass and biodiesel transport	13 g CO_2e/MJ biodiesel energy	Task 9, this document. Assumes 121-km (75-mi) one-way heavy truck haul distance for forest biomass material and 2414-km (1500-mi) liquid biodiesel transport by rail.
Conversion of woody biomass to biodiesel	4.22 kg feedstock/ litre biodiesel	O'Connor, 2013. High temperature syngas from wood residues.
Biodiesel energy content	33.9 MJ/litre	Wang and Bluestein, 2002. Lower heating value, 20% probability based on Monte-Carlo simulations, Fischer-Tropsch diesel.
Emissions from biodiesel production via Fischer-Tropsch pathway	130 g CO_2e /MJ	Marano and Ciferno, 2001; Van Vliet et al., 2009.
Emissions from biodiesel combustion	73 g CO_2e/MJ	Task 9, this document.

The quantity of biomass harvested and apportioned between wood product and bioenergy pools was determined from FVS reports. FVS-FFE partitions the C harvested as merchantable biomass into that emitted and that stored in wood products. We assumed that all C harvested in merchantable stems and not stored in wood products would be emitted with energy as a bi-product. For comparison with fossil fuel emissions, C emissions from conversion of biomass to energy and from wildfire and prescribed burning were converted to CO_2-equivalent (CO_2e) GHG emissions by multiplying by the ratio of the atomic mass of a carbon dioxide molecule to the atomic mass of a carbon atom: 44:12 (Environmental Protection Agency, 2005).

RESULTS

Treatment Simulation

Table 8 provides a summary of the area treated in each scenario. Scenario 1 (S1) was the most restrictive with respect to the land area available for treatment, which more than doubled between S1 and S3. Because treatment prescriptions varied with land designation (public, owl PAC, private), and the designations available for treatment varied between scenarios, the relative proportions of thinning and burning methods also varied between scenarios. Commercial and biomass thinning were applied more frequently in S3, which permitted treatment of private land, and in S1. Spotted owl activity centers composed 25% of the area treated in S2 versus 10% in S3 and 0% in S1, in which PACs were not subject to treatment. As a result, the area treated with hand thinning in S2 was more than twice that in S1 and S3. Due to the inclusion of PACs in S2 and both PACs and private land in S3, the proportion of area treated with pile burning increased between S1 and S3 while broadcast burn area exhibited an opposite trend. In general, despite the variation in land designations available for treatment, the locations of treatment sites were quite similar between scenarios (Figs. 3 and 4).

Table 8. Total area and proportion of area treated by category in each treatment scenario.

	------------SC1-----------		-----------SC2-----------		------------SC3-----------	
	Area (ha)	**Proportion of Area Treated**	**Area (ha)**	**Proportion of Area Treated**	**Area (ha)**	**Proportion of Area Treated**
Avail. for treatment*	22042.0	1.99	28997.9	2.62	45647.2	4.12
Treated	11080.7	1.00	11082.1	1.00	11081.4	1.00
Owl habitat treated	0.0	0.00	2769.0	0.25	1126.5	0.10
Private land treated	0.0	0.00	0.0	0.00	5684.5	0.51
Hand thin	1498.7	0.14	3819.4	0.34	1611.5	0.15
Biomass thin	8404.3	0.76	7240.0	0.65	9469.9	0.85

Commercial thin	7764.9	0.70	6916.4	0.62	9469.9	0.85
Broadcast burn	9409.6	0.85	7247.3	0.65	3785.4	0.34
Pile burn	1671.1	0.15	3834.8	0.35	7296.1	0.66

*Total land area potentially available for treatment in each scenario. As restrictions on the area available for treatment were increasingly relaxed from Scenarios 1 to 3, off-base area declined.

Landscape-scale Burn Probability and Fire Hazard

Conditional Burn Probability

The pixel-to-pixel change in conditional burn probability between the untreated scenario and each treatment scenario is mapped in Figs. 3 (low fuel model range, LO FM) and 4 (high range, HI FM). Treatment reduced landscape burn probability by approximately 50% (Table 9), from 0.0124 (NT) to 0.0062 (S1), 0.0059 (S2), and 0.0055 (S3). Within treatment units, average CBP fell by 69-76% to 0.0033-0.0035; outside of treated stands, CBP fell to 0.0060-0.0069. Some increases in CBP were also observed, particularly for the low fuel model range (Fig. 3).

The influence of treatment on owl PAC likelihood of burning was similar to that observed for stands in general. For treated PACs, average CBP fell by ~70% relative to no treatment CBP for the same stands. Although PACs were not eligible for treatment in S1, all treatment scenarios had a large impact on estimated PAC CBP. Average PAC CBP was reduced from 0.013 to 0.0063 in S1, 0.0049 in S2, and 0.0054 in S3, a 49-64% decrease relative to PACs in the no treatment landscape (Table 9).

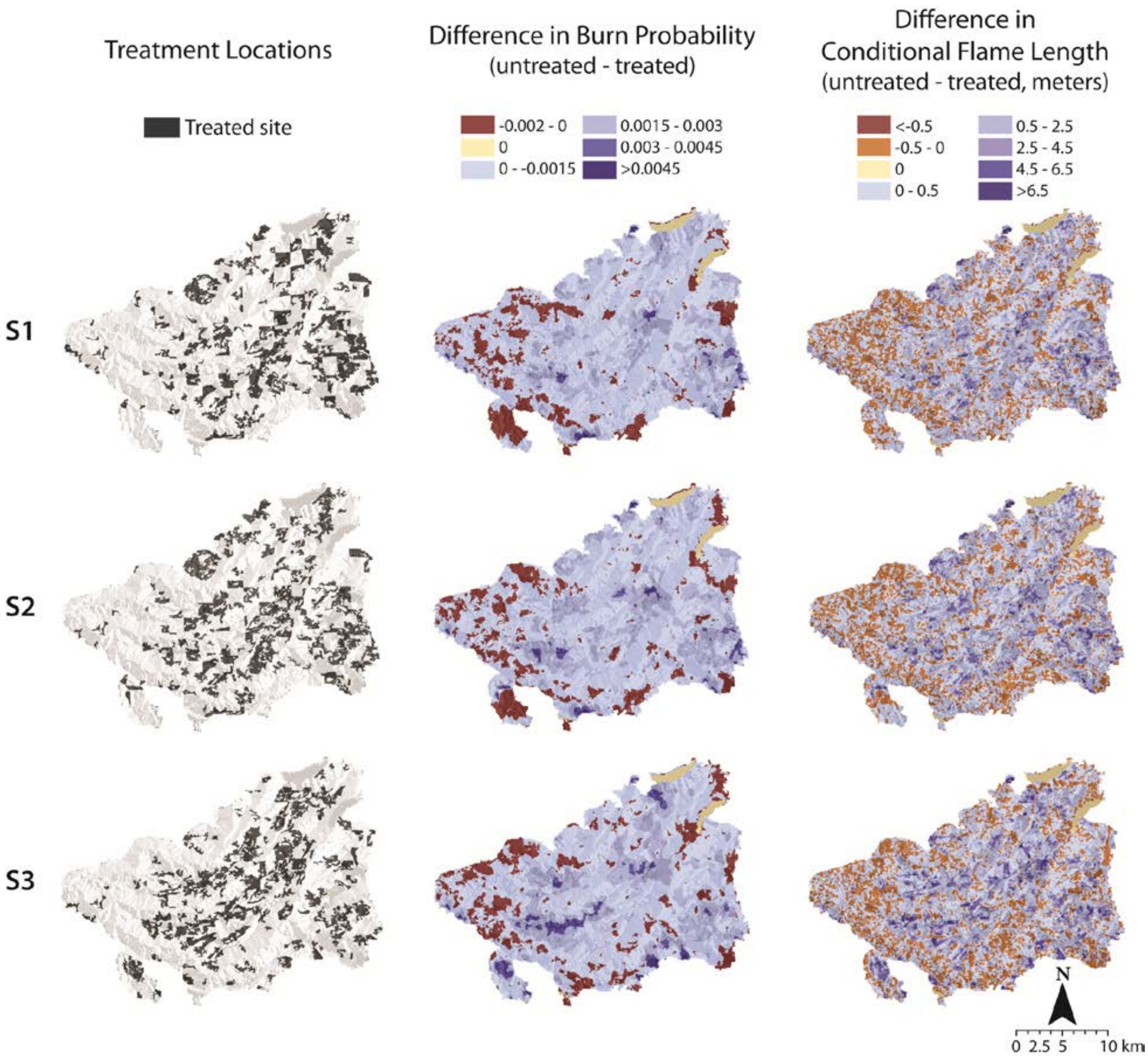

Figure 3. Low fuel model range treatment locations and difference in burn probability and conditional flame length (untreated-treated) for each treatment scenario. Negative values indicate an increase in burn probability or conditional flame length while positive values represent a reduction. Conditional burn probability is the likelihood that a pixel will burn given a single ignition on the landscape and assuming the simulation conditions described in Table 5 and in the text. Conditional flame length is the probability-weighted flame length, given these same assumptions.

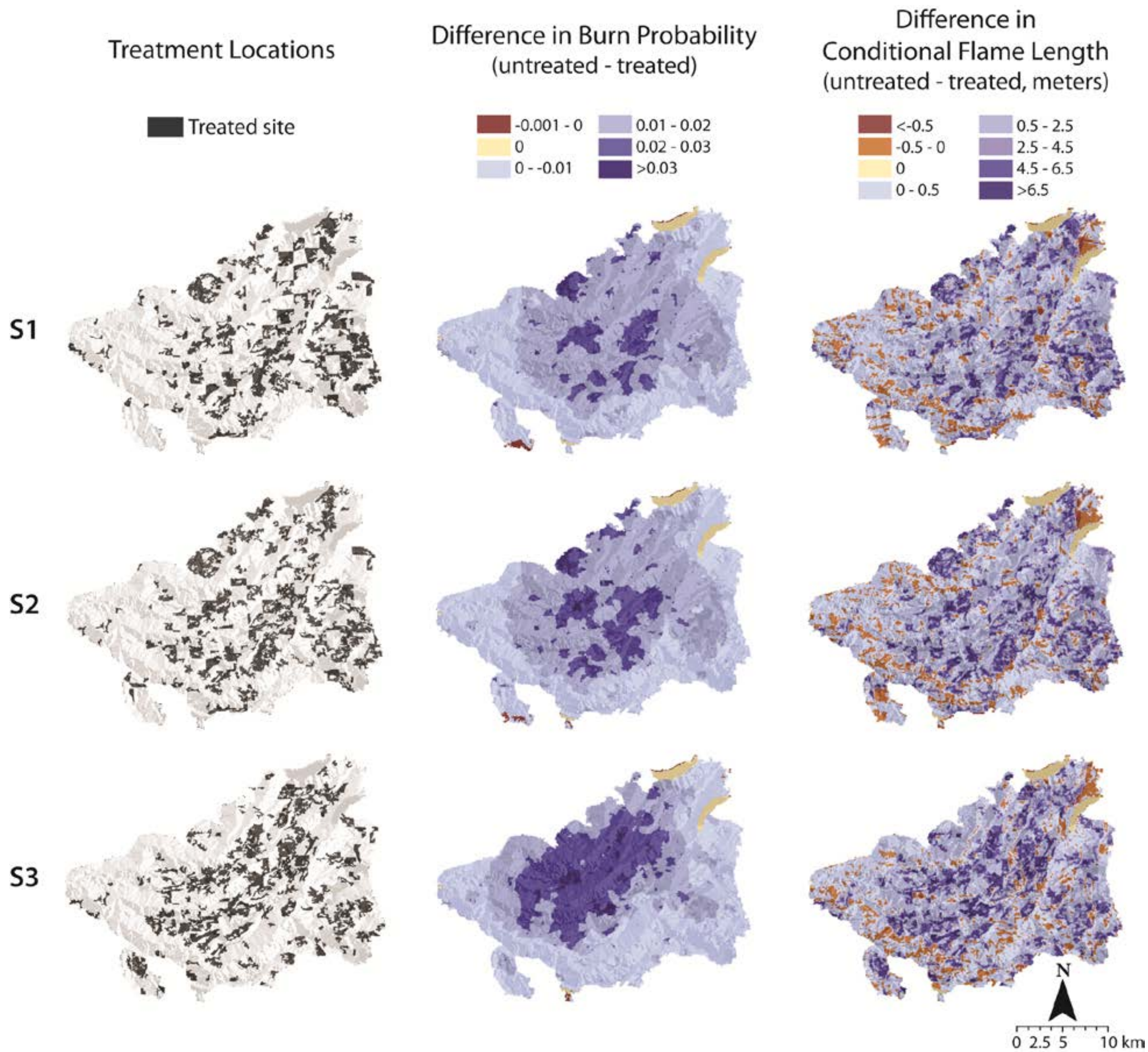

Figure 4. Treatment locations and high fuel model range difference in conditional burn probability and conditional flame length (untreated-treated) for each treatment scenario

Table 9. Proportional change in burn probability for treatment scenarios compared to the no treatment scenario. Proportions are ratios of treatment values to no treatment values as calculated for the same stands. Treatment and no treatment values were calculated as the average pixel value for the low and high fuel model range (LO FM and HI FM) within each stand category and treatment scenario.

	---------LO FM--------			---------HI FM---------			----------AVG---------		
	S1	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
	Proportional change relative to			*Proportional change relative to*			*Proportional change relative to*		

		NT			*NT*			*NT*	
All PACs	-0.45	-0.64	-0.56	-0.53	-0.63	-0.59	-0.49	-0.64	-0.57
Treated PACs	NA	-0.81	-0.76	NA	-0.57	-0.67	NA	-0.69	-0.72
Untreated PACs	-0.45	-0.53	-0.51	-0.53	-0.54	-0.58	-0.49	-0.53	-0.54
All stands	-0.44	-0.48	-0.53	-0.50	-0.53	-0.56	-0.47	-0.50	-0.54
Treated stands	-0.76	-0.79	-0.63	-0.72	-0.74	-0.74	-0.74	-0.76	-0.69
Untreated stands	-0.35	-0.39	-0.49	-0.45	-0.47	-0.51	-0.40	-0.43	-0.50

Table 10. Proportional change in conditional flame length for treatment scenarios compared to the no treatment scenario. Proportions are ratios of treatment values to no treatment values as calculated for the same stands. Treatment and no treatment values were calculated as the average pixel value for the low and high fuel model range (LO FM and HI FM) within each stand category and treatment scenario.

	---------LO FM--------			**---------HI FM---------**			**----------AVG---------**		
	S1	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
	Proportional change relative to NT			*Proportional change relative to NT*			*Proportional change relative to NT*		
All PACs	-0.09	-0.42	-0.28	-0.12	-0.43	-0.27	-0.10	-0.42	-0.28
Treated PACs	NA	-0.71	-0.75	NA	-0.71	-0.73	NA	-0.71	-0.74
Untreated PACs	-0.09	-0.14	-0.11	-0.12	-0.17	-0.14	-0.10	-0.16	-0.13
All stands	-0.22	-0.26	-0.31	-0.25	-0.26	-0.28	-0.24	-0.26	-0.30
Treated stands	-0.65	-0.69	-0.52	-0.71	-0.71	-0.73	-0.68	-0.70	-0.62
Untreated stands	-0.08	-0.09	-0.21	-0.11	-0.12	-0.12	-0.09	-0.10	-0.16

Fire Hazard

Treatments reduced average landscape CFL by ~1 m, from 3.6 m (NT) to 2.5-2.7 m. Pixel-level CFL was reduced by a maximum of 8.0 m (LO FM) and 9.0 m (HI FM). Increases in CFL were also observed, however, particularly near the study area's western and southwestern boundaries where treatments were least concentrated (Figs. 3 and 4). Maximum pixel-level CFL increases were 2.5 m (LO FM) and 3.1 m (HI FM).

Because fire hazard was used in prioritizing stands for treatment, the estimated pre-treatment CFL in stands selected for treatment (4.3-5.1 m) was greater than in stands not selected (3.2-3.3 m). After treatment, average CFL within treated stands fell to 1.3 (S1 and S2) and 1.7 m (S3). CFL in untreated stands was also reduced as a result of the influence of treatments on fire spread and intensity. CFL fell by 0.5-0.8 m (9-16%) relative to CFL in the same stands within the no treatment landscape (Table 10).

Although spotted owl PACs were not treated in S1, relative to PACs in the NT landscape, PAC CFL was reduced 10% (to 3.2 m) in S1. Treating PACs had a much larger impact on potential fire intensity, however. Average treated PAC CFL fell to 1.3 and 1.4 m in S2 and S3, respectively.

Carbon and Greenhouse Gas Consequences of Landscape Fuel Treatments

Prior to treatment, landscape carbon totaled 147.05 tonnes ha^{-1}, on average. Treatments removed 14% of pre-treatment C from treated stands, or 23.74 tonnes ha^{-1}, totaling 81,772-119,103 tonnes of C in biomass and merchantable material (Table 12). Due to the inclusion of privately managed stands in S3, the total C removed in harvested material was 21 and 44% greater than in S1 and S2, respectively. This is equivalent to 27-34% more woody biomass material and 17-18% more merchantable timber harvested in S3 than in S1 and S2 (Table 11).

Table 11. Woody biomass and merchantable timber removed in treatment scenarios.

Harvested Material	S1	S2	S3
Biomass C (tonnes)	73,654	66,993	100,976
Merchantable C (tonnes)	15,119	14,779	18,126
Total harvested C (tonnes)	88,773	81,772	119,103
Biomass (ft^3 (m^3))	177,302 (5,021)	260,986 (7,390)	212,946 (6,030)
Merchantable (board ft (m^3))	649,627 (1,533)	608,624 (1,436)	702,995 (1,659)

Both the treatment scenarios and the choice of fuel models were important influences on estimated C emissions from burning. As the least restrictive treatment scenario in terms of treatment location and the only scenario to include treatment of private land, where broadcast burning was precluded as a treatment option, the S3 treatment scenario was associated with the lowest wildfire and prescribed burning emissions (Table 12). For each treatment scenario, expected wildfire emissions increased by more than an order of magnitude between the low and high fuel model ranges. This difference was the result of increasing fire intensity as well as wildfire size. Average wildfire size nearly doubled between fuel model ranges in the treatment scenarios and tripled in the no treatment scenario. For a given treatment scenario (including no treatment), emissions on a per hectare basis increased by approximately two tonnes between the low and high fuel model ranges. In contrast to the large influence of fuel model choice on wildfire emissions, the effect of fuel model range on prescribed fire emissions was minimal, with only a 1% increase in emissions between the low and high fuel model ranges for a given treatment scenario.

Although treatment significantly reduced wildfire emissions, combined emissions from prescribed burning on 20% of the landscape and wildfire exceeded wildfire emissions in the no treatment scenarios (Table 12). Relative to the no treatment scenarios, treatment reduced estimated wildfire emissions by approximately 23% (low fuel model range), 46% (high fuel model range), and 36% (Large Fire [LF] scenarios). Yet prescribed burning was a far more significant source of emissions than were wildfires of moderate size, with emissions from treatment exceeding wildfire emissions by 94,777-164,552 tonnes. Even for the large wildfire simulations, where landscape treatments reduced estimated wildfire emissions by nearly

100,000 tonnes, the combined carbon emissions from prescribed burning and wildfire in the treatment scenario surpassed emissions from wildfire in the no treatment scenario. However, because emissions from treatment remained constant between the moderate and large wildfire scenarios while wildfire emissions increased more than five-fold, total emissions from burning in the large wildfire simulations were similar between the treatment and no treatment scenarios (Table 12, Fig. 5).

Table 12. Carbon emissions (tonnes) from wildfire and prescribed burning in the no treatment (NT) and treatment scenarios (S1-S3). LF indicates the Large Fire scenarios.

	Low fuel model range				High fuel model range					
	NT	**S1**	**S2**	**S3**	**NT**	**S1**	**S2**	**S3**	**NT-LF**	**S3-LF**
Pile burning	--	15,436	41,185	56,401	--	15,436	41,185	56,401	--	56,401
Broadcast burning	--	163,094	128,508	66,197	--	165,006	130,063	67,137	--	67,137
Total prescribed fire emissions	--	178,530	169,693	122,599	--	180,357	171,247	123,539	--	123,539
Wildfire	18,053	13,978	13,852	13,777	54,102	29,706	29,090	28,761	273,247	174,092
Total Emissions	18,053	192,508	183,545	136,376	54,102	210,063	200,337	152,300	273,247	297,630

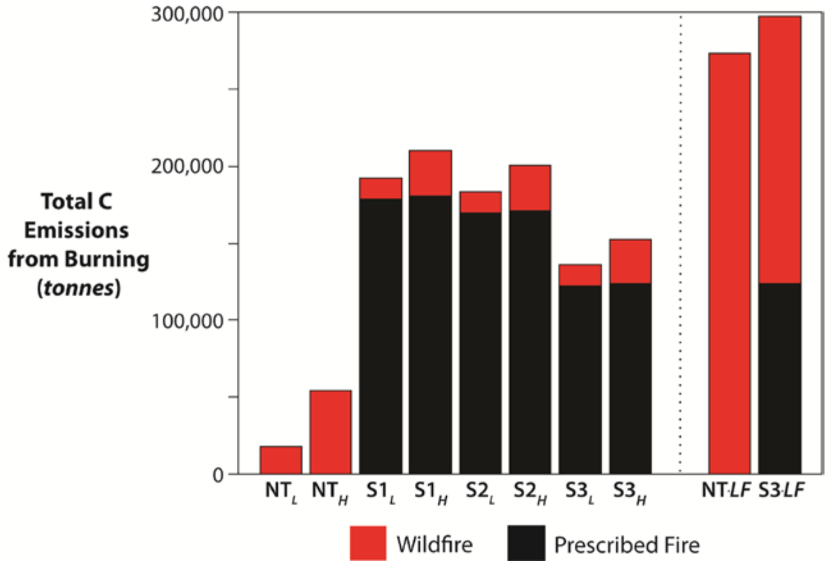

Figure 5. Carbon emissions (tonnes) from wildfire and prescribed burning. X-axis labels indicate no treatment (**NT**) and treatment scenarios (**S1-S3**); subscripts denote fuel model ranges used in fire modeling (L: low, H: high). Large Fire scenarios, which were modeled with the high fuel model range only, are indicated by **LF**.

The total quantity of C expected to remain on the landscape following treatment and a randomly ignited wildfire was greatest for the no treatment scenarios (Tables 13 and 14). For modeled wildfires of moderate size, treatment reduced both the live and dead C pools relative to the no treatment scenarios, and landscape C in the no treatment scenarios was 4-5% greater (323,316-434,960 tonnes) than in any of the treatment scenarios (Tables 13 and 14). In comparison, under large wildfire conditions, the treatment scenario retained slightly more live biomass C: ~15,000 tonnes, or 0.3% more than the no treatment scenario. However, treatment also reduced necromass C by 288,000 tonnes (12%), resulting in a 3% overall decrease in onsite biomass C relative to an untreated landscape (Table 14).

Table 13. Expected landscape C for no treatment (NT) and treatment (S1, S2, S3) scenarios using the low fuel model range in fire modeling. LF indicates the large fire scenarios. Expected C is that remaining in the core study area following treatment, if applicable, and a random ignition and wildfire in the larger buffered study area, as estimated from the simulation of many wildfires. Live C is that contained in live aboveground herb, shrub, and tree biomass and belowground roots of live trees; dead C is the C contained in litter, duff, woody surface fuel, tree snags and belowground roots of dead trees.

Carbon Pool	NT	S1	S2	S3
Untreated Stands	---------------------- *tonnes C*	----------------------		
Live	6,420,212	5,021,797	4,740,389	5,071,638
Dead	2,026,221	1,563,014	1,512,512	1,623,464
Treated Stands				

Live	--	1,131,385	1,376,328	1,061,072
Dead	--	337,984	382,244	284,599
Total Live	6,420,212	6,153,182	6,116,717	6,132,710
Total Dead	2,026,221	1,900,998	1,894,756	1,908,063
Grand Total	8,446,433	8,054,180	8,011,473	8,040,773

Table 14. Expected landscape carbon for no treatment (NT) and treatment (S1, S2, S3) scenarios using the high fuel model range in fire modeling. LF indicates the large fire scenarios. Expected C is that remaining in the core study area following treatment, if applicable, and a random ignition and wildfire in the larger buffered study area, as estimated from the simulation of many wildfires. Live C is that contained in live aboveground herb, shrub, and tree biomass and belowground roots of live trees; dead C is the C contained in litter, duff, woody surface fuel, tree snags and belowground roots of dead trees.

Carbon Pool	NT	S1	S2	S3	NT-LF	S3-LF
Untreated Stands	-------------------------------			*tonnes C* -------------------------------		
Live	6,299,243	4,976,661	4,700,864	5,032,172	5,883,595	4,810,615
Dead	2,120,118	1,600,997	1,546,687	1,656,227	2,429,955	1,821,161
Treated Stands						
Live	--	1,151,242	1,432,235	1,095,853	--	1,087,996
Dead	--	364,409	416,260	306,789	--	320,960
Total Live	6,299,243	6,127,903	6,133,099	6,128,024	5,883,595	5,898,611
Total Dead	2,120,118	1,965,406	1,962,946	1,963,016	2,429,955	2,142,121
Grand Total	8,419,361	8,093,309	8,096,046	8,091,040	8,313,550	8,040,732

The proportional changes in biomass C pools between the treatment and no treatment scenarios are summarized in Table 15. For all treatment scenarios, the consumption of duff, litter, and downed woody fuels with prescribed burning contributed to a net reduction in these C pools relative to the untreated landscape. Conversely, treatments protected more C in the live understory (herb and shrub) pool – the result of both reduced wildfire size and intensity in the treatment scenarios. Treatments in the moderate wildfire scenarios reduced live tree biomass C in comparison to no treatment levels (Fig. 6). Notably, in the large modeled wildfire scenarios (NT-LF and S3-LF), treatments resulted in a 400,000-tonne increase in landscape-level live tree C over the no treatment scenario.

Table 15. Proportional change in expected carbon by biomass pool for treatment scenarios compared to the no treatment landscape. For example, a value of -0.10 represents a 10% decline in biomass C from the no treatment scenario. Treatment and no treatment values were calculated as the average of low and high fuel model range values, except in the case of the Large Fire (LF) scenarios, which were modeled for the high fuel model range only. Expected C is that remaining after a random ignition and wildfire in the buffered study area as estimated from simulating 80,000 ignitions (LF: 40,000 ignitions).

Treatment scenario	Belowground dead	Standing dead	Down dead wood	Forest floor	Belowground live	Herb/ shrub	Live tree
S1	0.17	0.04	-0.17	-0.13	-0.03	0.14	-0.04
S2	0.16	0.01	-0.16	-0.12	-0.04	0.14	-0.04
S3	0.17	-0.01	-0.15	-0.10	-0.04	0.16	-0.04
S3-LF	-0.04	-0.16	-0.13	-0.08	0.00	0.17	0.00

C pool categories are those reported in FVS Carbon Reports. *Belowground dead*: roots of dead and cut trees, *Belowground live*: roots of live trees, *Standing dead*: aboveground portion of standing dead trees, *Down dead wood*: woody surface fuels, *Forest floor*: litter and duff, *Herb/shrub*: herbs and shrubs, *Live tree*: aboveground portion of live trees.

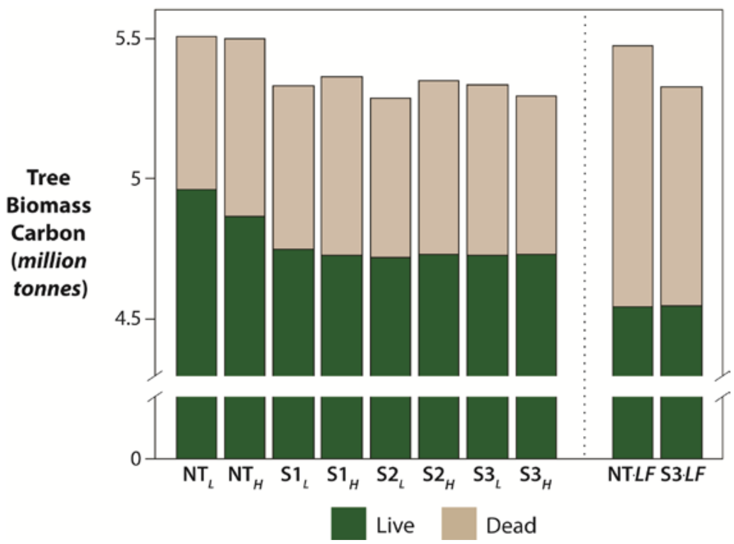

Figure 6. Expected carbon contained in aboveground live and dead tree biomass. Expected C is that remaining in the core study area following treatment (if applicable) and a single random ignition within the larger buffered study area. X-axis labels indicate no treatment (NT) and treatment scenarios (S1-S3); subscripts denote fuel model ranges used in fire modeling (L: low, H: high). Large Fire scenarios, which were modeled for the high fuel model range only, are indicated by LF.

Emissions from wildfire, landscape treatments, wood production, and biofuel production and combustion are summarized in Table 16. Estimated CO_2e emissions from bioenergy production and use were significant, representing 24-40% of total emissions. Yet even when these emissions were omitted from calculations, the no treatment scenarios were favorable with respect to GHG emissions (Table 16). Burning was responsible for the bulk of estimated emissions, at 57-75% of total emissions, and up to 98% of emissions when bioenergy-related emissions were excluded. Emissions produced in the collection and transport of forest biomass and merchantable timber, wood production, and biofuel transport were small by comparison, contributing only 1.4-2.4% of total emissions. Treatment GHG favorability improved when larger wildfires were simulated. CO_2e emissions for the Large Fire treatment scenario were 10-32% greater than for the no treatment scenario. In comparison, treatment scenario emissions were 3-15 times greater than equivalent no treatment scenarios when smaller wildfires were modeled.

Table 16. CO2-equivalent emissions (tonnes) from wildfire, landscape fuel treatments, wood production, and bioenergy production and combustion in the no treatment (NT) and treatment scenarios (S1-S3). Emissions are summed for a scenario in which bioenergy is assumed to replace fossil fuels (emissions from biodiesel production and combustion and electricity generation omitted), and one in which no emissions are treated as GHG neutral. LF indicates the Large Fire scenarios. Burning emissions include wildfire and prescribed fire emissions.

	Low fuel model range				High fuel model range					
Scenario	NT	S1	S2	S3	NT	S1	S2	S3	NT-LF	S3-LF
Burning	66,253	706,504	673,611	500,500	198,555	770,933	735,236	558,941	1,002,817	1,092,303
Biomass collection/transport and biofuel transport	--	15,382	13,990	21,087	--	15,382	13,990	21,087	--	21,087
Forest operations/wood production (merchantable timber)	--	172	161	186	--	172	161	186	--	186
Stored in wood products	--	37,392	36,551	44,830	--	37,392	36,551	44,830	--	44,830
Biodiesel production	--	153,816	139,905	210,874	--	153,816	139,905	210,874	--	210,874
Biodiesel combustion/ electricity generation	--	104,418	96,200	140,048	--	104,418	96,200	140,048	--	140,048
Net emissions if biofuel production and consumption, electricity generation considered GHG-neutral	66,253	722,057	687,763	521,773	198,555	786,486	749,388	580,215	1,002,817	1,113,577
Total emissions	66,253	980,292	923,868	872,695	198,555	1,044,721	985,493	931,137	1,002,817	1,464,499

DISCUSSION

Fuel treatments in protected habitat

Because there is often a perceived conflict between managing forests and protecting owl habitat, we assessed potential fire risk and hazard based on treatment scenarios that included and omitted treatment of PACs. Conducting fuels management outside of occupied owl habitat has been suggested as a means of reducing fire risk within occupied sites (Jenness et al., 2004). Ager et al. (2007) reported that fuel treatments on 20% of a western-Oregon landscape reduced the probability of northern spotted owl nesting and roosting habitat loss by 44%, even though that habitat type was not treated. As in Ager et al. (2007), we observed modifications in fire intensity and burn probability within owl habitat even when PACs were not treated. In the S1 treatment scenario, in which owl activity centers were not eligible for treatment, the effect of treating other stands produced modest changes in fire hazard within PACs (i.e., a 9-12% reduction in conditional flame length (CFL), or approximately 0.4 m), but considerable reductions in burn probability (~ 45%). Ager et al. (2007) noted that allowing treatment of owl habitat would have significantly reduced estimated habitat loss in their study. While we did not estimate habitat loss, we did observe much larger reductions in fire hazard within PACs that were treated as measured by CFL (71-75% reduction, equivalent to 2-3 meters).

One concern with holding some land area off base for treatment is that it may limit the potential for treatments to alter fire behavior across the landscape (e.g., Finney, 2001). While the land area potentially available for treatment more than doubled between S1 and S3, landscape-level effects of treatment on modeled fire risk and hazard were fairly similar (all-stand burn probability fell by 47-54% between S1 and S3 while CFL fell by 24-30%). Including all stands in the potential treatment pool allows the highest-priority stands to be treated, which would be expected to achieve the greatest reduction in fire behavior and effects. The modest changes in estimated fire metrics we observed may be due to similarity in the general pattern of treatment placement between scenarios, which may have led to similar effects on landscape-level fire behavior. The true effect of increasing treatment availability may be partially obscured by varying application of treatment methods between scenarios. For example, the hand thinning treatments applied within PACs would be expected to have a less significant impact on potential wildfire behavior than more severe prescriptions, and this treatment was twice as common in S2 as in the other scenarios.

Carbon and greenhouse gas consequences of treatments

Landscape treatments reduced wildfire emissions by reducing both emissions produced per area burned and wildfire size. On average, wildfires in the treated landscapes released 19.3-21.6 tonnes C ha^{-1}, while untreated landscapes released 23.4-25.4 tonnes C ha^{-1}. Simulated wildfires decreased in size by 7% (low fuel model range), 36% (high fuel model range), and 25% (large fire scenario) relative to untreated landscapes. Despite the influence of treatments on wildfire intensity, size, and expected emissions, treatment-related emissions exceeded the avoided wildfire emissions conferred by treatment. Prescribed burning in our study, a combination of broadcast and pile burning, released 11.1-16.3 tonnes C ha^{-1}. This rate was similar to that observed in other studies for similar forest types [e.g. 12.7 tonnes C ha^{-1} in warm, dry ponderosa pine habitat types (Reinhardt and Holsinger, 2010) and 14.8 tonnes C ha^{-1} in an old growth mixed conifer reserve in the southern Sierra Nevada (North et al., 2009a)]. Relative to the approximately 158,000 tonnes C emitted in prescribed burning, avoided wildfire emissions, at 4,075-25,341 tonnes for wildfires of moderate size, were small. In a southern Oregon study with average modeled wildfires of 2,350 and 3,500 ha (treatment scenario and no treatment scenarios, respectively), Ager et al. (2010) found that treatments reduced expected wildfire emissions by 6,157 tonnes C. When emissions from bioenergy production and use, which contributed the equivalent of 40-80% of prescribed fire emissions in the present study, were included in GHG accounting, avoided emissions owing to treatment were further eclipsed.

Surface fuels, represented with surface fuel models in commonly used modeling software, are the most influential inputs determining predicted fire behavior (Hall and Burke, 2006). Fire behavior, fire sizes, and emissions in this study varied according to fuel model assignment, highlighting the importance of selecting the appropriate fuel model to represent fuel conditions (see Collins et al., 2013). We show a doubling of emissions due solely to the choice of fuel models. Indeed, the range in fuel models used in recent studies investigating fuel treatments and simulated fire behavior in mixed conifer forests is noteworthy. Incorporating a range of fuel models into analyses such that outcome variability can be reported facilitates comparison of effects across studies.

Our estimates of the C benefits of treatment under the moderate wildfire scenarios, with average fire sizes of ≤2,133 ha, are likely conservative. The effect of modeled wildfire size on the GHG consequences of fuel treatment was considerable, emphasizing the importance of this variable in studies of the climate benefits of treatment. Avoided wildfire emissions resulting from treatment increased to 99,155 tonnes C when large wildfires (8,070-10,757 ha) were simulated. The treatment scenario, given large wildfires, also protected a greater portion of live tree C. If the ~40,000-ha King Fire is representative of the magnitude of future wildfires in the region, GHG accounting should improve with respect to treatment favorability. Similarly, if multiple wildfires were to encounter the study area within the effective lifespan of treatments, the GHG gains associated with avoided emissions in the treatment scenarios would increase.

Our approach to estimating the GHG consequences of fuel treatments has a number of limitations. A full accounting of treatment effects would project through time the consequences of both treatment and wildfire, and would include stochastic wildfire occurrence. Our estimates of burn probability are not estimates of the likelihood of wildfire occurrence based on historical fire sizes and frequency (e.g., Preisler et al., 2004; Mercer and Prestemon, 2005; Brillinger et al., 2006), but rather are conditional on a single randomly ignited wildfire within the buffered study area. Simulating wildfire in the year immediately following treatment maximizes the apparent benefits of treatment. In addition, our approach is static, incorporating only the short-term GHG costs and benefits of treatment. Over time, as surface fuels accumulate and vegetation regenerates, maintenance would be required to retain the effectiveness of treatments (Martinson and Omi, 2013), increasing the GHG costs of reduced fire hazard. In addition, the C contained in fire-killed biomass will ultimately be emitted to the atmosphere. Nevertheless, because it accounts for the influence of treatments on wildfire spread and size, our landscape-level analysis is more complete than static stand-level simulations.

CONCLUSIONS

Our findings support those of Campbell et al. (2011), who concluded from an analysis of fire-prone western forests that the C costs of treatments are likely to outweigh their benefits under current depressed fire frequencies. However, the current divergence of increasing surface air temperatures and low fire activity is unlikely to be sustained, suggesting greater future fire frequencies (Marlon et al. 2012). Due to the significant emissions associated with treatment and the low likelihood that wildfire will encounter a given treatment area, GHG accounting favored the no treatment scenarios. Only when large wildfires were modeled did landscape treatments protect more C in live tree biomass. While treatment favorability improved with large wildfire simulation, the no treatment scenario still produced fewer emissions than the treatment scenario. Given the potential for large wildfire in the region demonstrated by the 2014 King Fire, and the increasing frequency of large wildfires and area burned in California expected from climate modeling studies ((Lenihan et al., 2008; Westerling et al., 2011), we suggest that future studies of fuel treatment-wildfire-C relationships should incorporate the potential for large wildfires at a frequency greater than those observed over the last 20-30 years.

We also note that the potential benefits of fuels management are not restricted to avoided wildfire emissions. Here, we show that landscape fuel treatments can alter fire hazard across the landscape both within and outside of treated stands, and have the potential to affect the likelihood of burning and fire intensity within protected California spotted owl habitat. Underscoring the risk to sensitive habitat, the 2014 King fire encountered 31 PACs within our study area. Modest simulated treatments within activity centers significantly reduced potential fire intensity relative to both the no treatment landscape and a treatment scenario that did not permit treatment within PACs, supporting the argument that active management may be desirable to protect habitat in the long term (Roloff et al., 2012). Treatments also produced woody biomass and timber feedstocks that would offset the economic costs of treatments, benefit the local economy, and could potentially be used in bioenergy production to offset emissions from fossil fuels.

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