Forest Ecology and Management 261 (2011) 1115–1120

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

High-severity wildfire effects on carbon stocks and emissions in fuels treated and untreated forest

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ARTICLE INFO

Article history:
Received 21 October 2010
Received in revised form
28 December 2010
Accepted 29 December 2010
Available online 26 January 2011

Keywords:
Carbon storage
Climate change mitigation
Disturbance
Fire severity
Forest management
Sierra Nevada
Tree mortality

ABSTRACT

Forests contain the world's largest terrestrial carbon stocks, but in seasonally dry environments stock stability can be compromised if burned by wildfire, emitting carbon back to the atmosphere. Treatments to reduce wildfire severity can reduce emissions, but with an immediate cost of reducing carbon stocks. In this study we examine the tradeoffs in carbon stock reduction and wildfire emissions in 19 fuels-treated and -untreated forests burned in twelve wildfires. The fuels treatment, a commonly used thinning 'from below' and removal of activity fuels, removed an average of 50.3 Mg C ha^{-1} or 34% of live tree carbon stocks. Wildfire emissions averaged 29.7 and 67.8 Mg C ha^{-1} in fuels treated and untreated forests, respectively. The total carbon (fuels treatment plus wildfire emission) removed from treated sites was 119% of the carbon emitted from the untreated/burned sites. However, with only 3% tree survival following wildfire, untreated forests averaged only 7.8 Mg C ha^{-1} in live trees with an average quadratic mean tree diameter of 21 cm. In contrast, treated forest averaged 100.5 Mg C ha^{-1} with a live tree quadratic mean diameter of 44 cm. In untreated forests 70% of the remaining total ecosystem carbon shifted to decomposing stocks after the wildfire, compared to 19% in the fuels-treated forest. In wildfire burned forest, fuels treatments have a higher immediate carbon 'cost', but in the long-term may benefit from lower decomposition emissions and higher carbon storage.

Published by Elsevier B.V.

1. Introduction

Forests are important to the global carbon cycle for both their long-term storage and as the largest terrestrial sink for CO_2 (Canadell and Raupach, 2008). The world's four billion hectares of forest store more than double the amount of carbon present in the atmosphere (FAO, 2005) and terrestrial ecosystems, of which forests are major contributors, remove nearly 3 Pg C $year^{-1}$, absorbing about 30% of all CO_2 emissions from fossil fuel burning and net deforestation (Canadell et al., 2007). Carbon sequestered in forests, however, can be reversed by disturbance (Galik and Jackson, 2009). Of natural disturbances, wildfire has the greatest global impact on forest carbon stocks, contributing an estimated 3431 million tonnes of CO_2 into the atmosphere annually (FAO, 2006; Bowman et al., 2009). In recent decades, fire size, burn season length, and emissions have been increasing (Westerling et al., 2006; Canadell and Raupach, 2008) creating a positive feedback with warming temperatures.

In many dry temperate forests, frequent fires maintained an open forest structure that was resistant to high-severity wildfire. The advent of fire suppression policy in the western U.S.'s dry forests has contributed to prolonged fire-free periods that have altered forest structure, fuel loads, and fire behavior. These changes affect forest carbon storage (Fahey et al., 2010) and have produced a range of forest carbon stock responses. In some systems, the modern fire-excluded forest structure has a higher carbon density than the fire-maintained structure (Hurteau et al., 2010). In other systems, historic forests with an active fire regime had higher carbon stocks (Fellows and Goulden, 2008; North et al., 2009). In many forests, fire is essential for building an ecosystem's adaptation capacity (Stephens et al., 2010). Given the potential for increased fire prevalence on the landscape (Westerling and Bryant, 2008), quantification of the carbon trade-offs of different management practices is needed to develop forest policy under changing climatic conditions.

Forest management that reduces fuels can decrease fire severity (Safford et al., 2009; Prichard et al., 2010) and wildfire emissions but causes an immediate reduction in the carbon stock (North et al., 2009). The potential carbon tradeoffs between fuels treatments and reduced wildfire emissions have been modeled over several decades (Hurteau and North, 2009; Reinhardt and Holsinger, 2010;

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0378-1127/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.foreco.2010.12.039

Mitchell et al., 2009) and for the western U.S. (Wiedinmyer and Hurteau, 2010). These models, however, often contribute to controversy over the carbon costs and benefits of fuels treatments because carbon accounting outcomes depend on the time period, spatial scale, and assumptions of a model analysis (Meigs and Campbell, 2010). Building a better understanding of treatment effects on carbon dynamics in fire-prone forests will require a series of scale-specific, empirical studies of carbon storage and emissions.

In this study we use field measurements to assess immediate changes in carbon stocks and emissions between paired treated and untreated forest stands (10–30 ha) burned by wildfire. We also estimate carbon loss due to fuels treatments. Our objectives were to compare fuels-treated and -untreated forests burned by wildfires to assess differences in (1) carbon stocks, (2) carbon loss from treatments and wildfire, and (3) tree survival, mortality, and changes in live tree sizes and species composition.

2. Materials and methods

2.1. Study areas

Using Forest Service records, expert knowledge, and regional reports, we examined wildfires that had burned in mixed-conifer forests in California where fuels reduction treatments had been completed no more than five years before burning. Fuels treatments can take many forms varying in how trees are thinned and surface fuels are treated. In practice, costs and air quality restrictions often limit fuel treatment options to mechanical thinning and treating the activity fuels (i.e., the slash created by the thinning operation). We therefore limited our selection of sites to areas with mechanical treatments following a widely used 'thin from below' prescription (all trees below an upper diameter limit are cut). Such thinning increases the height to the base of the live tree crown reducing potential fire severity (Agee and Skinner, 2005). We also constrained site selection to treatment areas where activity fuels were removed from the site either through whole tree harvest or by being piled and burned. We focused on these treatments with their short-term release of all treated biomass carbon because they provide an upper bound on the carbon 'cost' of treatments. Sites where the activity fuels piles had not been burned or where they had been masticated (mechanically chipped into small pieces and spread over the treatment area) were excluded from the study because research suggests these additional fuels increase fire severity (Stephens and Moghaddas, 2005; Safford et al., 2009). We only selected sample areas where the wildfires burned unchecked through the fuels treatment and were unaffected by suppression efforts.

Using these criteria we identified twelve wildfires, with a total of 20 fuels treatment areas that had been burned. All areas were mixed-conifer forest. Locations ranged from Grass Valley (lat. 34°13.9′ N, long. 117°21.9′ W) east of Los Angeles to a wildfire near Pittville (lat. 40°53.6′ N, long. 121°19.2′ W), about 100 km south of the Oregon border (Fig. 1). Most of the sample sites are in the central and northern Sierra Nevada where more extensive implementation of fuels treatments has occurred. On fires where we sampled more than one fuels-treated area, sample areas were separated temporally by at least a 24 h time period (using daily burn perimeter maps) or spatially by at least one intervening area with high fuel loads. We imposed these conditions, which help to reset fire behavior, in an effort to reduce the potential for pseudoreplication sampling within a fire (van Mantgem and Schwilk, 2009).

In an effort to effectively pair untreated/burned and treated/burned stands we imposed several criteria. Paired stands must have similar slope, aspect, and slope position because these factors are known to influence fire intensity (Taylor and Skinner, 2003). Using fire progression maps we selected paired sites such that the advancing wildfire front would have burned both sites at approximately the same time under the same weather conditions. Most paired sites were within 200 m of each other on each side of the fuels treatment boundary (Fig. 2). Finally, after data collection, using reconstruction methods (described below), we compared pre-burn/untreated and pre-burn/pre-treatment basal area and density between the paired sites. We discarded any treatment area where initial condition (i.e., pretreatment) stand structure significantly differed (paired t-test, $p < 0.1$) between the paired sample stands.

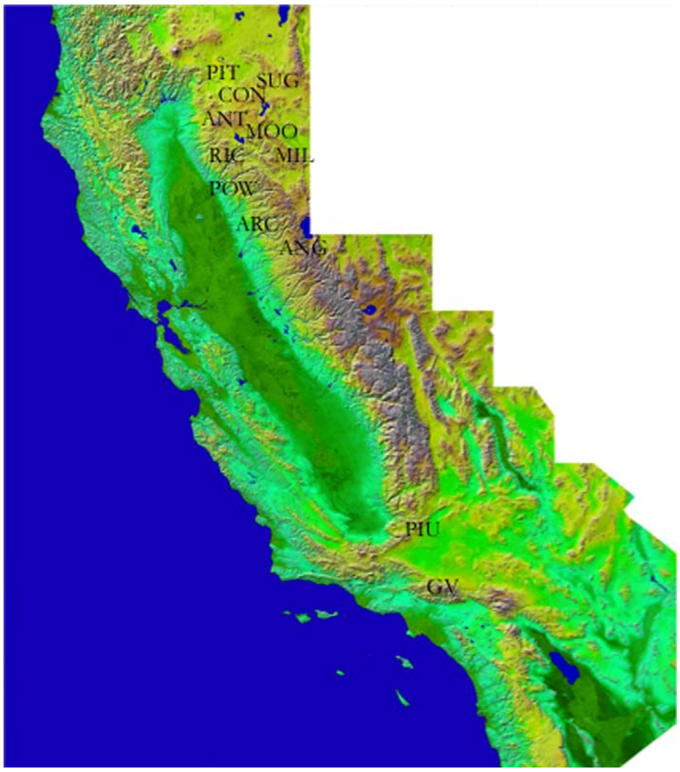

Fig. 1. Map of California showing the approximate location of the 12 wildfires analyzed in this study. *Abbreviations:* ANG—Angora, ANT—Antelope, ARC—American River Complex, CON—Cone, GV—Grass Valley, MIL—Milford, MOO—Moonlight, PIT—Pittville, PIU—Piute, POW—Power, RIC—Rich, and SUG—Sugarloaf.

2.2. Data collection

Within a treatment area, we randomly established 3–6 plots. We identified and measured all trees ≥5 cm diameter at breast height (dbh) within a 0.05 ha circular plot and all trees ≥50 cm dbh within a 0.1 ha circular plot. For live trees we measured scorch height, height to live crown base, and total height. For stumps and snags we measured total height and decay class, and for snags whether foliage, small branches, and bark were present. We also measured all burned stump holes in the soil and, using a subsample that still contained the tree stem, developed a regression equation for predicting pre-burn stem diameter from burn hole diameter (adj. $r^2 = 0.49$). We estimated the upper diameter limit used in the fuels treatment by sorting stump diameters and using the largest diameter size with three or more stumps to avoid including old stumps from large trees logged in the last century. At each plot, we took sighting tube densitometer readings every meter along a 10 m × 10 m grid to calculate canopy cover. Maximum height of char on the bole of each tree was directly measured for heights ≤3 m and estimated for heights >3 m, and averaged for each plot. We classified tree species as fire-sensitive if they were *Abies concolor*, *Abies* a

b

Fig. 2. Untreated (a) and treated (b) mixed-conifer stands 200 m apart in the Moonlight Fire, Lassen National Forest, California.

magnifica, and *Calocedrus decurrens*, and fire-resistant if they were *Pinus jeffreyi*, *Pinus ponderosa*, and *Pinus lambertiana*. We measured fuels using standard planar intercept methods (Brown, 1974) and shrub cover along these transects. We converted fuel volumes to mass (Mg ha^{-1}) using the specific gravities of van Wagtendonk et al. (1996, 1998). In each plot we composited three soil samples for the 0–10 cm depth and 10–30 cm depths.

2.3. Carbon calculations

To calculate carbon in the different tree components we used genus-specific allometric equations and estimates of the contribution of each component (foliage, stem bark, stem wood, branches, coarse roots) to total tree carbon (Jenkins et al., 2004). We included all components for live trees, but for snags we eliminated foliage, branches, and stem bark progressively, and decreased wood density with increasing decay class. For stumps we included only coarse roots, and stem wood and bark adjusted for each stump's height. We calculated carbon in the surface fuels assuming a carbon concentration of 50% in woody material and 37% in litter and duff (Smith and Heath, 2002; Penman et al., 2003). We converted shrub cover to carbon using an equation developed in earlier work (Hurteau and North, 2008). Fine roots were left in the soil samples and the whole sample was finely ground. Total soil and fine root carbon was calculated for the 0–10 and 10–30 cm horizons at the DANR lab at U.C. Davis.

The data collected by Forest Service crews in treated areas before the wildfire burns was limited to basal area estimates using a prism and photo series visual estimates of fuels, in plots which were not monumented. Without fixed area, direct measurement data, and in an effort to control for spatial variability, we used reconstruction methods to estimate stand structure before the wildfire and fuels treatments. We estimated pre-wildfire carbon pools by "restoring" snags to an estimated larger size or live tree status depending on current stem size and extent of charring. To estimate carbon removed from the site in the fuels treatment we "restored" stumps to live trees and than subtracted the stump and roots. To estimate fire emissions we used previously published methods (North et al., 2009) where we calculated the sum of the carbon stocks just before the fire and subtracted the sum of the current carbon stocks.

To estimate pre-wildfire canopy cover, soil C, and fuels, we identified stands immediately outside the fire perimeter. We took particular care to identify stands with similar topography, age, size, and species composition of trees, and time since disturbance. We wanted to accurately estimate pre-treatment surface fuel loads because they significantly affect wildfire intensity and carbon emissions. Reliable estimates of surface fuel loads in the Sierra Nevada have been made using tree species, tree size, and time since disturbance (van Wagtendonk and Moore, 2010). Therefore, for the areas we sampled outside the fire perimeter, we matched forest type, species composition, tree size, and time since disturbance to the burned sample sites within the fire. These areas were readily identified because each burn consumed only a part of larger watersheds that had similar management, disturbance histories, and forest conditions. Although these comparison stands outside the fire perimeter were matched as carefully as possible, there may have been pre-burn differences in fuel loads and soil carbon that we were unable to detect. In these comparison areas we randomly located plots and used the same sampling protocol.

All data were standardized to per hectare values. We evaluated each variable for normality with the Kolmogorov–Smirnov test and for homoscedasticity with Levene's test. We tested for significant differences in carbon values between treatments with ANOVA and used Tukey's hsd post hoc analysis to detect significant differences.

3. Results

Reconstructed pre-treatment/pre-wildfire stand structure did not significantly differ between sample sites for 19 of our 20 paired stands (*t*-test, $p > 0.1$). We discarded the single significantly different pair from further analysis. Before treatments and wildfire, live tree carbon averaged 145.3 Mg C ha^{-1} (range 117.5–159.5 Mg C ha^{-1}), density averaged 1536 stems ha^{-1} (range 920–2550 stems ha^{-1}) and surface fuels averaged 50.2 Mg C ha^{-1} (range 38.9–60.6 Mg C ha^{-1}) (Table 1). The average upper diameter thinned on the treated sites was 46 cm and the mean carbon removed by the treatments was 50.3 Mg C ha^{-1} (range 35.5–67.3) (Table 1), equivalent to 34% (range 28–43%) of the live tree C. After the wildfire, emissions of treated and untreated stands significantly differed (paired *t*-test, $p < 0.05$) averaging 29.7 Mg C ha^{-1} and 67.8 Mg C ha^{-1}, respectively (Table 1). Post-burn tree mortality also significantly differed between treated and untreated stands (paired *t*-test, $p < 0.05$) averaging 53% and 97%, respectively (Table 1).

Comparing the three stand conditions, preburn/pretreatment (initial), untreated/burned, and treated/burned, the largest wildfire impact was the proportional shift of total ecosystem carbon between different pools (Fig. 3). The live tree pool significantly differed between all treatments with 145.3, 7.8, and 100.5 of Mg C ha^{-1} in the preburn/pretreatment, untreated/burned, and treated/burned conditions, respectively. The average carbon pool in snags was significantly higher in the untreated/burned

Table 1
Initial condition, treatment removal, and wildfire effects for 19 paired sites of treated and untreated mixed-conifer forest on 12 wildfires. Initial condition live tree carbon, stem density, and surface fuels are the combined average for the paired sites before treatment and wildfire. Treatment values for the upper diameter (i.e., the cutting size limit), live tree carbon removed, and the percentage of the live tree carbon apply only to the fuels-treated sites of each paired comparison. Wildfire effects indicate the emissions and percentage mortality for each paired site of treated (Trt) and untreated (Unt) forest. The bottom two rows are the mean and standard deviation for the values in each column.

Site	Initial (pre-treatment and -wildfire)			Treatment			Wildfire effects			
	Live tree C (Mg C ha^{-1})	Density (trees ha^{-1})	Surface fuels (Mg C ha^{-1})	Upper diameter (cm)	Live C removed (Mg C ha^{-1})	% live (Mg C ha^{-1})	Emissions (Mg C ha^{-1})		Mortality (% of trees)	
							Trt	Unt	Trt	Unt
ANG	144.2	1620	38.9	46	58.0	40	24.8	76.3	51	98
ANT1	137.7	2230	39.8	43	40.5	29	30.8	79.9	65	92
ANT2	147.5	1530	41.9	46	52.4	36	27.1	66.4	46	99
ANT3	141.9	1430	39.1	48	57.5	41	25.9	63.7	53	100
ARC1	153.2	2550	56.1	48	56.4	37	26.5	64.3	58	93
ARC2	144.1	2150	59.3	43	46.2	32	26.3	58.8	63	100
CON1	138.4	1850	49.3	51	50.5	36	32.7	71.6	39	100
CON2	131.7	2050	44.8	41	37.3	28	27.8	66.7	49	97
GV1	146.9	1060	48.8	41	44.2	30	24.9	75.8	53	99
GV2	117.5	920	50.9	41	37.4	32	31.1	72.4	59	98
MIL	129.1	1850	60.0	41	35.5	27	34.0	76.7	48	100
MOO1	149.5	1410	55.1	46	52.7	35	38.2	66.4	59	91
MOO2	154.8	1000	45.5	46	44.9	29	31.6	69.2	62	93
PIT	149.1	1450	55.0	48	47.0	32	32.3	63.8	46	100
PIU	148.4	1370	54.7	48	50.8	34	20.9	51.2	48	98
POW	157.1	1080	60.6	51	67.3	43	37.6	68.1	57	99
RIC1	159.5	1170	41.4	48	60.3	38	24.1	82.4	59	92
RIC2	157.3	1070	60.4	48	57.9	37	36.7	61.9	51	98
SUG	152.6	1400	51.3	48	59.5	39	30.7	52.7	43	99
Mean	145.3	1536	50.2	46	50.3	34	29.7	67.8	53	97
Std	10.7	465	7.7	4	8.9	5	4.9	8.4	7	3

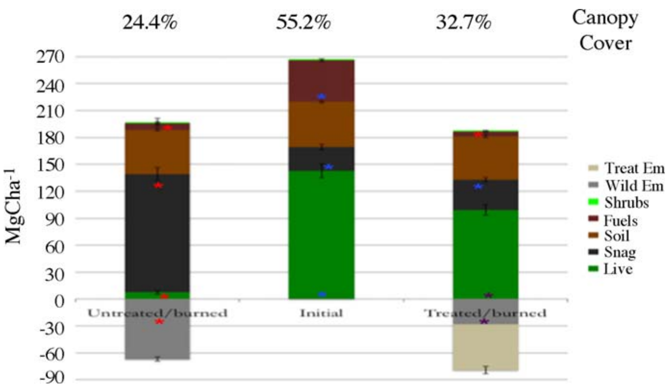

Fig. 3. Canopy cover (%) and carbon (Mg C ha^{-1}) stores and losses in three different forest treatments. Negative values are carbon losses from the site due to biomass removal (Treat em) and wildfire emission (Wild em). Standard errors are at the top of bars for stores and the bottom of bars for losses. Stores and losses with asterisks of different color are significantly different ($p < 0.05$) between treatments.

(128.5 Mg C ha^{-1}), than in the initial (19.8 Mg C ha^{-1}) and treated/burned (29.4 Mg C ha^{-1}), which did not significantly differ. Soil (48.4–57.1 Mg C ha^{-1}) and shrub (0.01–0.02 Mg C ha^{-1}) carbon pools did not significantly differ between treatments.

Wildfire emissions averaged 11% and 25% of total carbon stores in treated and untreated forest, respectively. If fuels treatments reductions are added to wildfire emissions, the treated/burned produced a higher mean net carbon loss (80.2 Mg C ha^{-1}) than the untreated/burned (67.8 Mg C ha^{-1}). The 'fate' of carbon removed in fuels treatments affects the carbon balance, as it can be rapidly released to the atmosphere (e.g., prescribed fire), stored in another form (e.g., wood products) or substituted for fossil fuel (e.g., energy production) (Stephens et al., 2009). In this study we focused on two commonly used treatments, pile and burn and whole tree harvest and chip, both of which release carbon within a few years of treatment (Finkral and Evans, 2008).

Following wildfire, untreated forest with 97% tree mortality (Table 1) averaged 32 live trees ha^{-1} with a quadratic mean diameter of 21 cm. Of these surviving trees, 45% remained fire-sensitive species (Fig. 4a). Of large trees (>50 cm dbh) that contain most of a forest's aboveground carbon, only 6% survived the wildfire in untreated stands. The high-severity burn transitioned 70% of total ecosystem carbon to decomposing pools (i.e., snags and surface fuels).

In contrast, wildfire burned at lower severity in the fuels-treated forests, with 53% mortality (Table 1), averaging 145 live trees ha^{-1} with a quadratic mean diameter of 44 cm, and 87% survivorship of large (dbh > 50 cm) trees (Fig. 4b). In the fuels treated stands, live tree composition had shifted to 84% fire-resistant species.

4. Discussion

Fuels treatments are designed to reduce fire severity and consequently should also reduce forest carbon loss from wildfire. We found that treatments did reduce wildfire emissions by 57% but when carbon removed from the site during treatment (50.3 Mg C ha^{-1}) is added to wildfire emissions, the total carbon loss is greater in fuels treated (80 Mg C ha^{-1}) than untreated (67.8 Mg C ha^{-1}) forest. If thinned trees were milled into lumber or the chips used as biofuel, a treatment's carbon loss could be reduced (Finkral and Evans, 2008). Fuels treatments and wildfire significantly changed initial condition (pre-treatment and pre-wildfire) stocks in live trees, snags, and fuels, while having little effect on soil and shrub carbon (due to sparse shrub cover at all sites). Of the carbon remaining (i.e., not emitted) in the untreated/burned forest, 70% (136.1 Mg C ha^{-1}) had transitioned to decomposing stocks (snags and fuels) compared to 19% (35.7 Mg C ha^{-1}) in the treated/burned forest. The substantial difference in stand conditions (47% vs. 3% survival) after the wildfire suggests carbon tradeoffs of fuels-treating forests may have very different short- and long-term costs.

We caution that our results should not be extrapolated to the entire area within a wildfire perimeter. Burn intensity is often

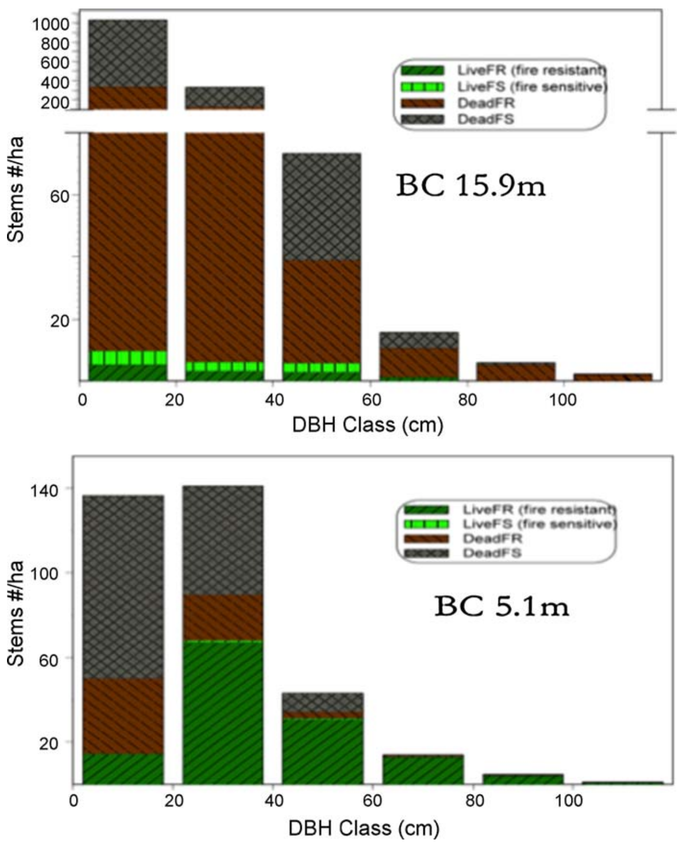

Fig. 4. Bole char (BC) heights (m) and density (stems ha^{-1}) of live and dead trees in six diameter classes by fire resistance in (a) untreated/burned and (b) treated/burned stands.

highly variable in Sierra Nevada wildfires, creating mosaics of different severity (Miller et al., 2009). We selected untreated/burned sites based on their comparability to the adjacent treated/burned sites. In many cases the untreated/burned sites were in wildlife protected activity centers (PACs), which bordered and limited the extent of fuels treatments implementation. These areas reserved for sensitive species such as the California spotted owl (*Strix occidentalis occidentalis*) and northern goshawk (*Accipiter gentilis*) typically have dense canopy cover from high stem densities, which can increase fire intensity. Not only was fire severity and carbon emissions high in these reserve areas, but also initial surveys in at least one wildfire suggest there is limited post-burn use by sensitive species (North et al., 2010).

Although forests covered in our study had a range of initial densities (920–2550 trees ha^{-1}) and live tree carbon (117.5–159.5 Mg C ha^{-1}), the common fuels treatment of thinning from below to an upper diameter limit produced a fairly consistent percentage (27–43%) of live tree carbon removed. This may result because the upper diameter limit (41–51 cm across our sites) is often set higher in stands with greater biomass yet rarely exceeds 51 cm dbh in an effort to reduce the potential for litigation. This limits the amount of carbon removed in a fuels treatment because most of a stand's live tree carbon is concentrated in the larger trees (North et al., 2009). Fire severity was also fairly consistent across fuels-treated stands (53% mortality, Std = 7%) because treated stands have a similar live crown base height, reducing crown fire potential and crown foliage mortality from surface fuel radiant heat. Removing small 'ladder fuel' trees and the resulting activity fuel is considered one of the most effective fuels treatments for reducing fire severity (Agee and Skinner, 2005; Stephens and Moghaddas, 2005). Wildfire effects on carbon storage, emissions, and tree survival would likely vary under different types of fuels treatments (i.e., mastication, prescribed burning, etc.).

Wildfire emissions in untreated forests were more than double emissions in treated forests largely due to foliage and small branch incineration, and nearly complete consumption of snags. Estimates of wildfire carbon release have varied widely depending on forest type, wildfire severity, and whether potential carbon release from wood decomposition was included (Auclair and Carter, 1993; Campbell et al., 2007; Meigs et al., 2009; Wiedinmyer and Hurteau, 2010). Our study found high-severity wildfire still left 75% of the forest's carbon onsite, but it transitioned most of the aboveground carbon to decomposing stocks. With their high biomass, large changes in carbon allocation between live and dead pools can transform forests from sinks to sources for several decades (Dore et al., 2008). Estimates of how much of the decomposing stock carbon is emitted greatly affect calculations of the carbon 'cost' of wildfires. In boreal forest, Auclair and Carter (1993) estimated that long-term decomposition emissions could be three times higher than the immediate emissions from high-severity wildfire. Rapid rates of wood decomposition have been reported for some species in the Sierra Nevada, with our studies' most common species, white fir, having an estimated half-life of only 14 years (Harmon et al., 1987). The untreated/burned forest, with 128.5 Mg C ha^{-1} in snags, has the potential to almost double its immediate fire emissions through decomposition in a few decades. However, this should be considered an upper bound estimate as it is likely that some snag carbon will be incorporated into soil stocks.

While our study focused on the short-term carbon costs and benefits of fuels treatment, mortality differences between treated (53%) and untreated (97%) forest suggest there will be long-term effects on carbon storage. Higher survivorship in treated areas, particularly of large trees, will likely shorten the time necessary for the carbon lost to wildfire to be re-sequestered through tree growth (Hurteau and North, 2010).

Increasing carbon density in existing forests has been suggested as a mitigation strategy to help offset rising anthropogenic CO_2 emissions (Canadell and Raupach, 2008; Keith et al., 2009; Hudiburg et al., 2009). In fire-prone forests, however, fire season length (Westerling et al., 2006) and severity (Miller et al., 2009) may be increasing, putting high-density forests at risk for larger wildfire emissions. Our study suggests that fuels treatments to reduce wildfire severity can be effective, but in the short term are a net carbon loss when compared with untreated/burned forest. However, the untreated forest's high rate of tree mortality shifted most of the carbon into decomposing stocks suggesting a long-term increase in emissions and a significant reduction in live-tree sequestered carbon.

Acknowledgements

We thank Chris Hamma, Dominic Ali, and Forest Service employees Colin Dillingham, David Kelly, Eric Knapp, Jon Lamb, Ryan Tompkins, Scott Williams, Debbie Mayer, Joan McNamara, Kyle Merriam, Martin Ritchie, Hugh Safford, and Carl Skinner. The USDA Forest Service, PSW Research Station provided funding.

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