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Fuel treatment longevity in a Sierra Nevada mixed conifer forest

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ABSTRACT

Understanding the longevity of fuel treatments in terms of their ability to maintain fire behavior and effects within a desired range is an important question. The objective of this study was to determine how fuels, forest structure, and predicted fire behavior changed 7-years after initial treatments. Three different treatments: mechanical only, mechanical plus fire, and prescribed fire only, as well as untreated control, were each randomly applied to 3 of 12 experimental units. Many aspects of the initial fuel treatments changed in 7 years. The overall hazard of the control units increased significantly indicating continued passive management has further increased already high fire hazards. Mechanical only fire hazard decreased after 7 years and are now similar to the two fire treatments, which both maintained low hazards throughout the study. Tree density declined significantly 7 years after the initial fire only treatments, while basal area in both fire treatments was unchanged relative to immediate post-treatment conditions. Our findings indicating reduced fire hazard over time in mechanical only treatments might provide an opportunity for a staggered treatment schedule that included prescribed fire which could increase overall treatment longevity to approximately 20 years. Changes in our mixed conifer forests after fuel treatment were generally larger than those reported from ponderosa pine forests in the Rocky Mountains.

1. Introduction

It is recognized that past and current management practices including harvesting, livestock grazing, and fire exclusion have increased fire hazards in western US forests that once burned frequently under low-moderate intensity fire regimes (Fulé et al., 2012; Stephens et al., 2012). Such forest conditions concern fire managers because the increased fuel loads and altered forest structure have made many forests vulnerable to fire severities outside of desired ranges (Miller et al., 2009). Changing climates in the next several decades will further complicate fire management by increasing temperatures and fire season length (McKenzie et al., 2004; Westerling et al., 2006), which further emphasizes the need to promote resilient forested ecosystems (Millar et al., 2007).

Research has determined that the reduction of surface fuels is the most important component of reducing forest fire hazards since this leads to lower fireline intensity and increased ability to manage fire when needed (Stephens et al., 2009). The second most important fuel stratum in terms of fire hazard reduction is commonly ladder fuels which can provide vertical continuity to move fire from the surface to the forest overstory. Retaining and growing larger trees is also an important aspect of fire hazards reduction treatments since these trees have a higher survival probability because of thicker bark and elevated crowns (Agee and Skinner, 2005; Fulé et al., 2007; Hurteau and North, 2009).

Several papers have analyzed the change in potential fire behavior resulting from initial fuels treatments using empirical field studies (Kilgore and Sando, 1975; Covington et al., 1997; Omi and Martinson, 2004; North et al., 2007; Stephens et al., 2009; Fiedler et al., 2010) or simulations with or without the aid of field data (Keane et al., 1990; van Wagtendonk, 1996; Stephens, 1998). Far fewer studies have investigated how forests that have received fuel treatments change over time (Peterson et al., 1994; Sackett and Haase, 1998; Fulé et al., 2005, 2007; Fajardo et al., 2007) and most of these studies have occurred in relatively xeric Rocky Mountain ponderosa pine (*Pinus ponderosa*) forests.

Understanding the longevity of fuel treatments in terms of their ability to maintain fire behavior and effects within a desired range is an important management question. Initial treatment effects such as reduced surface and ladder fuels will diminish over time (van Wagtendonk, 1985; Kiefer et al., 2006) and information from longer-term studies can assist managers in providing important information to aid in deciding how to allocate finite resources, e.g., maintenance of existing fuel treatment versus implementation of new fuel treatments. The objective of this study was to determine how fuels, forest structure, and predicted fire behavior have changed 7-years after initial fuel treatments in mixed conifer forests in the northern Sierra Nevada. The null hypothesis

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investigated is there will be no differences in forest structure and predicted fire behavior 1-year post-treatment (Stephens and Moghaddas, 2005a) as compared to similar measurement and analysis 7-years post-treatment.

2. Methods

2.1. Study area and treatments

This study was performed at the University of California Blodgett Forest Research Station (Blodgett Forest), approximately 20 km east of Georgetown, California. Blodgett Forest is located in the mixed conifer zone of the north-central Sierra Nevada at latitude 38°54′45″N, longitude 120°39′27″W, between 1100 and 1410 m above sea level, and encompasses an area of 1780 ha (Fig. 1). Tree species in this area include sugar pine (*Pinus lambertiana*), ponderosa pine, white fir (*Abies concolor*), incense-cedar (*Calocedrus decurrens*), Douglas-fir (*Pseudotsuga menziesii*) Franco, California black oak (*Quercus kelloggii*), tanoak (*Lithocarpus densiflorus*), bush chinkapin (*Chrysolepis sempervirens*), and Pacific madrone (*Arbutus menziezii*).

Soils at Blodgett Forest are well-developed, well-drained Haploxeralfs (Alfisols), derived from either andesitic mudflow or granitic/granodiorite parent materials (Moghaddas and Stephens, 2007). Cohasset, Bighill, Holland, and Musick are common soil series. Soils are deep, weathered, sandy-loams overlain by an organic forest floor horizon. Common soil depths range from 85–115 cm. Slopes across Blodgett Forest average less than 30%.

Climate at Blodgett Forest is Mediterranean with a summer drought period that extends into the fall. Winter and spring receive the majority of precipitation which averages 160 cm (Stephens and Collins, 2004). Average temperatures in January range between 0 °C and 8 °C. Summer months are mild with average August temperatures between 10 °C and 29 °C, with infrequent summer precipitation from thunderstorms (averaging 4 cm over the summer months from 1960 to 2000) (Stephens and Collins, 2004).

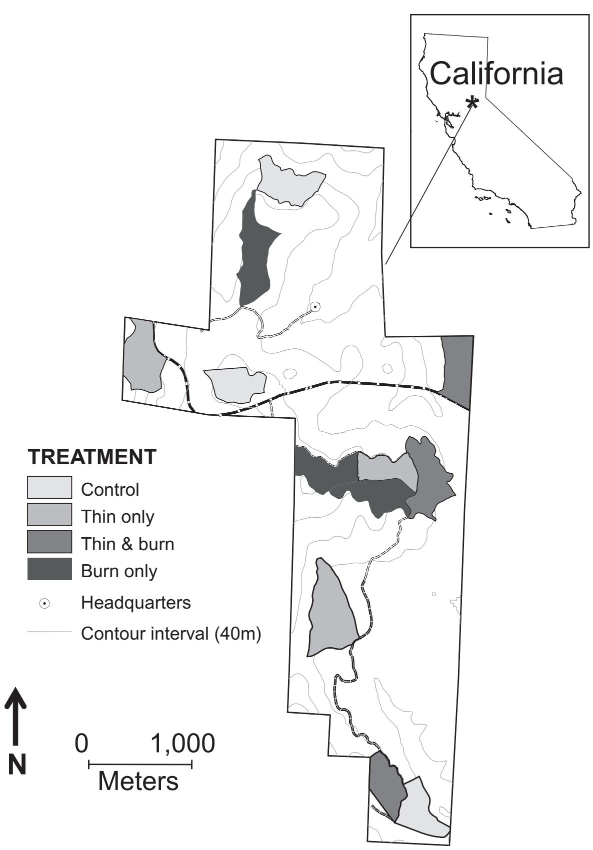

Fig. 1. Experimental units (three replicates per treatment type) within Blodgett Forest, California, USA.

Fire was a common ecosystem process in the mixed conifer forests of Blodgett Forest before the policy of fire suppression began early in the 20th century. Between 1750 and 1900, median composite fire intervals at the 9–15 ha spatial scale were 4.7 years with a fire interval range of 4–28 years (Stephens and Collins, 2004). Forested areas at Blodgett Forest have been repeatedly harvested and subjected to fire suppression for the last 100 years reflecting a management history common to many forests in California and elsewhere in the Western US (Graham et al., 2004).

2.1.1. Fuel treatments

The primary objective of the treatments was to modify stand structure such that 80% of the dominant and co-dominant trees in the post-treatment stand would survive a wildfire modeled under 80th percentile weather conditions (McIver et al., 2009). The secondary objective was to create a stand structure that maintained or restored several forest attributes and processes including, but not limited to, snag and coarse woody debris recruitment, floral and faunal species diversity, nutrient cycling, and seedling establishment. To meet these objectives, three different treatments: mechanical only, mechanical plus fire, and prescribed fire only, as well as untreated control, were each randomly applied (complete randomized design) to 3 of 12 experimental units that varied in size from 14 to 29 ha. Total area for the 12 experimental units was 225 hectares. To reduce edge effects from adjoining areas, data collection was restricted to a 10 ha core area in the center of each experimental unit (Stephens and Moghaddas, 2005a).

Control units received no treatment during the study period (2000–2012). Mechanical only treatment units had a two-stage prescription; in 2001 stands were crown thinned followed by thinning from below to maximize crown spacing while retaining 28–34 m^2 ha^{-1} of basal area with the goal to produce an even species mix of residual conifers (Stephens and Moghaddas, 2005a). Individual trees were cut using a chainsaw and removed with either a rubber tired or track laying skidder. During harvests, some hardwoods, primarily California black oak, were coppiced to facilitate their regeneration. All residual trees were well spaced with little overlap of live crowns in dominant and co-dominant trees. Following the harvest, approximately 90% of understory conifers and hardwoods up to 25 cm diameter at breast height (DBH) were masticated in place using an excavator mounted rotary masticator. Mastication shreds and chips standing small diameter live and dead trees in place and this material was not removed from the experimental units. The remaining un-masticated understory trees were left in scattered clumps of 0.04–0.20 ha in size.

Mechanical plus fire experimental units underwent the same treatment as mechanical only units, but in addition, they were prescribed burned using a backing fire. Fire only units were burned with no pre-treatment using strip head-fires. All initial prescribed burning was conducted during a short period (10/23/2002 to 11/6/2002; the fire only units were burned a 2nd time in fall 2009 but this study will not include the results of these fires) with the majority of burning being done at night because relative humidity, temperature, wind speed, and fuel moistures were within predetermined levels to produce the desired fire effects (Kobziar et al., 2007). Prescribed fire prescription parameters for temperature, relative humidity, and wind speed were 0–10 °C, >35%, and 0.0–5 km h^{-1}, respectively. Desired ten-hour fuel stick moisture content was 7–10%.

2.1.2. Vegetation measurements

Overstory and understory vegetation was measured in twenty 0.04 ha circular plots, installed in each of the 12 experimental units

(240 plots total) in 2001 (PRE), 2003 (POST-1YR), and 2009 (POST-7YR). Individual plots were placed on a systematic 60 m grid with a random starting point. Plot centers were permanently marked with a pipe and by tagging witness trees to facilitate plot relocation after treatments. Tree species, DBH, total height, height to live crown base, and crown position (dominant, co-dominant, intermediate, and suppressed) were recorded for all trees greater than 15 cm DBH. Canopy cover was measured using a 25 point grid in each 0.04 ha plot with a site tube.

2.1.3. Fuel measurements

Surface and ground fuels were sampled with two random azimuth transects at each of the 240 plots using the line-intercept method (Brown, 1974) on the same schedule as the vegetation measurements. A total of 480 fuel transects were installed and the same azimuths were used here as done in the original measurements in 2001 and 2003 (Stephens and Moghaddas, 2005a). One-hour (0–0.64 cm) and 10-h (0.64–2.54 cm) fuels were sampled from 0 to 2 m, 100 h (2.54–7.62 cm) fuels from 0 to 3 m, and 1000 h (>7.62 cm) and larger fuels from 0 to 11.3 m on each transect. Duff and litter depth in cm were measured at 0.3 and 0.9 m on each transect (same points as done previously). Surface and ground fuel loads were calculated using appropriate equations developed for California forests (van Wagtendonk et al., 1996, 1998). Coefficients required to calculate all surface and ground fuel loads were arithmetically weighted by plot basal area fraction to produce accurate and precise estimates of ground and surface fuel loads (Stephens and Moghaddas, 2005a).

2.2. Fire modeling

We modeled potential fire behavior for each inventory plot, at each time step, with the Fire and Fuels Extension (FFE) to the Forest Vegetation Simulator (Reinhardt and Crookston, 2003). FFE uses established equations to predict fire behavior and crown fire potential based on user-input tree lists and fire weather (Reinhardt, 2003; Rebain, 2010). We used the conditions during large spread events in two nearby wildfires (2001 Star Fire, 2008 American River Complex) for the weather inputs (Table 1). By using actual conditions from nearby wildfires that posed substantial fire control problems we believe predicted fire behavior may better characterize wildfire potential as opposed to using conditions based on fire-weather percentile thresholds.

We used surface fuel models for different treatment/time period combinations (Table 2). These fuel model assignments were based on both measured plot fuel loads for each treatment/time period and observed fuelbed characteristics in the field. We opted to use the standard 13 Anderson (1982) surface fuel models to maintain consistency with previous analyses for the same study area (Stephens and Moghaddas, 2005a,b) and regionally within the FFS network (Stephens et al., 2009). We modeled fire behavior and crown fire potential for each plot/time period combination ($n = 702$). Note that a total of six plots were removed from the analysis because we did not have complete records at each time step.

Table 1
Weather parameters used in fire modeling in mixed conifer forests at Blodgett Forest.

Weather parameter	Value
Wind speed (km h^{-1})	32
Fuel moisture (%)	
1 h	3
10 h	4
100 h	5
Live herbaceous	70
Live woody	70

Table 2
Plot fuel model assignments based on treatment type and time period. Assignments were based on both measured plot fuel loads and observed fuelbed characteristics in the field.

Time period	Anderson (1982) fuel model by treatment			
	Control	Burn only	Thin only	Thin and burn
PRE	10	10	10	10
POST-1YR	10	8	12	8
POST-7YR	10	9	11	9

Our analysis focused on two fire behavior outputs from FFE: total flame length and torching probability (*P*-torch). The calculation of *P*-torch first involves randomly populating 0.01 ha sub-plots from the stand tree list using a Monte Carlo simulation. For each sub-plot FFE computes the surface fire flame length that would be required to cause torching. Next the program computes the height above the ground that the predicted surface fire can ignite crowns based on discussion in Scott and Reinhardt (2001, p. 13). The torching probability is based on whether this predicted height exceeds the flame length needed to ignite tree crowns. Rebain (2010) explains that torching probability is the proportion of stand area where crowns of larger trees can be ignited by surface fire or flames from burning crowns of small trees. Rebain (2010) argues that this index may better characterize hazard due to torching compared to the conventionally used torching index (see Scott and Reinhardt, 2001), due to the lack of dependence on the problematic calculation of canopy base height. We also report canopy base height and canopy bulk density for each treatment/time period combination, which was derived from FFE.

2.3. Data analysis

Based on the plot-level tree measurements we calculated live tree basal area, live tree density, and species composition (based on live tree basal area proportion). We used these calculated metrics along with plot-level estimates of canopy cover, fuel loads in four classes: duff, litter, fine woody (1–100 h time lag classes), and coarse woody (1000 h time lag class), FFE-derived canopy base height, FFE-derived canopy bulk density, predicted flame length, and torching probability to test for differences among time periods (PRE, POST-1YR, and POST-7YR) and among treatments (control, fire only, mechanical only, and mechanical plus fire) with a repeated measures analysis (Proc Mixed – SAS, 2009). We examined diagnostic plots of the residuals to check compliance with normality and homogeneity of variance assumptions for all variables. Several variables were log + 1 transformed and some were arcsine square-root transformed to meet assumptions. We used an autoregressive covariance structure for all variables. Differences among time periods and treatments were inferred from Tukey–Kramer adjusted *P*-values, with $\alpha = 0.05$. Pairwise comparisons among treatments and time periods were only investigated when either the time period or treatment fixed effect was significant and the time period-treatment interaction was significant.

3. Results

Tree density was similar in the control across time periods (PRE, POST-1YR, POST-7YR), while both live basal area and canopy cover increased significantly POST-7YR relative to the PRE and POST-1YR (Fig. 2). Both mechanical treatments significantly reduced tree density and basal area POST-1YR, relative to PRE levels and POST-1YR control. By POST-7YR tree densities were unchanged in both mechanical

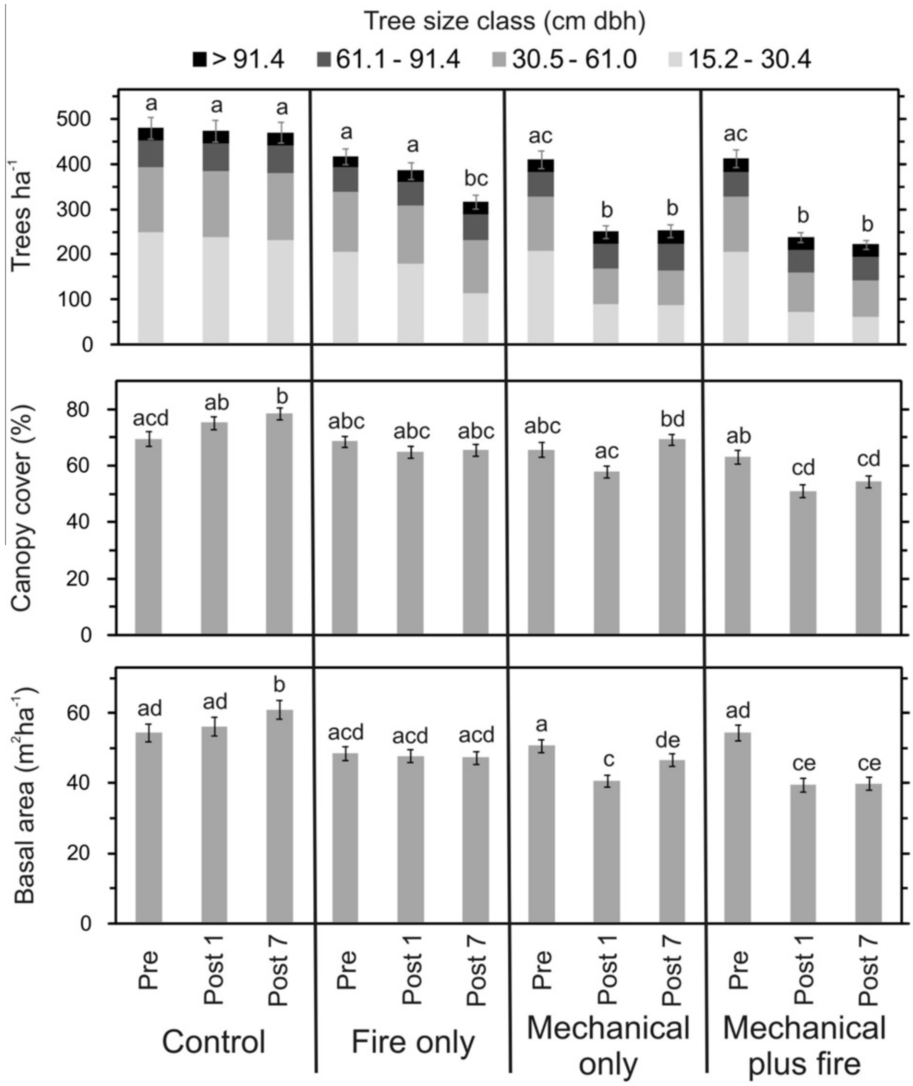

Fig. 2. Average forest structure attributes by time period and treatment type. These attributes were constructed using only live trees ⩾ 15 cm diameter at breast height (dbh). Error bars represent the standard error for each mean. Letters above bars indicate significantly different time period/treatment estimates based on pairwise comparisons ($n = 66$) using Tukey–Kramer adjusted P-values. Comparisons indicated for tree density are for aggregated tree density (all trees > 15 cm dbh).

treatments, relative to post-1yr, while basal area and canopy cover increased significantly in the mechanical only, relative to post-1yr (Fig. 2). Despite this increase, basal area in the mechanical only post-7yr was significantly lower than that in both the mechanical only pre and the control post-7yr. Canopy cover and basal area in the mechanical plus fire treatment was unchanged post-7yr relative to post-1yr, and was significantly below that for the control post-7yr (Fig. 2).Tree density did not change initially in the fire only treatment, but did decline significantly by post-7yr, relative to post-1yr and pre levels, as well as all three time periods for the control. Basal area and canopy cover in the fire only treatment did not change significantly over time (Fig. 2).

Species composition was generally stable across time periods and treatments, with a few exceptions. Both mechanical treatments in post-1yr and post-7yr had a significantly lower proportion of incense-cedar, relative to pre levels (Fig. 3, significance not reported). Pine proportion in both mechanical treatments post-7yr was significantly greater than pre levels. In the mechanical plus fire treatment, pine proportion post-7yr was significantly higher than all other treatments post-7yr, while both hardwood and white fir proportion post-7yr was significantly lower than pre mechanical plus fire only (Fig. 3).

Duff, litter, fine woody, and coarse woody fuel loads were significantly reduced in both burning treatments post-1yr, relative to pre levels, as well as post-1yr for the control (Fig. 4). These reductions relative to pre levels held post-7yr in all fuel classes, but were not statistically different from post-7yr control for all fuel classes except duff (Fig. 4). Litter loads increased post-7yr in both burning treatments relative to post-1yr for the same treatments, and were not different from the other treatments post-7yr (Fig. 4). Litter and duff loads in the mechanical only treatment were stable over time and statistically indistinguishable from the control at all time periods (Fig. 4). Fine woody fuel loads in the mechanical only treatment increased significantly from pre to post-1yr, and then decreased significantly from post-1yr to post-7yr (Fig. 4). The only statistically significant difference in fine woody fuel loads among treatments post-7yr is between the mechanical only (higher) and the mechanical plus fire (lower) treatments (Fig. 4). Coarse woody fuel loads in the mechanical only treatment did not change pre to post-1yr, but decreased significantly from post-1yr to post-7yr (Fig. 4). There were no differences in coarse woody fuel loads among treatments post-7yr.

Canopy base height was stable in the control and fire only treatments from pre to post-1yr, but decreased for the control and

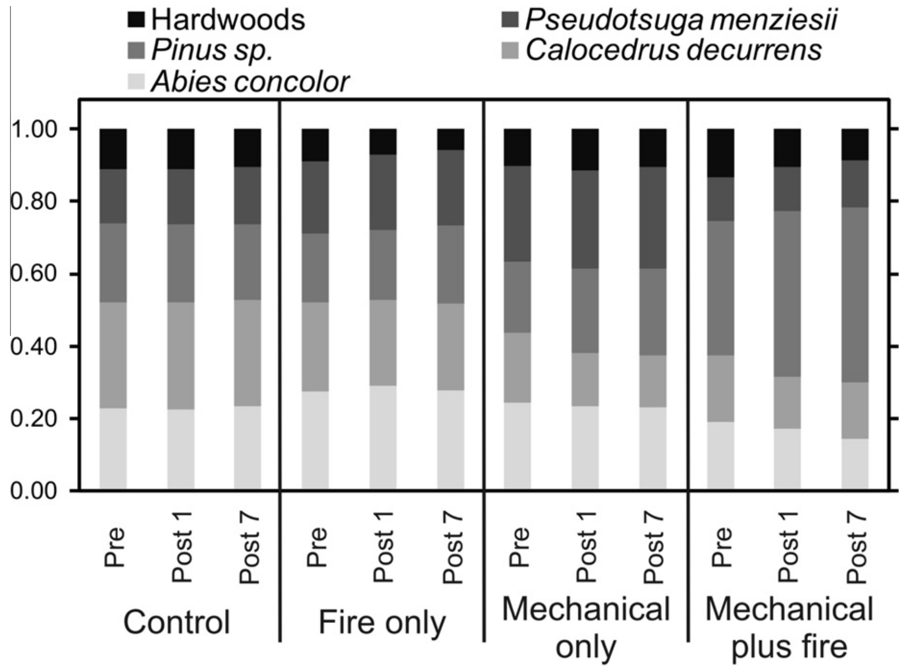

Fig. 3. Average tree species composition, based on live basal area proportion, by time period and treatment type, at Blodgett Forest.

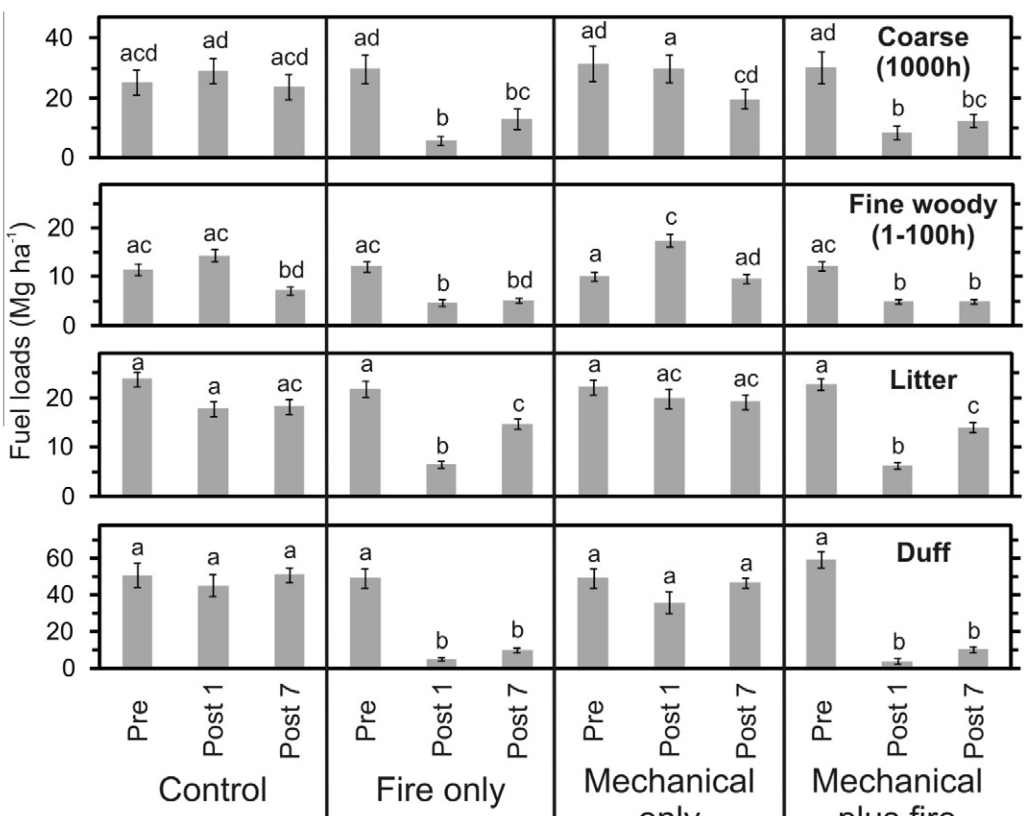

Fig. 4. Average fuel loads by time period and treatment type. Error bars represent the standard error for each mean. Letters above bars indicate significantly different time period/treatment estimates based on pairwise comparisons (n = 66) using Tukey–Kramer adjusted P-values.

increased in the fire only from POST-1YR to POST-7YR (Fig. 5). Canopy bulk density was stable across all three time periods in the control, and from PRE to POST-1YR for the fire only. By POST-7YR in the fire only treatment, canopy bulk density decreased significantly relative to PRE and POST-1YR (Fig. 5). Canopy base height increased significantly and canopy bulk density decreased significantly from PRE to POST-1YR for both mechanical treatments. These relationships held POST-7YR, relative to PRE, with the exception of canopy base height for mechanical only, which decreased significantly and was not statistically different from the PRE level (Fig. 5). Predicted flame length

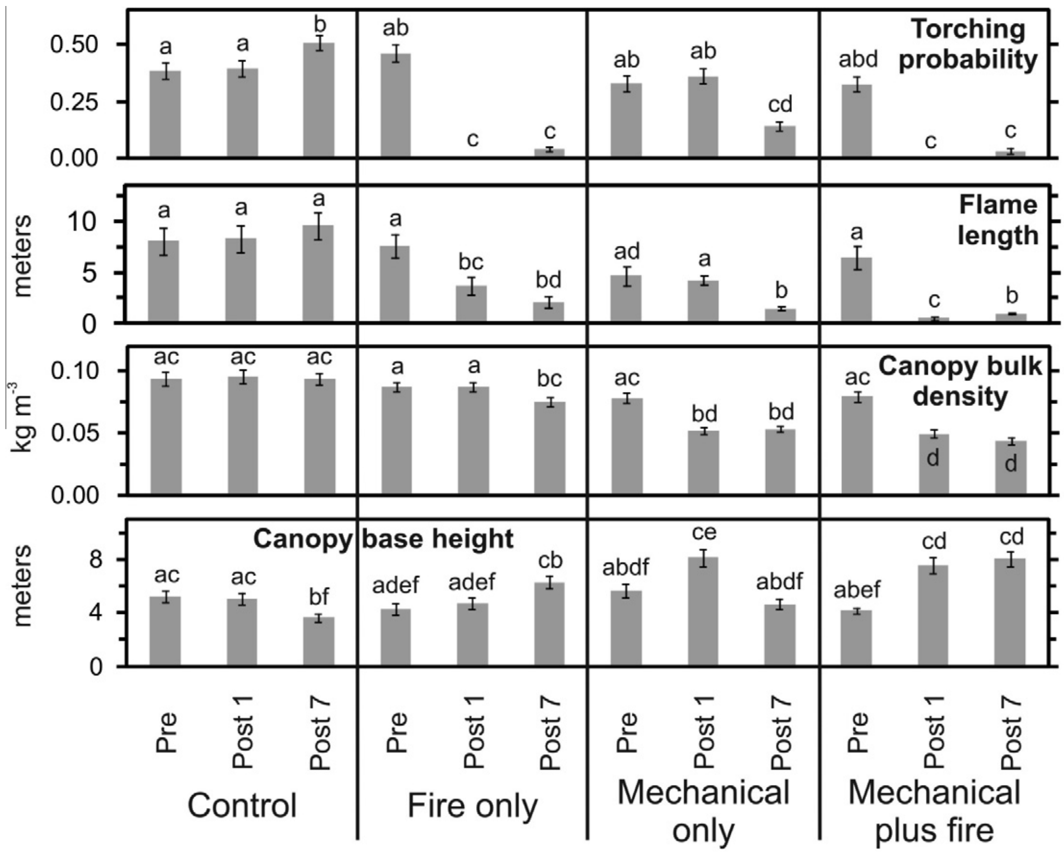

Fig. 5. Average canopy structure and predicted fire behavior by time period and treatment type. These values were derived from the Fire and Fuels Extension to the Forest Vegetation Simulator (Rebain, 2010). Error bars represent the standard error for each mean. Letters above bars indicate significantly different time period/treatment estimates based on pairwise comparisons ($n = 66$) using Tukey–Kramer adjusted P-values.

and torching probability was significantly lower in the two burning treatments POST-1YR and POST-7YR relative to PRE levels and to the control at all time periods (Fig. 5). In the mechanical only treatment, predicted flame length and torching probability was unchanged from PRE to POST-1YR, but by POST-7YR both decreased significantly, and were statistically indistinguishable from POST-7YR in the two burning treatments (Fig. 5). Predicted flame length was stable in the control across all time periods, but torching probability increased significantly POST-7YR, relative to both PRE and POST-1YR (Fig. 5).

4. Discussion

Many aspects of the 2002 fuel treatments in our Sierra Nevada mixed conifer forests have changed in 7 years, both when compared to control conditions and to immediate post-treatment conditions. Fire hazard initially following the mechanical only treatment was unchanged due to the interaction between increased fine woody fuels as a result of activity fuel inputs from thinning and mastication and the overall reduction in canopy fuels (increased canopy base height and decreased canopy bulk density) (Figs. 4 and 5). Seven years after treatment fine fuel loads in these stands have decreased, likely due to decomposition, while canopy bulk density has remained the same, and canopy base height has decreased to what it was before treatment. The net effect is that fire hazard (indicated by predicted flame length and torching probability) noticeably decreased POST-7YR and is similar to the two fire treatments (Fig. 5) which was surprising. The increased time after initial treatment has been very favorable to the mechanical only treatments at Blodgett Forest from a fire hazard standpoint.

Both fire treatments appear to have limited stand-level growth. The lack of change in canopy cover and basal area in the fire treatments seven years after initial treatment is in strong contrast to the mechanical only and control stands, which grew significantly over the same period (Fig. 2). Apparently the backing fires in the mechanical plus fire treatment and the strip-head fires in the fire only treatment used to reduce surface and ladder fuels caused residual damage to many remaining trees, limiting the ability of these trees to grow and take advantage of the reductions in stand density, particularly in the mechanical plus fire treatment. This damage can be seen today with large fire scars on the lower boles of many trees. The similarity between the two fire treatments in limiting stand-level growth despite the different applications of fire, and resulting fire intensity, are likely due to the additional fuel inputs from the thinning and mastication operations in the mechanical plus fire treatment. We hypothesize that these additional fuel inputs increased fire residence time, which resulted in similar overall damage to the higher intensity fire in the fire only treatment (Kobziar et al., 2007). How long tree growth will continue to remain relatively stagnant is a question for future research. As an interesting anecdote regarding tree damage in the mechanical plus fire treatment, forest operators working to remove recent snags within fall distance to roads for safety reasons reported difficulty in felling due to unnoticed rotten wood under the bark (K. Sunmmers, personal comm., 2011).

The fire only treatment did not result in changes in tree density initially, but after 7 years, tree density significantly declined and was similar to both treatments that included mechanical methods (Fig. 2). This change in tree density was primarily driven by a decrease in the smallest tree size class (Fig. 2), and is indicative of delayed secondary mortality after fire. This longer-term response apparently did not affect larger trees (>30.4 cm dbh) enough to result in significant mortality. The lack of change in canopy cover and tree basal area over time provides evidence that although our strip-headfires, with flame lengths of approximately 1 m (Kobziar et al., 2007), may have affected growth, the fires did not kill many overstory trees. Other studies have determined high resistance to prescribed fire mortality of larger mixed conifer trees in the Sierra Nevada (Miller and Urban, 2000; Stephens and Finney, 2002). As tree size increases it becomes more and more difficult to kill them with a fire only treatment since most prescribed fires are designed to be of low-moderate intensity.

Coarse wood remains at relatively low levels in the fire only and mechanical plus fire treatments because of initial high consumption of these fuels (Stephens and Moghaddas, 2005c). The fire only treatments did result in a significant decrease in crown bulk density and an increase in canopy base height after 7 years (Fig. 5), coupling this with very low levels of fine woody fuels results in continued very low torching probabilities. It is clear that both treatments that included prescribed fire continue to produce stands that are very resistant to high severity fires. Use of prescribed fire also has the distinct advantage of incorporating the most fundamental ecosystem process back into these forests which has been shaping them for millennia (Swetnam, 1993).

Tree species composition remained similar over the course of the study with a few exceptions. The mechanical plus fire and mechanical only treatments resulted in a significantly higher proportion of pine (ponderosa and sugar pine) 7-years post-treatment (Fig. 3) which follows our marking prescription that emphasized leaving more pines and removing more of the shade tolerant species. The mechanical plus fire treatment also had the lowest proportion of white fir and California black oak 7-years after treatment. Reduction of California black oak is likely a result of high heat loads to tree boles from flaming and smoldering combustion that top-killed many oaks; some of these top-killed trees resprouted but this was not universal. Both treatments that included mechanical methods resulted in a significantly lower proportion of incense-cedar. This is partially explained because this species has the highest lumber value in the Sierra Nevada and these treatments did produce positive revenues (Hartsough et al., 2008).

Control plots continued to grow with basal area and canopy cover significantly increasing over the 7-year period (Fig. 2). In addition to these changes, canopy base height decreased but crown bulk density was unchanged. All of these changes were somewhat expected as Blodgett Forest has productive soils with moderately high precipitation (Moghaddas and Stephens, 2007). A bit more surprising is the significant reduction in fine fuels POST-7YR in the control units from both the PRE and POST-1YR levels (Fig. 4). Reduction in woody understory fuels in the control units must have been from decomposition since no other treatments were applied. The history of all 12 experimental units used in this experiment at Blodgett Forest may assist in an explanation for this reduction. All of the experimental units were commercially thinned from below 5–10 years before the initiation of this study in 2000. The past harvests left all activity fuels on site, a common practice in the Sierra Nevada and elsewhere in the western US (Graham et al., 2004). We believe those activity fuels likely reached a decomposition state that moved them from the fine woody category into the duff layer (duff load did increase POST-7YR versus POST-1YR but not significantly). Despite this reduction in fine woody fuels, the overall hazard of the control units increased significantly POST-7YR from both PRE and POST-1YR levels (Fig. 5) indicating that continued passive management (Agee, 2003) has further increased the already high fire hazards in these forests.

The duff, litter, and fine fuel loads were similar in the fire only and mechanical plus fire treatment across the whole study period (Fig. 4). This is probably explained with surface and ground fuel loads that were initially high (approximately 120 t/ha), relatively homogeneous with few discontinuities, and low fuel moisture contents during burning (Stephens and Moghaddas, 2005a). Managers that desire to retain more of the surface or ground fuels for wildlife habitat could explore the use of spring prescribed fires (Knapp et al., 2005; Stephens et al., 2012).

Our findings indicating reduced fire hazard over time in the mechanical only treatment might provide an opportunity for a staggered treatment schedule. Initial mechanical treatments did not reduce the torching probability (this work) but did increase the probability that larger trees would survive wildfire (Stephens and Moghaddas, 2005a). This study determined that decomposition was sufficient to significantly reduce fine woody fuel loads to a point where fire hazards were low 7-years post-treatment. Canopy base height has declined to a value similar to the PRE condition, whereas it was significantly increased POST-1YR. Implementing a prescribed fire in the next 2–4 years would reduce fine woody and litter fuels, increase canopy base height (remove tree saplings and shrubs), and would result in a forest condition that would be very resistant to wildfire. It could effectively double the longevity of the overall treatment plus re-introduce the most fundamental ecosystem process into these forests. Timing the prescribed fire approximately 10-years post-treatment would also be a benefit to prescribed fire operations because most of the dead leaves and small woody fuels would be either decomposed or compressed from snow resulting in a less intense prescribed fire. A prescribed fire in these conditions could also be ignited over a wider range of weather conditions which would be an advantage for fire managers. Burning 10-years post-treatment may create an effective fuel treatment for up to 20 years in these forests, but further research would need to be done to verify this estimate.

Under certain initial stand conditions first-entry prescribed fire treatments can lead to elevated surface fuels as small fire-killed trees fall to the ground; these conditions likely necessitate reburning to maintain treatment effectiveness. Another response that can limit treatment longevity following first-entry prescribed fire is shrub regeneration from soil-stored seed. However, under higher fuel moisture conditions shrubs could act as a heat sink during burning and lower fire intensity and this has been observed during some wildfires (e.g., Ritchie et al., 2007).

Anecdotal observations from mixed conifer forests at Blodgett suggest treatment effectiveness from the initial fire only treatment may have begun to diminish at approximately 10 years post-treatment. Re-burning these stands will likely increase this effectiveness interval by an additional 15–20 years from the consumption of residual downed wood from the death of many small trees. Mechanical followed by fire treatments at Blodgett have a longer effectiveness interval initially (possibly 15–20 years) because of low post-prescribed fire tree mortality and high initial surface fuel consumption. Shrub responses after mechanical plus fire or fire only treatments may necessitate the application of a patchy, low intensity prescribed fire to break up the horizontal continuity of shrub fuels but this will probably not be required in most areas. After installing initial fire hazard reduction treatments moving these areas into a wildfire management regime where lightning fires are used to manage these ecosystems may be desirable from both an economic and ecological perspective (North et al., 2012).

5. Conclusion

Results from this study on the mid-term effects of fuels treatments agree with some aspects of previous research but the changes recorded here are larger than those found in most Rocky Mountain studies. Fulé et al. (2007) working in ponderosa pine-Gambel oak (*Quercus gambelii*) forests in the southwest US found changes in forest structure were relatively minor 5-years after treatment. They found that prescribed fire was an effective treatment in reducing tree density but the combined full restoration treatment (including thinning and prescribed fire) was the most effective in promoting pre 1890 conditions. Severe drought during their study period made causation of tree mortality difficult to identify, but trees in treated stands significantly increased in growth rate except those in the burn only treatment. Similarly, Sackett and Haase (1998), also working in the southwest ponderosa pine forests, found repeated prescribed fires reduced tree density, lowered surface and ground fuels, and increased tree growth, especially in stands treated every 4–6 years with prescribed fire.

Working in ponderosa pine forests in the Northern Rocky Mountains, Fajardo et al. (2007) found delayed mortality in ponderosa pine after their mechanical plus fire treatment. They concluded 'Special consideration needs to be taken on the cut–burn treatments (relative to cut-only), which appeared to dampen response in terms of growth and vigor, particularly for mature and young trees.' Blodgett Forest does not contain a large number of old-growth trees because of the history of early railroad logging in this area (Stephens and Collins, 2004), but we did also see a reduced growth response from our prescribed fire treatments. Perhaps increasing the interval between the mechanical treatment and prescribed fire would have resulted in lower residual tree damage due to both decomposition of the augmented surface fuel pool and potential increases in tree vigor from reduced competition. Additionally, increasing the interval between mechanical treatment and prescribed burning could result in a longer period for which treated areas have low fire hazards.

While this research investigated the mid-term responses to some of the most common fuel treatments in mixed conifer forests in the Sierra Nevada, continued research is needed to quantify the effects of repeated treatments on the same area. Once areas are treated to reduce fire hazards, managed wildfire (Collins and Stephens, 2007; Collins et al., 2009; North et al., 2012) would also be a good option to maintain low fuel hazards and improve ecosystem resiliency, which may be even more important as climate continues to warm (Stephens et al., 2010). The changes we found in Sierra Nevada mixed conifer forests after fuel treatments were generally larger than those reported from the Rocky Mountains, this is probably explained by the higher productivity of the forests in the Sierra Nevada, which would enable change to occur more rapidly.

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