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Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest

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Abstract

Fuel treatments have been suggested as a means to limit the size and intensity of wildfires but few experiments are available to analyze the effectiveness of different treatments. This paper presents information from a replicated, stand level experiment from mixed conifer forests in the north-central Sierra Nevada that investigated how control, mechanical (crown thinning, thinning from below followed, rotary mastication), prescribed fire, and mechanical followed by prescribed fire treatments affected fuels, forest structure, potential fire behavior, and modeled tree mortality at 80th, 90th, and 97.5th percentile fire weather conditions. Fuels Management Analyst was used to model fire behavior and tree mortality. Thinning and mastication each reduced crown bulk density by approximately 19% in mechanical only and mechanical plus fire treatments. Prescribed burning significantly reduced the total combined fuel load of litter, duff, 1, 10, 100, and 1000 h fuels by as much as 90%. This reduction significantly altered modeled fire behavior in both mechanical plus fire and fire only treatments in terms of fireline intensity and predicted mortality. The prescribed fire only and mechanical followed by prescribed fire treatments resulted in the lowest average fireline intensities, rate of spread, and predicted mortality. The control treatment resulted in the most severe modeled fire behavior and tree mortality. Mechanical only treatments were an improvement over controls but still resulted in tree mortality at severe fire weather when compared with the treatments that included prescribed fire. Restoration of mixed conifer ecosystems must include an examination of how proposed treatments affect fire behavior and effects. Variation in existing stand structures will require solutions that are site specific but the principals outlined in this work should help managers make better decisions.

Keywords: Fire hazard; Fire surrogates; Forest restoration; Fuels management; Sierra Nevada

1. Introduction

Forest structure, fuel characteristics, and fire regimes of mixed conifer forests in the Western United States (US) have been dramatically altered

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since the early 20th century (Kilgore and Taylor, 1979; Biswell, 1989; Skinner and Chang, 1996; Graham et al., 2004; Stephens and Collins, 2004). Changes in fire regimes and possibly climate (Millar and Woolfenden, 1999) during the last 90–100 years have increased stand densities of shade tolerant species such as white fir (*Abies concolor* [Gord. and Glend.] Lindl.) and incense cedar (*Calocedrus decurrens* [Torr.] Floren.) in most mixed conifer forests in the Sierra Nevada (Parsons and DeBendeetti, 1979; Ansley and Battles, 1998; North et al., 2002; Taylor and Skinner, 2003). Other causes of forest change in the last century include past harvesting practices, livestock grazing, and planting trees at high densities after wildfires or clear-cutting (Franklin and Agee, 2003; Romme et al., 2003).

The practice of using prescribed burning to modify potential wildfire behavior was in use at least 90 years ago in the Western US (Clar, 1959; Biswell, 1989). This early management practice utilized ‘‘light burning’’ in the forests of the northern Sierra Nevada and southern Cascades Mountains of California. Most federal managers and scientists at this time were not supportive of light burning because of the potential for fire escapes and the creation of basal tree injuries that might allow heart-rot fungi to enter (Boyce, 1921). Many also believed that western forests were understocked and that the elimination of fire would eventually allow higher yields of wood products (Show and Kotok, 1924).

Currently over 10 million ha of coniferous forests in the Western US are in moderate or high fire hazard condition classes (NWCG, 2001). Several recent fire policies and initiatives such as the National Fire Plan (USDA–USDI, 2000), 10-year comprehensive strategy (WGA, 2001), and Healthy Forest Restoration Act (HFRA, 2003) have been enacted to address the national US wildfire management problem. All of the recent statutes emphasize forest thinning as the integral tool for reducing high fire hazards in Western US forests.

The current debate over the appropriateness, technique, and timing of treatments utilized to modify or restore vegetation structure, fuel loads, and fire behavior is currently on-going at local, state, and national levels (USDA, 2004; Stephens and Ruth, 2005). Though there have been qualitative and comparative studies on the effectiveness of various fuel treatments, controlled empirical studies using modern fuel reduction techniques are rare (van Wagtendonk, 1996; Omi et al., 1998; Stephens, 1998; Fule et al., 2001; Pollet and Omi, 2002; Graham et al., 2004; Stephens and Moghaddas, 2005a). Researchers have modeled the impacts of different fuel treatments on potential fire behavior in mixed conifer forests (van Wagtendonk, 1996; Stephens, 1998; Miller and Urban, 2000) but these analyzes are constrained by model assumptions and uncertainties.

The National Fire and Fire Surrogate Study (FFS) has implemented a series of controlled empirical experiments to study the effects of fuel treatments on vegetation structure, fuel loads, and a suite of other ecological variables at 13 locations across the continental US (Weatherspoon and McIver, 2000). In this paper, we report results from the Blodgett Forest FFS study site in the north-central Sierra Nevada. These results reach beyond the discipline of fire behavior and will help form a basis of how common fuel hazard reduction treatments affect forest structure.

The objective of this study is to determine how four different fuel treatments affect fuel loads, vegetation structure, and potential fire behavior and effects. The four treatments include: (1) control (no treatment), (2) thinning (crown thinning and thinning from below) followed by rotary mastication, (3) prescribed fire, and (4) a combination of thinning (crown thinning and thinning from below), rotary mastication, and prescribed fire. We tested for treatment effects at four different treatment stages: (1) pretreatment, (2) post-harvest, (3) post-mastication, and (4) post-treatment. The null hypothesis is that there will be no significant difference ($p < 0.05$) in vegetation structure, fuel load, fire behavior, and predicted mortality between treatment types and treatment stages.

2. Methods

2.1. Study location

The study was undertaken in Sierra Nevada mixed conifer forests in the north-central Sierra Nevada at the University of California Blodgett Forest Research Station (Blodgett Forest), approximately 20 km east of Georgetown, California. Blodgett Forest is located 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. Tree species in this area include sugar pine (*Pinus lambertiana* Dougl.), ponderosa pine (*Pinus ponderosa* Laws), white fir, incense-cedar, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), California black oak (*Quercus kelloggii* Newb.), tan oak (*Lithocarpus densiflorus* (Hook. & Arn.) Rehder), bush chinkapin (*Chrysolepis sempervirens* (Kell.) Hjelmg.), and Pacific madrone (*Arbutus menziezii* Pursh). Mixed conifer forests cover 3.2 million ha (7.8%) of California's total land base (CDF, 2003).

Soils at Blodgett Forest are well-developed, well-drained Haploxeralfs (Alfisols), derived from either andesitic mudflow or granitic/granodiorite parent materials (Hart et al., 1992). 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 to 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 and 8 °C. Summer months are mild with average August temperatures between 10 and 29 °C, with infrequent summer precipitation from thunderstorms (averaging 4 cm over the summer months from 1960 to 2000) (Stephens and Collins, 2004).

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 90 years reflecting a management history common to many forests in California (Laudenslayer and Darr, 1990; Stephens, 2000) and elsewhere in the Western US (Graham et al., 2004).

2.2. 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 (Weatherspoon and Skinner, 2002). 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, and seedling establishment. To meet these objectives, four different treatments including no treatment (control), mechanical only, mechanical plus fire, and prescribed fire only 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 ha. To reduce edge effects from adjoining areas, data collection was restricted to a 10 ha core area in the center of each treatment unit.

Control units received no treatment during the study period (2000–2005). 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 with the goal to produce an even species mix of residual conifers. Individual trees were cut using a chainsaw and removed with either a rubber tired or track laying skidder. During harvests, hardwoods, primarily California black oak, were coppiced to facilitate their regeneration (McDonald and Tappeiner, 1996). 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 between 2 and 25 cm diameter at breast height (DBH) were masticated in place using an excavator mounted rotary masticator. Mastication shreds and chips standing small diameter (2–25 cm DBH in this case) live and dead trees in place. Masticated material was not removed from the experimental units. The remaining unmasticated 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 (Martin and Dell, 1978). Fire only units were burned with no pretreatment using strip head-fires (Martin and Dell, 1978), one of the most common ignition patterns used to burn forests in the Western US. All prescribed burning was conducted during a short period (23 October 2002–6 November 2002) with the majority of burning being done at night because relative humidity, temperature, wind speed, and fuel moistures were within pre-determined levels to produce the desired fire effects (Knapp et al., 2004). Prescribed fire prescription parameters for temperature, relative humidity, and wind speed were 0–10 °C, >35%, and 0.0–7 km h^{-1}, respectively. Desired 10-h fuel stick moisture content was 7–10%.

2.3. Vegetation measurements

Vegetation was measured using 25 0.04 ha circular plots installed in each treatment unit (300 total plots). Individual plots were placed on a systematic 60 m grid with a random starting point. Plot centers were permanently marked with a pipe and three witness trees were tagged to facilitate plot relocation after treatments. Tree species, DBH, total height, height to live crown base, and crown position (dominant, co-dominant, intermediate, suppressed) were recorded for all trees greater than 10 cm DBH. Similar information was also recorded for all trees greater than 1.37 m tall on a 0.004 ha nested subplot in each of the 25 plots. Canopy cover was measured at 25 points on each 0.04 ha plot using a 5 m × 5 m grid using a GRS densitometer (Gill et al., 2000).

2.4. Ground and surface fuel characteristics

Surface and ground fuels were sampled with two random azimuth transects at each of the 300 plots using the line-intercept method (van Wagner, 1968; Brown, 1974). A total of 600 fuel transects were installed. 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 0–3 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. Fuel depth (cm) was measured at three points along each transect.

Fuel transects were sampled prior to treatment (2001), after the commercial harvest (for mechanical only and mechanical plus fire units in 2001), after mastication (for mechanical only and mechanical plus fire units in 2002), and 8 months after burning was completed (all treatment units). 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 the basal area fraction to produce accurate and precise estimates of ground and surface fuel loads (Stephens, 2001).

2.5. Fire behavior modeling

Fire behavior was modeled under the upper 80th, 90th, and 97.5th percentile fire weather conditions. Percentile weather was computed using Fire Family Plus (Main et al., 1990). Forty-one years (1961–2002) of weather data from the Bald Mountain Remote Access Weather Station (RAWS) (NFAM, 2004), 4 km west of Blodgett Forest, were analyzed with Fire Family Plus to determine percentile weather conditions (Table 1). 80th, 90th, and 97.5th percentile fire weather represent moderate, high, and extreme fire weather, respectively.

Fuels Management Analyst Plus (FMA) was used to model fire behavior, crowning index, torching

Table 1
Upper 80th, 90th, and 97.5th percentile fire weather for Blodgett forest research station, California

Weather parameter	80th percentile conditions	90th percentile conditions	97.5th percentile conditions
Probable maximum 1 min wind speed (NOAA, 2004) (km h^{-1})	22	27	31
Wind direction (of origin)	North to northeast	North to northeast	North to northeast
Dry bulb temperature (°C)	29	32	33
Relative humidity (%)	25	17	15
1 h fuel moisture (%)	3.9	3	1.8
10 h fuel moisture (%)	5.2	3.7	2.3
100 h fuel moisture (%)	7.7	6.6	4.2
Herbaceous fuel moisture (%)	62.1	30	30
Foliar fuel moisture (estimated) (%)	100	80	75

index, scorch height, and tree mortality (Carlton, 2004). Torching and crowning indices are the 6.1 m wind speed required to initiate torching (passive crown fire) or sustain a crown fire (active crown fire) within a stand (Scott and Reinhardt, 2001). Fire behavior predictions were made for stand and fuel structures at each treatment stage (pretreatment, post-harvest, post-mastication, post-treatment).

FMA incorporates established published methodologies for computing crown bulk density, fire behavior, and predicted scorch and mortality by species. FMA uses information from field measurements (tree species, DBH, tree crown ratio, tree crown position, percent canopy cover, surface and ground fuel loads), topography, and fire weather to model fire behavior and effects at the stand scale. Table 2 summarizes methodologies used for these computations.

2.6. Data analysis

Measurements were taken at four different time periods: pretreatment, post-harvest, post-mastication and post-treatment. Normally a single, repeated measures analysis to include all of the data for each dependent variable would be performed to account for potential serial correlation in time because of repeated measurements on the same experimental units. But because the fire only and control experimental units were not measured during the post-harvest and post-mastication measurement times, fitting a single model would be complex and would require more stringent assumptions than for separate analyses using two time periods for each analysis with the treatments measured in those two time periods. Such a process, while not potentially as efficient as a single analysis, requires

Table 2
Methodologies used by Fuels Management Analyst to compute stand, fire behavior, and fire effects characteristics

Variable	Input data	Output	Citation
Canopy bulk density (CBD)	Individual tree measurements taken from 20 0.04 ha plots	Treatment unit average CBD (kg m^{-3}) from allometric equations	Brown (1978) and Snell and Little (1983)
Surface and ground fuel load	Fuel transects	Fuel load (1, 10, 100, 1000 h timelag, herbaceous, duff and litter), fuel depth	Anderson (1982) and Brown (1974)
Percentile fire weather	Archived RAWS weather station data. Fire Family Plus used to compute percentile weather	Probable maximum 1-min wind speed and direction, dry bulb temperature, relative humidity, fuel moisture (1, 10, 100, 1000, foliar, woody, and herbaceous fuel moistures)	Main et al. (1990)
Fire rate of spread (ROS)	Stand characteristics, fuel model, topography, and weather data	ROS (m min^{-1} or ft min^{-1})	Rothermel (1972)
Flame length	Stand characteristics, fuel model, topography, and weather data	Flame length (m or ft)	Rothermel (1991)
Fire line intensity	Stand characteristics, fuel model, topography, and weather data	Fire line intensity (kW/s or BTU/ft/s)	Albini (1976)
Fire type, crown fire initiation, rate of spread, and critical fire line intensity	Stand characteristics, fuel model, topography, and weather data	Surface fire, passive crown fire, active crown fire plume dominated	Alexander (1988) and van Wagner (1977, 1993)
Probability of mortality	Stand characteristics, fuel model, weather data, and fire behavior outputs	Percent probability of mortality on an individual tree basis	Reinhardt et al. (1997)
Torching index	Stand characteristics, fuel model, weather data, and fire behavior outputs	Wind speed required to initiate a torching event	Scott and Reinhardt (2001)
Crowning index	Stand characteristics, fuel model, weather data, and fire behavior outputs	Wind speed required to sustain a crown fire	Scott and Reinhardt (2001)

fewer assumptions (constant variance across all time periods, etc.) For each pair of measurement periods considered an analysis of covariance (ANCOVA) (Zar, 1999) was performed using the measurement at the prior time period as the covariate. Bonferroni multiple pairwise comparisons (Zar, 1999) evaluated at the mean value of the covariate were used to determine if significant differences ($p < 0.05$) existed in vegetation (trees ha^{-1}, basal area ha^{-1}, height to live crown base, canopy cover, crown bulk density), fuels (fuel depth, litter and duff load, 1, 10, 100, 1000 h sound and rotten timelag fuel loads, total fuel load), fire behavior (rate of spread, fire line intensity, flame length, torching index, crowning index), and fire effects (predicted tree mortality) after each treatment stage (Miliken and Johnson, 2002). The Jump Statistical Software package (Sall et al., 2001) was used in all analyses.

3. Results

3.1. Forest structure and fuels

In the pretreatment year, 5414 individual live trees were measured over the 12 experimental units. The 12 experimental units were not significantly different in any vegetation, fire behavior, or modeled fire effects characteristics before implementation of treatments (Table 3). Commercial thinning removed an average of 68.0 m^3 ha^{-1} of sawlogs in forest areas that were treated by mechanical methods (Erik Drews and BruceHartsough, personal communication, 2004) (Table 3).

After all treatments were completed, trees ha^{-1} greater than 2.5 cm DBH were significantly reduced in mechanical only, mechanical plus fire, and fire only treatments (Table 4). Average quadratic mean diameter (QMD) was significantly increased in the mechanical plus fire treatment when compared with the controls (Table 4). Basal area was significantly reduced in mechanical and mechanical plus fire treatments but not in fire only treatment (Table 4). Percent canopy cover was significantly reduced in mechanical only and mechanical plus fire treatments (Table 4). Average post-treatment canopy cover remained above 50% in all treatments.

Height to live crown base (HTCB) increased in both mechanical and mechanical plus fire treatments when compared with the controls (Table 4). The only measured change in species composition after treatments was a relative increase in sugar pine in the mechanical only treatment when compared to the fire only treatment (Table 5).

Table 3
Average pretreatment vegetation structure (standard error) for all trees greater than 2.5 cm DBH at Blodgett forest research station, California

	Control	Mechanical only	Mechanical plus fire	Fire only
Basal area (m^2 ha^{-1})	55.1 (3.1)	51.9 (2.0)	55.1 (1.5)	49.4 (2.2)
Trees (ha^{-1})	1100.9 (67.3)	972.0 (226.2)	823.3 (187.3)	850.1 (16.8)
Average quadratic mean diameter (cm)	25.3 (0.7)	27.3 (3.4)	30.3 (3.2)	27.2 (0.5)
Tree height (m)	15.6 (0.8)	16.7 (1.1)	16.5 (1.2)	15.8 (0.5)
Tree height to crown base (m)	7.6 (0.6)	7.9 (0.6)	7.8 (0.8)	6.8 (0.4)
Percent canopy cover	69 (6.0)	66 (4.0)	63 (5.0)	68 (1.0)

Table 4
Average post-treatment vegetation structure (standard error) for all trees greater than 2.5 cm DBH at Blodgett Forest Research Station, California

	Control	Mechanical only	Mechanical plus fire	Fire only
Basal area (m^2 ha^{-1})	56.4 a (3.0)	40.9 b (0.8)	39.3 b (2.5)	47.8 a (2.5)
Trees (ha^{-1})	1109.5 a (84.2)	428.7 b (139.7)	238.9 b (20.9)	441.5 b (32.1)
Average quadratic mean diameter (cm)	25.5 a (0.3)	37.7 ab (5.7)	46.2 b (3.5)	37.2 ab (0.5)
Tree height (m)	15.6 a (0.7)	22.7 bc (0.9)	20.4 c (0.6)	17.8 ab (0.5)
Tree height to crown base (m)	7.5 a (0.6)	9.5 b (0.5)	9.5 b (0.8)	7.4 ab (0.3)
Percent canopy cover	75 a (5)	58 b (1)	51 b (4)	65 ab (3)

Mean values in a row followed by the same letter are not significantly different ($p < 0.05$).

Table 5
Average pre- and post-treatment percent species by basal area (standard error) at Blodgett Forest Research Station, California

	California black oak	Douglas-fir	Incense-cedar	Ponderosa pine	Sugar pine	White fir	Tanoak, Pacific madrone, bush chinkapin
Pretreatment							
Control	8.4 (2.5)	16.8 (3.6)	27.9 (3.5)	16.6 (8.2)	4.6 (2.6)	23.9 (3.4)	1.9 (1.6)
Mechanical only	9.9 (4.3)	25.2 (4.1)	19.3 (3.7)	5.5 (3.4)	15.1 (7.7)	23.0 (4.9)	2.1 (1.3)
Mechanical plus fire	13.9 (3.5)	11.1 (5.3)	18.4 (4.2)	22.5 (6.4)	15.2 (7.2)	18.9 (3.2)	0.2 (0.1)
Fire only	5.7 (3.0)	19.7 (4.7)	22.8 (4.6)	10.3 (4.2)	10.1 (2.0)	26.4 (3.9)	5.1 (5.0)
Post-treatment							
Control	8.5 (2.6)	16.8 (3.5)	27.8 (3.3)	16.6 (8.1)	4.9 ab (2.7)	23.6 (2.9)	1.9 (1.5)
Mechanical only	11.5 (5.2)	25.7 (3.5)	14.4 (4.2)	6.1 (3.4)	19.3 a (9.4)	21.4 (4.0)	1.6 (1.0)
Mechanical plus fire	11.3 (3.5)	11.5 (4.8)	13.3 (3.2)	28.3 (8.8)	18.2 ab (9.1)	17.2 (3.5)	0.1 (0.1)
Fire only	4.3 (2.2)	21.0 (5.1)	22.0 (5.0)	10.9 (4.5)	10.5 b (2.0)	27.4 (4.4)	3.8 (3.8)
"Average" 1899 mixed conifer stands (Stephens, 2000)	2	24	20	43	7	4	–

Mean values in a column followed by the same letter are not significantly different ($p < 0.05$).

After thinning was completed (post-harvest), the 1000 h sound fuel load significantly increased in the mechanical plus fire treatment (before prescribed fire) when compared to the control (Table 6). Duff was significantly reduced in the mechanical only treatment when compared with the control (Table 6). After thinning, combined 1, 10, and 100 h surface fuel loads were significantly higher in the mechanical only treatment when compared with the control and mechanical plus fire treatments (Table 6). Fuel depth was increased in both mechanical and mechanical plus fire treatments (before prescribed fire) when compared with the control (Table 7).

Prescribed burning in both mechanical plus fire and fire only treatments significantly reduced litter and duff loads relative to control and mechanical only treatments (Table 8). One-hour fuels were significantly reduced in fire only and mechanical plus fire treatments relative to the mechanical only but not to the control treatment. Ten, 100 h, and 1, 10, and 100 h combined fuel loads were significantly reduced in mechanical plus fire and fire only relative to the control and mechanical only treatments; 10, and 1, 10, and 100 h combined fuel loads were increased in the mechanical only unit when compared with the control (Table 8).

Thousand-hour sound and rotten fuel loads were significantly reduced by prescribed burning in mechanical plus fire and fire only treatments relative to controls (Table 8). Post-burn fuel depths in the fire

Table 6
Average (standard error) post-harvest fuel loads (metric t ha^{-1}; depth in cm) by treatment at Blodgett Forest Research Station, California

Fuel component	Control	Mechanical only	Mechanical plus fire	Fire only[a]
Duff	48.8 a (0.9)	27.8 b (7.1)	38.1 ab (1.6)	–
Litter	23.2 (1.6)	16.4 (1.6)	16.3 (1.6)	–
1 h	1.0 (2.8)	0.6 (9.7)	0.7 (5.8)	–
10 h	3.8 (0.2)	3.5 (0.0)	3.7 (0.1)	–
100 h	6.7 (0.8)	8.5 (0.1)	7.4 (0.3)	–
1–100 h	11.6 a (0.8)	12.7 b (1.3)	11.9 a (0.4)	–
1000 h sound	8.0a (1.6)	23.7 b (1.2)	28.9 b (0.7)	–
1000 h rotten	16.4 (2.8)	11.4 (5.9)	4.5 (1.0)	–
Total fuel load	120.3 (2.4)	101.1 (3.3)	113.6 (1.3)	–

Mean values in a row followed by the same letter are not significantly different ($p < 0.05$).

[a] Fire only units not treated during this treatment stage.

Table 7
Average (standard error) post-mastication fuel loads (metric t ha^{-1}; depth in cm) by treatment at Blodgett Forest, California

Fuel component	Control	Mechanical only	Mechanical plus fire	Fire only[a]
Duff	48.8 (0.9)	32.0 (7.3)	31.7 (3.7)	–
Litter	23.2 (1.6)	17.1 (2.2)	17.2 (0.4)	–
1 h	1.0 (2.8)	1.0 (10.3)	1.1 (4.0)	–
10 h	3.8 (0.2)	4.8 (0.1)	4.6 (0.0)	–
100 h	6.7 (0.8)	9.0 (0.4)	8.7 (0.4)	–
1–100 h	11.6 (0.8)	14.8 (0.6)	14.5 (0.8)	–
1000 h sound	8.0 (1.6)	13.3 (1.1)	21.3 (1.3)	–
1000 h rotten	16.4 (2.8)	9.9 (1.5)	9.2 (2.2)	–
Total fuel load	120.3 (2.4)	131.2 (3.7)	109.3 (6.3)	–
Fuel depth	8.7 a (4.7)	14.7 b (5.2)	14.6 b (7.9)	–

Mean values in a row followed by the same letter are not significantly different ($p < 0.05$).

[a] Fire only units not treated during this treatment stage.

only treatment were significantly lower relative to both control and mechanical only treatments. Post-burn fuel depths in the fire only treatment were significantly lower than those in the mechanical only and control treatments (Table 8).

3.2. Fire behavior

After harvest, predicted rate of spread, fire line intensity, and flame length increased significantly in mechanical plus fire (before mastication and prescribed fire) and mechanical only treatments when compared to the control (Table 9). Post-harvest crowning index remained significantly higher in mechanical and mechanical plus fire treatments when compared with controls at all percentile weather conditions. At 97.5th percentile fire weather, fire line intensity and rate of spread of both mechanical plus fire (before mastication and prescribed fire) and mechanical only treatments was significantly lower than that of controls (Table 9).

After mastication, torching index and crowning index were significantly higher in mechanical plus fire (before prescribed fire) and mechanical only treatments compared to the controls (Table 10).

Post-treatment (after all treatment activities were done), rate of spread and flame lengths were significantly different between each treatment type, with fire only having the lowest and the control having the highest values at 80th percentile fire weather conditions (Table 11). At 90th percentile conditions, flame length and rate of spread were significantly different between treatments (Table 11), with fire only having the lowest and the mechanical only having the

Table 8
Average (standard error) post-treatment fuel loads (metric t ha^{-1}; depth in cm) by treatment at Blodgett Forest, California

Fuel component	Control	Mechanical only	Mechanical plus fire	Fire only
Duff	44.1 a (3.9)	34.3 a (8.6)	3.6 b (1.3)	5.1 b (0.7)
Litter	17.3 a (0.3)	19.4 a (1.7)	6.2 b (0.4)	6.5 b (0.8)
1 h	0.7 ab (0.4)	1.2 a (0.6)	0.4 b (0.2)	0.4 b (0.1)
10 h	3.4 b (0.2)	4.9 a (0.2)	1.7 c (0.0)	1.3 c (0.0)
100 h	10.0 a (0.2)	10.9a (0.4)	2.6 b (0.1)	2.7 b (0.2)
1–100 h	14.2 a (1.1)	17.1 b (0.8)	4.8 c (0.2)	4.4 c (1.0)
1000 h sound	13.3 a (1.2)	12.9 ab (0.8)	5.7 c (0.4)	5.1 bc (1.2)
1000 h rotten	16.2 a (3.5)	16.4 ab (2.0)	2.4 bc (0.9)	0.8 c (0.9)
Total fuel load	114.1 a (3.0)	111.9 a (6.2)	28.9 b (1.6)	25.7 b(0.1)
Fuel depth	7.6 a (3.2)	11.6 b (7.9)	4.8 ac (2.5)	3.5 c (1.0)

Mean values in a row followed by the same letter are not significantly different ($p < 0.05$).

Table 9
Post-harvest modeled fire behavior at Blodgett Forest, California

Weather percentile	Treatment	Fire type	Fire rate of spread (m min^{-1})	Fire line intensity (kW m^{-1})	Flame length (m)	Torching index (km h^{-1})	Crowning index (km h^{-1})
80th	Control	100% SF	1.9 a (0.0)	353.5 a (0.0)	1.2 a (0.0)	52.8 (3.1)	49.1 (2.2)
	Mechanical only	100% SF	2.8 b (0.0)	435.1 b (5.8)	1.3 b (0.0)	86.4 (38.1)	66.7 (2.8)
	Mechanical plus fire	100% SF	2.8 b (0.0)	430.0 b (5.8)	1.3 b (0.0)	70.2 (17.4)	66.7 (2.2)
	Fire only[a]	–	–	–	–	–	–
90th	Control	33% SF, 66% PCF	5.8 a (1.8)	826.0 a (0.0)	2.5 a (0.5)	26.2 (1.7)	32.2 (1.5)
	Mechanical only	66% SF, 33% PCF	4.0 b (0.2)	701.1 ab (53.7)	1.8 b (0.3)	54.4 (26.7)	45.3 (2.2)
	Mechanical plus fire	66% SF, 33% PCF	3.8 b (0.0)	633.5 b (7.0)	1.7 b (0.1)	46.2 (11.6)	44.3 (1.4)
	Fire only[a]	–	–	–	–	–	–
97.5th	Control	33% ACFPD, 66% PCF	30.1 a (3.2)	1186.5 a (0.0)	15.0 a (8.2)	20.3 (1.4)	30.4 (1.4)
	Mechanical only	33% SF, 66% PCF	13.5 b (5.2)	1001.0 b (10.5)	3.7 b (1.1)	39.0 (17.9)	42.1 (1.8)
	Mechanical plus fire	33% SF, 66% PCF	10.8 b (5.6)	990.5 b (10.5)	3.0 b (1.1)	31.7 (8.1)	42.1 (1.4)
	Fire only[a]	–	–	–	–	–	–

Mean values (standard error) in a column (blocked by percentile weather of 80th, 90th, and 97.5th) followed by the same letter are not significantly different ($p < 0.05$). SF = surface fire; PCF = passive crown fire; ACFPD = active crown fire plume dominated.

[a] Fire only units not treated during this treatment stage.

highest values. Fire line intensity was significantly higher in mechanical only treatments compared to controls (Table 11). At 90th percentile conditions, torching index were similar in control and mechanical only treatments with torching index being significantly higher in fire only and mechanical plus fire treatments. At 97.5th percentile fire weather conditions, mechanical only, mechanical plus fire, and fire only treatments did not have significantly different rates of spread though as a group, they were significantly lower than the control treatment. Torching index and crowning index were all significantly higher in fire and mechanical plus fire treatments when compared to control and mechanical only treatments (Table 11). Post-treatment canopy bulk density was significantly reduced in the mechanical

Table 10
Post-harvest and mastication modeled fire behavior at Blodgett Forest, California

Weather percentile	Treatment	Fire type	Fire rate of spread (m min^{-1})	Fire line intensity (kW m^{-1})	Flame length (m)	Torching index (km h^{-1})	Crowning index (km h^{-1})
80th	Control	100% SF	1.9 a (0.0)	353.5 a (0.0)	1.2 a (0.0)	52.8 a (3.1)	49.1 a (2.2)
	Mechanical only	100% SF	3.9 b (0.0)	645.1 b (9.3)	1.6 b (0.0)	112.5 b (10.3)	75.8 b (1.4)
	Mechanical plus fire	100% SF	3.9 b (0.0)	636.0 b (9.3)	1.5 b (0.0)	114.6 b (6.5)	76.6 b (1.5)
	Fire only[a]	–	–	–	–	–	–
90th	Control	33% SF, 66% PCF	5.7 (1.8)	826.0 a (0.0)	2.5 a (0.5)	26.2 a (1.7)	32.2 a (1.5)
	Mechanical only	100% SF	5.3 (0.1)	948.5 b (10.5)	1.9 b (0.0)	74.4 b (6.9)	50.4 b (1.0)
	Mechanical plus fire	100% SF	5.3 (0.1)	938.0 b (10.5)	1.9 b (0.0)	76.0 b (4.3)	51.0 b (1.0)
	Fire only[a]	–	–	–	–	–	–
97.5th	Control	33% ACFPD, 66% PCF	30.9 a (3.2)	1186.5 a (0.0)	15.0 a (8.2)	20.3 a (1.4)	30.4 a (1.4)
	Mechanical only	100% SF	7.0 b (0.2)	1428.0 b (49.1)	2.2 b (0.0)	51.5 b (4.8)	47.8 b (0.9)
	Mechanical plus fire	100% SF	7.2 b (0.1)	1467.6 b (15.2)	2.2 b (0.0)	52.6 b (2.9)	48.5 b (0.9)
	Fire only[a]	–	–	–	–	–	–

Mean values in a column (blocked by percentile weather of 80th, 90th, and 97.5th) followed by the same letter are not significantly different ($p < 0.05$). SF = surface fire; PCF = passive crown fire; ACFPD = active crown fire plume dominated.

[a] Fire only units not treated during this treatment stage.

Table 11
Post-treatment modeled fire behavior at Blodgett Forest, California

Weather percentile	Treatment	Fire type	Fire rate of spread (m min^{-1})	Fire line intensity (kW m^{-1})	Flame length (m)	Torching index (km h^{-1})	Crowning index (km h^{-1})
80th	Control	100% SF	1.9 a (0.0)	353.5 a (0.0)	1.2 a (0.0)	58.2 a (0.0)	50.7 a (2.0)
	Mechanical only	100% SF	3.9 b (0.0)	645.1 b (9.3)	1.6 b (0.0)	112.5 a (10.3)	75.8 b (1.4)
	Mechanical plus fire	100% SF	0.7 c (0.0)	21.0 c (0.0)	0.3 c (0.0)	899.8 b (22.2)	81.0 b (1.7)
	Fire only	100% SF	0.5 d (0.0)	14.0 c (0.0)	0.3 d (0.0)	668.3 c (53.0)	54.6 a (1.3)
90th	Control	100% SF	4.0 a (0.0)	826.0 a (0.0)	1.7 a (0.0)	29.3 a (0.0)	33.3 a (1.3)
	Mechanical only	100% SF	5.3 b (0.1)	948.5 b (10.5)	1.9 b (0.0)	74.4 a (6.9)	50.4 b (1.0)
	Mechanical plus fire	100% SF	1.0 c (0.0)	29.1 c (1.2)	0.4 c (0.0)	669.6 b (16.5)	53.9 b (1.1)
	Fire only	100% SF	0.7 d (0.0)	21.0 c (0.0)	0.3 d (0.0)	497.1 c (39.5)	35.8 a (0.9)
97.5th	Control	33% ACFPD, 66% PCF	28.6 a (3.9)	1186.5 a (0.0)	13.9 (7.7)	22.7 a (0.0)	31.5 a (1.3)
	Mechanical only	100% SF	7.0 b (0.2)	1428.0 b (49.1)	2.2 (0.0)	51.5 a (4.8)	47.8 b (0.9)
	Mechanical plus fire	100% SF	1.3 b (0.0)	43.1 c (1.2)	0.4 (0.0)	543.4 b (13.4)	51.2 b (1.1)
	Fire only	100% SF	0.9 b (0.0)	9 c (0.0)	0.4 (0.0)	403.2 c (32.1)	34.1 a (0.9)

Mean values in a column (blocked by percentile weather of 80th, 90th, and 97.5th) followed by the same letter are not significantly different ($p < 0.05$). SF = surface fire; PCF = passive crown fire; ACFPD = active crown fire plume dominated.

and mechanical plus fire treatments after mastication relative to control and fire only treatments (Table 13).

3.3. Tree mortality

Probability of mortality was modeled in four diameter classes (2.5–25, 25–51, 51–76 cm, greater than 76 cm) as well as aggregated for all diameter classes. Mortality in the 2.5–25 cm size class was significantly higher in control and mechanical only treatments when compared with the fire only and mechanical plus fire treatments (Table 12).

For trees in the 25–51 cm diameter class, predicted mortality was significantly higher in mechanical only treatments at 80th percentile fire weather conditions. There was no distinction between control, mechanical plus fire, and fire only treatments for trees >51 cm DBH at 80th percentile weather conditions (Table 12).

Table 12
Average post-treatment percent predicted mortality (standard error) for conifer species by diameter class and treatment type at Blodgett Forest, California

Percentile weather	DBH range (cm)	Control	Mechanical only	Mechanical plus fire	Fire only
80th	2.5–25	72.2 a (0.6)	85.3 b (4.2)	50.4 c (0.3)	48.9 c (0.4)
	25–51	25.1 b (1.2)	39.7 a (4.9)	21.0 b (2.1)	21.6 b (1.6)
	51–76	6.9 (0.6)	7.3 (0.5)	6.3 (0.1)	7.2 (0.5)
	>76	3.2 (0.0)	3.1 (0.2)	2.6 (0.2)	2.9 (0.3)
	All	45.7 a (3.6)	46.9 a (3.8)	23.0 b (1.6)	31.0 c (2.2)
90th	2.5–25	97.7 a (0.6)	96.1 a (1.9)	50.4 b (0.3)	48.9 b (0.4)
	25–51	59.8 a (5.8)	58.1 a (5.8)	21.0 b (2.1)	21.6 b (1.6)
	51–76	9.7 a (0.7)	8.0 ab (0.7)	6.3 b (0.1)	7.2 ab (0.5)
	>76	3.2 (0.0)	4.5 (1.5)	2.6 (0.2)	2.9 (0.3)
	All	70.4 a (6.2)	56.6 a (3.3)	23.0 b (1.6)	31.0 b (2.2)
97.5th	2.5–25	99.6 a (0.0)	99.4 a (0.1)	50.4 b (0.3)	48.9 b (0.4)
	25–51	98.0 a (0.1)	77.0 b (1.6)	21.0 c (2.1)	21.6 c (1.6)
	51–76	91.8 a (1.8)	16.1 b (3.0)	6.3 c (0.1)	7.2bc (0.5)
	>76	77.1 a (6.1)	6.4 b (2.4)	2.6 b (0.2)	2.9 b (0.3)
	All	97.1 a (0.7)	65.3 b (2.5)	23.0 c (1.6)	31.0 c (2.2)

Mean values in a row followed by the same letter are not significantly different ($p < 0.05$).

Table 13
Average canopy bulk density (kg m^{-3}) (standard error) for all treatments at each treatment stage from Blodgett Forest, California

All species	Control	Mechanical only	Mechanical plus fire	Fire only
Pretreatment (2001)	0.085 (0.009)	0.069 (0.009)	0.070 (0.003)	0.076 (0.005)
Post-harvest	0.085 (0.009)	0.056 (0.005)	0.056 (0.004)	[a]
Post-mastication	0.085 a (0.009)	0.046 b (0.002)	0.045 b (0.002)	[a]
Post-treatment (2003)	0.081 a (0.007)	0.046 b (0.002)	0.042 b (0.002)	0.072 a (0.003)

Mean values in a row followed by the same letter are not significantly different ($p < 0.05$).

[a] Fire only units not treated during this treatment stage.

As stands were tested under more severe weather conditions, predicted mortality in fire only and mechanical plus fire treatments generally remained significantly lower than control and mechanical only treatments (Table 12). At 97.5th percentile conditions, the control had the highest probability of mortality.

For trees 51–76 cm, there was no significant difference among treatments in predicted mortality at 80th percentile fire weather conditions (Table 12). At 90th percentile fire weather conditions mechanical plus fire treatments had significantly lower probability of mortality than the controls. At 97.5th conditions, the control had the highest overall predicted mortality for trees greater than 25 cm DBH (Table 12).

For trees greater than 76 cm, there was no significant difference in predicted mortality between treatments at 80th and 90th percentile fire weather conditions. At 97.5th percentile conditions, the control remained significantly higher than the mechanical only, mechanical plus fire, and fire only treatments, which were statistically similar to each other (Table 12).

When the analysis was completed for all diameter classes, tree mortality in the control and mechanical only treatments remained significantly higher than the mechanical plus fire and fire only treatments (Table 12). At 97.5th percentile conditions, mortality in the controls was significantly higher than all other treatments (all trees).

4. Discussion

The effects of the thinning treatment (crown and thinning from below) was reflected in the reduction of density of trees along with an increase 1000 h fuel loads (Tables 4 and 6). Canopy bulk density was effectively reduced by thinning and mastication (Table 13). The combination of thinning and mastication each reduced crown bulk density by approximately 19% (Table 3) in mechanical only and mechanical plus fire treatments. Similar reductions in crown fuels from thinning treatments have been reported in northeast Oregon (McIver et al., 2003) and Arizona (Fule et al., 2001).

Overall, the treatments had little effect on both conifer and hardwood species composition (Table 5). When compared to quantitative plot data from this region taken by George Sudworth in 1899 (Stephens, 2000), both treated areas and controls have a higher percent species composition of white fir, sugar pine, and California black oak, though the presence of ponderosa pine is lower than previously measured during this period (Table 5). Prior to influence of fire suppression and early 20th century harvesting practices, California black oak comprised approximately 2% (by basal area ha^{-1}) or 6% (by trees ha^{-1}) of mixed conifer forests near the study area (Stephens, 2000). Current composition of California black oak ranges from 4 to 11% (by basal area ha^{-1}) in post-treatment stands (Table 5).

Torching and crowning indices were not significantly changed after harvesting alone (Table 9). The addition of mastication resulted in significant increases in torching and crowning indices (Table 10) primarily from the increased height to live crown base (Table 4) from mastication. Reducing crown bulk density in these stands with crown thinning alone did not substantially change potential fire behavior or effects.

In this study, the most effective method for crown fuel reduction is the removal of trees in the 2.5–25 cm diameter class, which compose the dominant ladder fuels. Overall, mastication is effective in reducing ladder fuels and increasing height to live crown base. The tradeoff is an increase in surface fuel depth and continuity. The longevity of this change in fuel load will depend on the size distribution and species composition of the activity fuels and the local rates of decay for these types of biomass. It is noted that logging slash in the 100 and 1000 h size classes can remain in Sierra Nevada forests for 20–30 years (Bob Heald, personal communication, 2003). This suggests that activity fuels may contribute to increased surface fuel loads for decades after treatment.

Prescribed burning was effective in reducing tree density in the 2.5–25 cm DBH class but there was not a corresponding reduction in crown bulk density (Table 13). Even though crown bulk density was not significantly reduced in fire only treatments, predicted fire behavior and mortality were more effectively reduced relative to controls and mechanically only treatments. This is likely due to the reduction in surface fuels, which in turn reduced flame length and fireline intensity, resulting in a decreased probability of crown fire and tree mortality.

The prescribed fire treatment resulted in a significant decrease in the 2.5–25 cm DBH class (Table 4), though most of the stems killed by fire remained as standing dead trees. In the case of mastication, that material remained on the ground surface. Standing dead fuels can contribute more to increased spotting over long distances whereas surface fuels contribute directly to rate of spread, fire line intensity, and flame lengths (Rothermel, 1972; Alexander, 1988). Both scenarios can increase the difficulty of fire suppression. The standing dead trees in the fire only treatment will fall to the ground in a relatively short time and additional prescribed fires will be needed to maintain low fire hazards.

Canopy cover was reduced in all active treatments though it remained relatively high in units treated mechanically (51–58%) (Table 4). While many co-dominant and dominant trees were removed, the majority of the canopy was harvested or masticated from the intermediate and suppressed canopy layers, leaving the overstory canopy relatively unchanged. One-year post-burn, the prescribed fire treatment did not substantially remove dominant or co-dominant trees because fire behavior was not severe enough to kill many trees over 30 cm DBH. It is important to note that indirect mortality from increased insect activity, periods of drought, and pathogens, may increase mortality in larger trees in prescribed fire and mechanical followed by fire treatments (Stephens and Finney, 2002).

Changes in fuel structure occurred in sound 1000 h fuel loads after harvesting in the mechanical and mechanical plus fire treatments (Table 6). This increase is likely attributable to increase in tree-tops and larger diameter limb wood resulting from harvest activities. Thousand-hour fuels typically contribute more to spotting, smoldering combustion, and cambial injury where adjacent to live trees. Though it was not quantified, it appeared that fuels were more continuous in masticated units when compared with the post-thinning, post-burn, and controls. This continuity appeared to have contributed to more severe fire behavior when prescribed burns were implemented in the mechanical plus fire treatment. The period of flaming combustion was higher in the mechanical plus fire treatment (approximately 15–20 min) versus fire only treatment (approximately 3–10 min).

Prescribed burning significantly reduced the total combined fuel load of litter, duff, 10, 100, and 1000 h fuels by as much as 90% (Table 8) in fire only and mechanical plus fire treatments. This reduction significantly altered fire behavior in both mechanical plus fire and fire only treatments in terms of fireline intensity and predicted mortality (Tables 11 and 12). The reduction in coarse woody debris (CWD) due to prescribed burning may be of concern to wildlife habitat for many species (Smith, 2000), though there are currently more standing dead trees available for CWD recruitment in fire only than mechanical plus fire treatments compared to their pretreatment state. This increase in the CWD recruitment pool after burning has been described in other studies (Tinker and Knight, 2000). When discussing the role of CWD in current ecosystems, it is important to have an understanding of the quantity, quality, and distribution there may have been during the pre-historical fire interval of 4.7 years (fire interval range of 4–28 years) (Stephens and Collins, 2004; Stephens, 2004; Stephens and Moghaddas, 2005b) reported for areas within the current Blodgett Forest property boundaries.

All three active treatments significantly reduced predicted tree mortality when compared with the control. Mechanical treatments, as implemented here, were effective at moderating fire behavior and effects. Treatments which incorporated a surface fuel treatment showed a higher degree of fire behavior reduction than mechanical only treatments. Reduction of slash (activity fuels) is a critical component of a successful fuel treatment (Stephens, 1998; Fule et al., 2001).

Prescribed burning was more effective at reducing fire behavior in terms of fireline intensity, flame length, and rate of spread at 90th percentile conditions. Pollet and Omi (2002) conclude that ''. . . sites with mechanical treatments dramatically reduced fire severity compared to sites withy prescribed fire only''. This work was done after wildfire in uncontrolled conditions and appears to contradict the findings of this study but different site characteristics could have influenced these results. Reduction in surface (natural and activity) fuels after harvesting also decreased tree mortality in areas subjected to the Cone Wildfire at Blacks Mountain Experimental Forest, California (Carl Skinner, personal communication, 2003).

The mechanical plus fire and fire only treatments had significantly lower predicted mortality in the 2.5–76 cm size class (Table 12). At 80th and 90th percentile fire weather conditions, trees greater than 76 cm DBH had similar predicted mortality when compared with the control (Table 12). At 97.5th percentile conditions, trees greater than 76 cm DBH in controls had significantly higher mortality than in actively treated units (Table 12). This is likely to due the combination of reduced surface fuels (in units treated with fire) and increased height to crown base. It is apparent from this study that the no treatment option (control) was not effective at reducing predicted fire behavior and tree mortality.

High fire hazards in unmanaged second-growth forests were noted as early as the 1920s in California (Show and Kotok, 1924). Reducing surface fuel load can reduce predicted mortality of trees in the 2.5–76 cm size class. Removing ladder fuels and raising the average height to crown base can be effective in reducing predicted mortality of trees >51 cm under 97.5th percentile fire weather conditions (Table 12). Others have found that similar ''thin from below'' or ''low thinning'' approaches can reduce the chance of torching and crown fire initiation (Peterson et al., 2003).

Treatments that utilized fire as the primary treatment (fire only) or secondarily after mechanical treatments (mechanical plus fire) had the lowest predicted probability of mortality under the three modeled weather conditions (Table 12). Even under the most severe modeled conditions, the probability of tree mortality in burned treatments remained relatively low.

Direct fire damage including percent crown volume scorched (Stephens and Finney, 2002) and bark char have been shown to be key factors in predicting post-fire tree mortality (van Mantgem and Schwartz, 2003). It is also important to note that other factors (level of bark beetle activity, root pathogen density, drought severity) can also influence the probability of mortality. van Mantgem et al. (2003) found that white fir trees with slower pre-burn growth rates suffered significantly higher rates of mortality than faster growing trees which suffered a similar degree of crown volume scorch. Pre-burn growth rates are likely affected by species composition, stand age, density, and past management history, suggesting that treatment prescriptions should be designed for the stand they are being implemented in as opposed to a more generic prescription that may not have the capacity for such variation.

5. Conclusions

While all three active treatments were effective in modifying fire behavior and predicted tree mortality, it is important to understand the tradeoffs of implementing any individual treatment on a site-specific basis. Mechanical treatments can be effective in reducing predicted mortality but increased fire behavior from activity fuels may hinder suppression activities. Both mechanical and fire treatments may be logistically difficult near developed areas or could be socially unacceptable for various reasons by stakeholders and the general public. Results from this study indicate that the no-treatment (control) option was ineffective at reducing predicted fire behavior and tree mortality.

With any fuel treatments, it is important to identify short and long term management goals before implementation. An assessment should determine the level of fire hazard from surface, ladder, and crown fuels, and determine what level of risk that hazard poses to other resources or assets. The treatment should then be designed to mitigate that particular risk by treating the appropriate component of the fuel complex from which the hazard is derived. Fundamentals to any fuel treatment include (a) reducing surface fuel loads (particularly in areas where existing surface fuels are at high level) to decrease fire intensity, (b) not substantially increasing surface fuel loads by adding activity fuels (Stephens, 1998), and (c) adequately raising height to crown base to reduce passive crown fire (Keyes and O'Hara, 2002; Peterson et al., 2003; Graham et al., 2004). Reducing crown bulk density in these stands with crown thinning alone did not substantially change potential fire behavior or effects.

Understanding potential rates of tree mortality is critical in predicting future forest structure and function. In particular, higher levels of mortality will increase the rate of snag recruitment and in turn, influence coarse woody debris recruitment. This recruitment may in turn affect both wildlife and insect populations in addition to surface fuel loads. High mortality may also influence other structural components including tree canopy cover, tree regeneration, and understory plant responses. From a timber management perspective, high post-fire mortality will reduce commercial values. High tree mortality may also impair visual resources associated with forest ecosystems to some human populations.

Gaining an understanding of how different fuel treatments affect basic vegetation structure, fuel characteristics, and predicted fire behavior and effects is necessary for making informed decisions about which treatment will meet management objectives (Stephens and Ruth, 2005). Increasing our knowledge of the short and long-term effects of these treatments is also essential to understanding their ecological effects at multiple temporal and spatial scales. Further research is needed on how fuel treatments affect other components of the ecosystem including wildlife populations, insects activity, soil characteristics, coarse woody debris availability, snag density, and live biomass accumulation.

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