Research Article

Effect of Fuel Treatments on Fuels and Potential Fire Behavior in California, USA, National Forests

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ABSTRACT

In many parts of California, past timber harvesting, livestock grazing practices, and fire exclusion have changed the fire regime from low to mixed severity to a high severity regime with an increase in active crown fire. Land managers responded by implementing hazardous fuel treatment projects to reduce the risk of such uncharacteristic stand-replacing crown fires. Various fuel treatments have been implemented using either mechanical methods or prescribed fire in forested ecosystems across 14 national forests in California, USA. Mechanical treatments significantly altered forest structure (tree density, 75th percentile quadratic mean diameter, canopy cover, canopy base height, and canopy bulk density) and generally increased surface fuel loads as compared to pre-treatment conditions. Prescribed fire significantly reduced ground and surface fuel loads and increased canopy base height, but did not appreciably alter other forest structure metrics. The changes in forest and fuel structures from prescribed fire reduced predicted fire behavior metrics (fire type, flame length, fireline intensity, and rate of spread); mechanical methods showed mixed effects on resulting fire behavior metrics. Modeled fire type, in addition to predicted flame length, fireline intensity, and rate of spread, is an essential metric for managers when choosing where to implement fuel treatments and for assessing the effectiveness of completed treatments. Under 90th percentile windspeed, out of the five forest treatment combinations, three exhibited some passive crown fire before treatment and only one exhibited passive crown fire after treatment. Using gusting windspeed, four of the five combinations maintain the potential for crown fire (passive or conditional) after treatment. If reducing the potential for uncharacteristic crown fire is the main priority for fuel treatments, it might be beneficial to prioritize areas with elevated risk and to combine both mechanical methods and prescribed fire in order to achieve desired fire behavior under more extreme conditions.

Keywords: fire behavior modeling, fuel treatment effectiveness, wildland fire risk

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INTRODUCTION

Fire has been a part of California's ecosystems for thousands of years (Sugihara *et al.* 2006). Throughout California and the western United States, fire exclusion, timber harvesting, and livestock grazing over the past century have altered forest structure. Today, forests are characterized by smaller trees and higher fuel loads than in the past (Agee and Skinner 2005). The transformation of fuel conditions coupled with a changing climate (Westerling *et al*. 2006, Millar *et al.* 2007, Miller *et al.* 2009) has altered the historical fire regime in coniferous forests of California (e.g. Beaty and Taylor 2001, Stephens and Collins 2004, Fry and Stephens 2006, Moody *et al*. 2006, Vaillant 2008). Land managers are concerned about the increase in stand-replacing crown fires in ecosystems that historically burned with low or mixed severity (Covington 2000, Miller *et al.* 2009).

In response, the National Fire Plan (USDA-USDI 2000), the 10-Year Comprehensive Strategy (WGA 2001), and the Healthy Forests Restoration Act (HFRA 2003) were enacted to address the problem of elevated fuel loading and facilitate the reduction of wildland fire risk. All three documents include clauses to reduce the risk of catastrophic wildland fires that threaten people, communities, and natural resources. Risk reduction can occur in areas such as the wildland urban interface, threatened or endangered species habitat, municipal water supplies, and other values at risk. Proposed fuel reduction treatments include, but are not limited to, prescribed fire, mechanical treatments, and livestock grazing. The three documents give priority to treatments where the risk of negative impacts from wildland fire is the greatest.

The current extent and frequency of stand-replacing crown fire is historically uncharacteristic in the Sierra Nevada (Miller *et al.* 2009). Fuel treatments break the continuity of surface, ladder, and crown fuels, reducing the risk of crown fire (Van Wagner 1977, Agee *et al.* 2000, Scott and Reinhardt 2001, Agee and Skinner 2005). The most common types of hazardous fuel reduction treatments include mechanical methods (i.e., thinning and mastication), prescribed burning, and a combination of the two. Mechanical treatments are most effective at altering forest structure by reducing tree density and canopy bulk density, and by increasing canopy base height (Keyes and O'Hara 2002; Pollet and Omi 2002; Stephens and Moghaddas 2005a, b; Agee and Lolley 2006; Huggett *et al.* 2008; Stephens *et al.* 2009). This alteration in forest structure breaks the horizontal and vertical connection between surface and crown fuels. However, depending on the type of mechanical treatment employed, surface fuel loads may be at an elevated level post-treatment (Kalabokidis and Omi 1998, Stephens 1998, Raymond and Peterson 2005, Stephens and Moghaddas 2005a). Prescribed fire reduces surface and ladder fuels (Knapp *et al.* 2005, Keifer *et al.* 2006) but does not often alter canopy fuels (Stephens and Moghaddas 2005a, Agee and Lolley 2006, Vaillant *et al.* 2009, Stephens *et al.* 2009). The combination of mechanical treatments followed by prescribed burning has proven to be the most effective at reducing potential fire behavior and effects (van Wagtendonk 1996, Peterson *et al.* 2003, Stephens and Moghaddas 2005a, Ritchie *et al.* 2007, Stephens *et al.* 2009).

Ideally, the effectiveness of a fuel treatment to lessen potential fire behavior (i.e., reduced flame height) can be observed during or after a fire passes through the treatment. Fuel treatments have proven to be effective at reducing fire intensity, severity, and extent (Agee *et al.* 2000, Pollet and Omi 2002, Martinson and Omi 2003, Finney *et al.* 2005, Ritchie *et al.* 2007), and in aiding in suppression efforts during wildfires (Moghaddas and Craggs 2007). Observational evidence has also shown fires to burn into and through known treatments under extreme conditions (Pollet and Omi 2002). In the absence of this opportunity, and in necessity for fuel treatment planning, most researchers evaluate or predict fuel treatment effectiveness with fire behavior modeling. Fire behavior modeling can be done as a theoretical practice or with pre- and post-treatment fuel measures. Theoretical modeling can be completed to better understand the influence of potential fuel treatments on fire behavior metrics (van Wagtendonk 1996, Stephens 1998, Schmidt *et al.* 2008, Vaillant 2008). Fire behavior modeling that utilizes pre- and post-treatment fuel measurements allows managers to assess the effectiveness of completed fuel treatments to alter potential fire behavior (Stephens and Moghaddas 2005a, b; Roccaforte *et al.* 2008; Schmidt *et al.* 2008; Vaillant *et al.* 2009).

In 2000, the Pacific Southwest Region of the Forest Service initiated a region-wide fuel hazard reduction treatment monitoring project. The monitoring project was designed to quantify the effectiveness and effects of fuel treatments on major vegetation types across California. Monitoring plots were established in 17 out of the 18 national forests in coniferous forest and chaparral ecosystems. Treatment types included prescribed fire, mechanical treatments, a combination of the two, and wildfire. To date, most of plots that received treatment are in coniferous forests and were treated with mechanical methods or prescribed fire. The objective of this study was to determine how prescribed fire and mechanical treatments affect fuel loads, forest structure, and potential fire behavior for three forest types in California. Information from this study can be used to assist in the development of forest management plans that use prescribed fire and mechanical methods to reduce fire hazard.

METHODS

Study Sites

Personnel on each national forest in California were asked to provide at least one candidate project that would be treated the following year. Although it would have been ideal to randomly select study sites (treatment units), preference was given to those sites most likely to be treated. Plot locations were randomly selected within each study site.

From 2001 through 2006, 255 permanent monitoring plots were established in coniferous forests. Plots were assigned subjectively to three forest types based on dominant tree species, similarities in fuel characteristics, and expected fire behavior. The forest types include short-needle dominated conifer stands, long-needle dominated conifer stands, and red fir (*Abies magnifica*) stands. The red fir group was not included in the short-needle conifer group because of differences in fuel characteristics, including smaller needles, less productive environments, and higher surface fuel compaction due to snow. The long-needle group is dominated by ponderosa pine (*Pinus ponderosa*), Jeffrey pine (*Pinus jeffreyi*), or Coulter pine (*Pinus coulteri*). Other tree species present include white fir (*Abies concolor*), black oak (*Quercus kelloggii*), incense-cedar (*Calocedrus decurrens*), Douglas-fir (*Pseudotsuga menziesii*), and sugar pine (*Pinus lambertiana*). The short-needle group is dominated by Douglas-fir, white fir or a combination of both. Other tree species present include ponderosa pine, sugar pine, incense-cedar and black oak. The red fir group is dominated by red fir but may also contain white fir.

Given the geographic extent encompassed by this monitoring project, study sites occurred on a wide variety of elevations, slopes and aspects. Elevation ranged from 200 m to 2595 m (average 1467 m) with slopes from 0% to 80% (average 22%) on all aspects.

Treatments

All fuel reduction treatments were conducted by the individual national forests and included prescribed fire and mechanical methods. Treatments were implemented across entire study sites (treatment units), not strictly within individual plot areas. Both the short-needle and long-needle forest types received either prescribed fire or mechanical treatments, while the red fir group was only treated with mechanical methods. Mechanical methods included hand cutting and piling of fuels, which were sometimes burned; thinning; thinning followed by chipping; mastication; and whole tree biomass removal. Due to a lack of sufficient replicates in any of the given methods, all mechanical treatments were combined into one category.

Study sites, and therefore plots, were divided into forest and treatment type combinations for comparison. The resulting five forest-treatment types are: short-needle mechanical treatment (SN-MT), long-needle mechanical treatment (LN-MT), red fir mechanical treatment (RF-MT), short-needle prescribed fire (SN-PF) and long-needle prescribed fire (LN-PF) (Figure 1, Table 1).

Field Data Collection

Different monitoring protocols were used depending on the establishment year of the

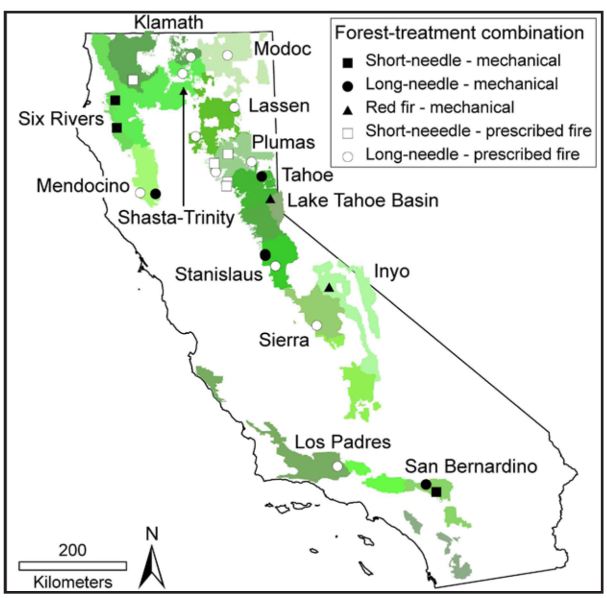

Figure 1. Location of study sites by forest-treatment combination in California. Only the national forests labeled are included in the study.

Table 1. Number of plots and sites by forest and treatment type in California.

Forest type	Mechanical treatment # plots	Mechanical treatment # sites	Prescribed fire # plots	Prescribed fire # sites
Short-needle	11	3	12	5
Long-needle	18	5	30	11
Red fir	11	2		

study site (Table 2). Variations of the protocol were modified versions of the National Park Service's fire monitoring protocol (NPS 2003). Starting in 2003, the number of plots per site increased, and quantity of data decreased in order to better capture the inherent variation in understory plant composition and surface fuels. The number of plots increased from three per site to six per site, with three each of detailed plots and rapid plots. The detailed plots included collection of tree data, whereas the rapid plots did not. In addition, the number of shrub transects, fuel transects, and canopy cover readings were reduced in 2003 (Table 2). All post-treatment plots were re-read according to the initial protocol one year after treatment.

Tree data were collected on all plots established before 2003, and only on detailed plots starting in 2003. Overstory, pole-size, and seedling tree information were gathered within circular fixed area nested plots sized 0.1 ha, 0.025 ha, and 0.005 ha, respectively. Overstory trees included those greater than 15 cm diameter at breast height (dbh), pole-sized trees were ≥2.5 cm and ≤15 cm dbh, and seedlings were <2.5 cm dbh. For all live overstory and pole-sized trees, species, dbh, height to live crown base, total height, and canopy position (dominant, co-dominant, intermediate, or suppressed) were recorded. For snags, species, dbh, and total height were measured.

The number of canopy cover, shrub, and herbaceous plant and grass transects was reduced from two to one starting in 2003. A

Table 2. Details of forest structure and fuel composition data collection for the different protocols used.

	Pre-2003	2003-2006 (detailed)	2003-2006 (rapid)
Tree data[1]	yes	yes	no
Canopy cover transects/points	2/100	1/50	0/0
Shrub transects	2	1	1
Herbaceous plant transects/quadrats	2/10	1/5	1/5
Fuel transects	4	2	2

[1] Tree data include circular nested plots for overstory (0.1 ha), pole-sized (0.025 ha), and seedlings (0.005 ha).

canopy sight tube (Gill *et al.* 2000) was used to measure overstory canopy cover (50 points) along each 50 m transect. Shrub data were collected along the same transect and included species, vigor (live or dead), range along the transect, and average height. Herbaceous plants and grasses were quantified in five one-by-one meter quadrats located every 10 m along each transect. Within each quadrat, species, cover class (ocular estimate in 10 classes), and vigor (live or dead) for each rooted herbaceous plant and grass was recorded.

Surface and ground fuels were assessed using the planar-intercept method (VanWagner 1968, Brown 1974) starting along the canopy cover, shrub, and herbaceous plant and grass transect and extending outward. Plots established before 2003 had four 15.24 m fuel transects per plot. Starting in 2003, only two transects were established per plot. One-hour (≤0.64 cm diameter) and 10 h (>0.64 cm to ≤2.54 cm diameter) time lag fuels were tallied along the first 1.83 m of each transect. One-hundred-hour (>2.54 cm to ≤7.62 cm diameter) time lag fuels were tallied for the first 3.66 m of each transect. Finally, species, diameter, and condition (rotten or sound) for all 1000 h (>7.62 cm diameter) time lag fuels were recorded along the entire transect. Litter and duff depths were measured at 10 locations along each transect. Maximum fuel bed depth was measured for 10 equidistant intervals along each transect.

Using different protocols to collect data might have some impact on individual plot averages and variance for forest and fuel characteristics. However, because of the type of analysis used (grouping by functional forest type and treatment), we felt that this did not alter the results for this study.

Modeled Fire Behavior

Predicted fire behavior was simulated using NEXUS (ver. 2.0, Scott 1999) for each plot. NEXUS is a stand-level fire behavior model that predicts fire type (surface, passive crown, conditional crown, or active crown fire), crowning and torching indices, rate of spread, flame length, and fireline intensity. Canopy and surface fuel characteristics (canopy base height, canopy bulk density, canopy fuel loading, fuel model, and live and dead fuel moistures), wind data (speed, direction, and reduction factor), and slope are required to run NEXUS.

Pre- and post-treatment canopy characteristics for each plot were entered into NEXUS. Pre- and post-treatment fuel models were assigned to plots based on the calculated surface fuel loads, vegetation type, and the presumed carrier of fire (Anderson 1982, Scott and Burgan 2005). Fuel model selection was performed by highly trained wildland firefighting personnel and qualified research scientists using photographs, understory plant abundance and composition, and fuel loading data collected in the field (Table 3). Although this method is subjective, short of using custom fuel models, there is no better way to assign standard

Table 3. Lists of pre- and post-treatment fuel models used for each of the five forest-treatment combinations. Fuel model codes are consistent with Anderson (1982) or Burgan and Scott (2005). 2, timber (grass and understory); GS, grass-shrub; SB, slash-blowdown; SH, shrub; TL, timber-litter; TU, timber-understory.

Forest-treatment[1]	Pre- and post- treatment fuel models
SN-MT	Pre, TU1, TU2, TL1, TL2, TL3, TL6
	Post, TU1, TU2, TL1, TL2, SB1, SB2
LN-MT	Pre, GS2, TU1, TU3, TU5, TL3, TL4, TL5, TL8
	Post, 2, GS2, TU1, TL4, TL5, TL8, SB1
RF-MT	Pre, TU1, TL1, TL3, TL5
	Post, TU1, TL1, TL3, TL5
SN-PF	Pre, TU1, TU5, TL3, TL4, TL5
	Post, TU1, TL1, TL3, TL5
LN-PF	Pre, SH1, SH2, TU1, TU3, TU5, TL1, TL3, TL4, TL5, TL8
	Post, GS1, SH2, TU1, TU2, TU5, TL1, TL3, TL4, TL5, TL8

[1] SN-MT, short needle mechanical treatment; LN-MT, long needle mechanical treatment; SN-PF, short needle prescribed fire; LN-PF, long needle, prescribed fire.

fuel models. Custom fuel models have their pitfalls as well; they often need to be modified to accurately predict potential fire behavior. Such validation requires burning under prescribed fire and wildland fire conditions, which is often infeasible (Agee and Lolley 2006).

Initial dead fuel moisture values were set to 3 %, 4 %, and 5 % for 1 h, 10 h, and 100 h fuel moistures, respectively; and were then conditioned for each plot based on topography (slope, aspect, and elevation), shading (cloud and canopy cover), weather (temperature and relative humidity) and wind, similar to methods employed in FlamMap (Finney 2006). Ten years of hourly weather data were collected from National Weather Service weather stations within 25 km of each study site for a three-day period in August to calculate 90th percentile wind and weather (NOAA 2007). These data were used to condition dead fuel moistures to create more realistic fuel conditions for fire behavior modeling, resulting in different dead fuel moisture conditions for each plot. Live fuel moistures were set to 30 % for herbaceous fuels, 60 % for woody fuels, and 100 % for foliar fuels for all simulations to create dry, late season conditions.

The 90th percentile windspeed was calculated using 10 years of data from 96 airports across California for August (WRCC 2007). Next, a wind gustiness table was used to account for possible wind gust speeds not captured with windspeed averages (Crosby and Chandler 1966). Simulations were run using both the 90th percentile windspeed (18 km h^{-1}) and the gust speed (30 km h^{-1}). Finally, a wind adjustment factor (a function of canopy cover, stand height, and crown ratio) was applied to each plot to more accurately model mid-level windspeed with varying changes of stand structure (Albini and Baughman 1979). Wind adjustment factors ranged between 0.13 and 0.38, depending on the above-mentioned metrics creating different mid-level windspeeds for each plot.

Data Analysis

Canopy base height, canopy bulk density, and canopy fuel loading were calculated using Canopy Fuels Inventory Processor (CFIP) (Larry Wilson; Larkspur, California; unpublished report). The CFIP is a vegetation simulation program largely based on the algorithms used in the Forest Vegetation Simulator

(Crookston and Stage 1991) and the Fire and Fuels Extension (Reinhardt and Crookston 2003). The processor incorporates a post-treatment reduction in canopy bulk density and canopy base height for hardwoods and select conifers in California. To represent changes in canopy bulk density and canopy base height post-treatment, the fraction of crown length removed was multiplied by the average crown mass (Noonan-Wright *et al.* 2006). This reduced crown mass value was then applied to the vertical distribution for calculations of canopy base height and canopy bulk density for each plot. Otherwise, for hardwoods such as black oak, and conifers such as red fir and white fir, measured changes in individual tree crown base height would have resulted in higher values of crown bulk density, post-treatment. Surface and ground fuel loads were calculated using Brown *et al.* (1984) with coefficients specific to California tree species (van Wagtendonk *et al.* 1996).

Pairwise comparisons of mean responses or transformed mean responses were performed assuming an analysis of variance (ANOVA) model for repeated measures from the family of Mixed General Linear Models (McCulloch and Searle 2001) to assess the effect of treatment through time (pre- and post-treatment) on different forest types (short-needle, long-needle, and red fir) using SAS (SAS Institutes Inc., North Carolina, USA). Plots were used as replicates with study site included as a blocking factor to account for potential error associated with pseudoreplication. To maintain ANOVA assumptions, the data were tested for normality with the Kolmogorov-Smirnov test and the Levene's test (Zar 1999). If variables were found to be significantly non-normal, data were normalized and unbiased estimators were used in the statistical analysis. The comparisons' significance was assessed using the Bonferroni correction (Zar 1999). Fire modeled outputs were not statistically analyzed due to the number of assumptions associated with fire behavior modeling (Stephens and Moghaddas 2005b, Vaillant *et al.* 2009). Rather, proportion of fire type and the average pre- and post-treatment flame length, fireline intensity, and rate of spread are presented for each forest-treatment combination.

RESULTS

Forest Stand Characteristics

Of the 255 established plots, 82 plots received treatment at 26 sites on 14 national forests in California. Only those plots receiving treatment were used for this study (Table 1, Figure 1). The study included 2563 trees greater than 2.5 cm dbh and 242 fuel transects.

Mechanical treatments had a greater impact on forest stand characteristics than prescribed fire (Table 4). Canopy base height and 75th percentile quadratic mean diameter significantly increased ($p < 0.01$) and tree density, canopy cover, and canopy bulk density significantly decreased ($p < 0.01$) for SN-MT, LN-MT, and RF-MT due to treatment. Prescribed fire did not alter stand characteristics as significantly as mechanical treatments. Canopy base height significantly increased ($p < 0.01$) for both SN-PF and LN-PF. For the short-needle forest type, prescribed fire significantly ($p < 0.05$) decreased canopy bulk density and increased 75th percentile quadratic mean diameter.

Surface and Ground Fuel Loads

Prescribed fire altered surface and ground fuel loads more than mechanical treatment (Table 5). For SN-PF, prescribed fire significantly reduced ($p < 0.01$) duff, litter, 1 h, 10 h and 1000 h fuel loads, and fuel bed depth. The LN-PF combination significantly reduced duff, litter, 10 h fuel loads, and fuel bed depth. Mechanical treatments did not significantly alter fuel loads for the red fir forest type and increased loads for the short-needle and long-

Table 4. Pre- and post- treatment average (standard error) stand characteristics for the five forest-treatment combinations. Due to changes in sampling procedure, not all plots had tree data collected. Sample size (number of plots) for each forest-treatment combination is noted in the table.

Forest-treatment[1]	Status	Tree density (ha^{-1})	Canopy cover (%)	Canopy base height (m)	Canopy bulk density (kg m^{-3})	Quadratic mean diameter[2] (cm)
SN-MT *n* = 6	Pre	1201 (183)[a]	71 (11)[a]	1.2 (1.8)[a]	0.104 (0.006)[a]	17.8 (7.6)[a]
	Post	578 (141)[a]	54 (11)[a]	3.4 (3.0)[a]	0.066 (0.014)[a]	25.4 (7.6)[a]
LN-MT *n* = 14	Pre	427 (126)[a]	60 (7)[a]	4.0 (1.2)[a]	0.054 (0.005)[a]	38.1 (5.1)[a]
	Post	183 (96)[a]	34 (8)[a]	7.6 (2.1)[a]	0.039 (0.007)[a]	45.7 (5.1)[a]
RF-MT *n* = 6	Pre	893 (198)[a]	38 (13)[a]	1.2 (2.1)[a]	0.178 (0.0035)[a]	33.0 (7.6)[a]
	Post	561 (151)[a]	28 (12)[a]	4.3 (3.4)[a]	0.122 (0.036)[a]	43.2 (7.6)[a]
SN-PF *n* = 10	Pre	462 (141)	74 (7)	4.3 (1.2)[a]	0.063 (0.009)[b]	35.6 (5.1)[b]
	Post	351 (106)	74 (10)	7.3 (2.4)[a]	0.049 (0.009)[b]	38.1 (5.1)[b]
LN-PF *n* = 27	Pre	408 (86)	49 (5)	3.7 (0.3)[a]	0.084 (0.008)	35.6 (2.5)
	Post	356 (69)	46 (6)	6.1 (1.5)[a]	0.074 (0.007)	38.1 (2.5)

[1] SN, short-needle; LN, long-needle; RF, red fir; MT, mechanical treatment; PF, prescribed fire
[2] 75th percentile quadratic mean diameter
[a] denotes a significant difference ($p < 0.01$) and [b] denotes a significant difference ($p < 0.05$) before and after treatment for the given forest-treatment combination for the specific metric

Table 5. Pre- and post- treatment average (standard error) surface and ground fuel loads for the five forest-treatment combinations. Number of plots for each forest-treatment combination is noted in the table. SN, short-needle; LN, long-needle; RF, red fir; MT, mechanical treatment; PF, prescribed fire.

Forest-treatment	Status	Duff	Litter	1 h	10 h	100 h	1000 h	Fuel bed depth
		t ha^{-1}						cm
SN-MT *n* = 11	Pre	58.3 (22.4)	39.7 (4.0)	1.1 (0.2)	2.5 (1.6)[b]	3.4 (2.2)	33.6 (40.4)[a]	18.3 (9.1)
	Post	56.0 (13.5)	67.3 (2.2)	1.6 (0.3)	4.7 (1.3)[b]	6.5 (2.2)	47.1 (0.2)[a]	18.3 (2.7)
LN-MT *n* = 18	Pre	121.1 (15.7)	185.2 (2.7)	0.2 (0.2)	2.9 (1.1)[a]	3.6 (1.6)[a]	42.6 (29.1)	15.2 (6.1)
	Post	103.1 (11.2)	141.2 (17.9)	0.7 (0.2)	7.4 (1.1)[a]	10.3 (1.8)[a]	17.9 (0.2)	21.3 (2.1)
RF-MT *n* = 11	Pre	87.4 (26.9)	26.2 (4.7)	1.3 (0.4)	5.6 (2.0)	4.7 (2.5)	42.6 (49.3)	15.2 (9.1)
	Post	89.7 (15.7)	25.1 (2.5)	1.8 (0.4)	6.5 (1.3)	5.4 (2.5)	24.7 (0.4)	12.2 (2.7)
SN-PF *n* = 12	Pre	130.0 (13.5)[a]	116.3 (2.5)[a]	1.3 (0.2)[a]	9.0 (1.1)[a]	9.6(1.3)	98.6 (26.9)[a]	18.3 (6.1)[a]
	Post	44.8 (11.2)[a]	9.6 (2.0)[a]	0.2 (0.2)[a]	2.5 (1.1)[a]	4.9(2.0)	4.5 (0.2)[a]	9.1 (2.4)[a]
LN-PF *n* = 30	Pre	94.2 (9.0)[a]	133.2 (1.8)[a]	0.7 (0.1)	3.6 (0.7)[b]	3.8 (0.9)	29.1 (17.9)	24.4 (3.0)[a]
	Post	40.4 (9.0)[a]	14.6 (1.3)[a]	0.2 (0.2)	1.8 (0.7)[b]	3.4 (1.3)	15.7 (0.2)	6.1 (1.5)[a]

[a] denotes a significant difference ($p < 0.01$)
[b] denotes a significant difference ($p < 0.05$) before and after treatment for the given forest-treatment combination for the specific metric

needle forest types. Both 10 h ($p < 0.05$) and 1000 h ($p < 0.01$) fuel loads significantly increased for SN-MT, and 10 h and 100 h fuel loads significantly ($p < 0.01$) increased for LN-MT after treatment.

Modeled Fire Behavior

Pre-treatment modeled fire type for all fuel treatment combinations was either surface or passive crown fire with 90th percentile wind-speed (Figure 2a) and surface, passive crown, conditional crown, or active crown fire with the gust windspeed (Figure 2b). Post-treatment modeled fire type is less intense than pre-treatment for most forest-treatment combinations under both wind scenarios. The exception is for the SN-MT and RF-MT groups under the 90th percentile windspeed where they remained unchanged as surface fire (Figure 2a).

Flame length (FL), fireline intensity (FI), and rate of spread (ROS) were higher for the gust windspeed when compared to 90th percentile windspeed pre- and post-treatment for all forest types (Figure 3). Flame length typically decreased post-treatment, except for the short-needle and red fir forest types with mechanical treatment for 90th percentile windspeed where there was an increase and no change, respectively (Figure 3a). Fireline intensity also tended to decrease post-treatment (Figure 3b). Exceptions were seen with increasing FI for SN-MT under 90th percentile windspeed. Rate of spread decreased post-treatment with prescribed fire treatment (Figure 3c). Mechanical treatment had varied effects on ROS for the two windspeed scenarios; ROS remained unchanged pre- and post-treatment for LN-MT and RF-MT under gust and 90th percentile windspeeds, respectively (Figure 3c).

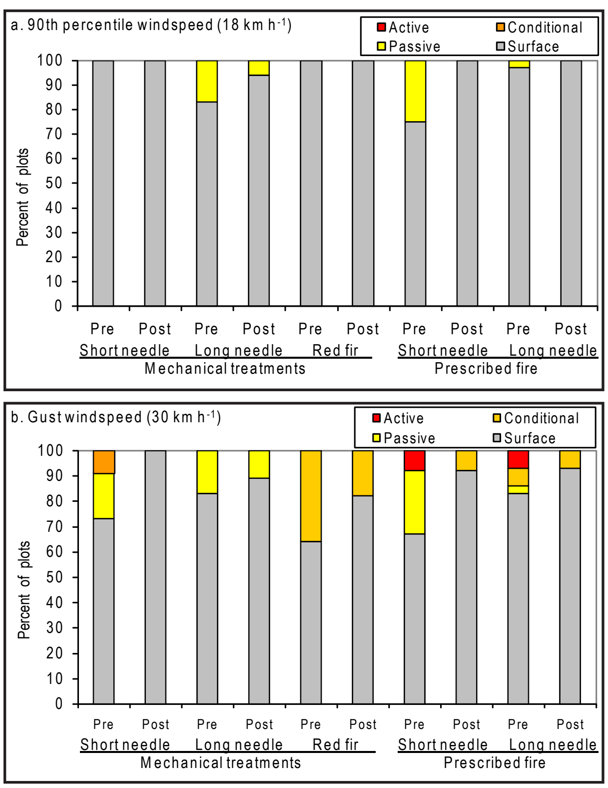

Figure 2. Pre- and post-treatment modeled fire type (surface, passive crown, conditional crown and active crown) for the a) 90th percentile and b) gust wind scenarios for the five forest-treatment combinations.

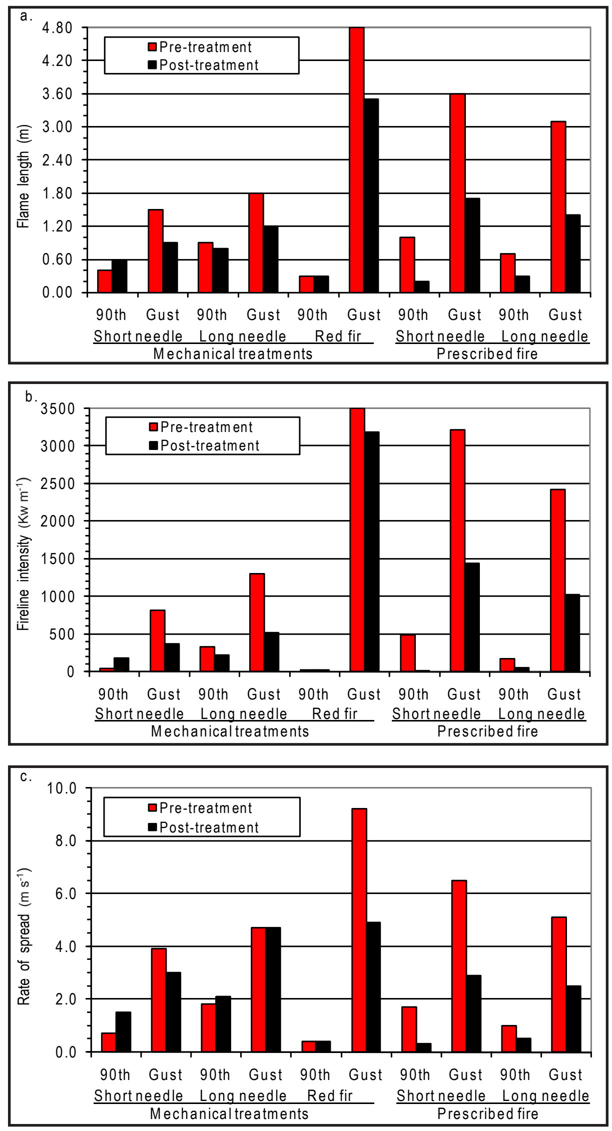

Figure 3. Pre- and post-treatment modeled a) flame length, b) fireline intensity, and c) rate of spread for the 90th percentile and gust wind scenarios for the five forest-treatment combinations.

DISCUSSION

Fire behavior modeling that utilizes pre- and post-treatment fuel measurements allows managers to assess the effectiveness of completed fuel treatments to reduce undesirable fire behavior. Specifically, modeled fire type can be used to assess the effectiveness of completed fuel treatments to alter predicted fire behavior based on changes to surface, ladder, and crown fuels. Mechanical treatments significantly reduced tree density, canopy cover, and canopy bulk density and increased canopy base height and 75th percentile quadratic mean diameter for all three forest types, which is consistent with past studies (Pollet and Omi 2002, Stephens and Moghaddas 2005a, Harrod *et al.* 2007). These changes in stand metrics correlate to reductions in both ladder and canopy fuels. Levels of surface fuel loads are dependant on the type of mechanical treatment utilized and are often higher than pre-treatment conditions (Stephens 1998, Raymond and Peterson 2005, Stephens and Moghaddas 2005b, Stephens *et al.* 2009). General trends in this study suggest that mechanical treatments will result in a decrease of ladder and canopy fuels, and an increase in larger diameter surface fuels.

Mechanical treatments had mixed effects on fire type. With 90th percentile windspeed, two of the three forest types were predicted to have surface fire pre- and post-treatment, and the third experienced a reduction in potential passive crown fire as a result of treatment. With gusty winds, all three forest types were predicted to experience some passive or conditional crown fire pre-treatment, and two of the three sites maintained some crown fire post-treatment, although the proportion was reduced. The mixed results found in this study are likely due to the relatively low number of replicates and the variety of mechanical treatments implemented. Some of the mechanical treatments targeted overstory fuels (i.e., whole tree removal and thinning) and others ladder and surface fuels (i.e., hand cutting and piling, thinning followed by chipping, and mastication). For example, RF-MT had the highest post-treatment canopy bulk density out of all five forest-treatment combinations, resulting in the highest proportion of post-treatment conditional crown fire. The LN-MT treatments had elevated levels of 1 h, 10 h and 100 h fuels post-treatment, resulting in the only post-treatment forest-combination to retain some passive crown fire. The variety of treatments completed and the fact that no fuel treatment will uniformly alter forest and fuel structure due to the inherent variability in natural ecosystems explains part of the resulting modeled fire type.

Prescribed fire significantly reduced ground and surface fuel loads without large changes to overstory canopy fuels, which is consistent with many studies in forested ecosystems in California (i.e., van Wagtendonk 1996, Knapp *et al.* 2005, Stephens and Moghaddas 2005a, Keifer *et al.* 2006, Vaillant *et al.* 2009). The increase in canopy base height and decrease in small diameter trees found in many of the prescribed fire treated plots of this study represent a reduction of ladder fuels. This reduction of ladder and surface fuels is important because it decreased or eliminated post-treatment potential for crown fire behavior, resulting in lower potential tree mortality and fire severity. Further treatment targeting overstory canopy fuels would likely reduce or eliminate modeled conditional crown fire under gusting winds.

Predicted flame length and fireline intensity are also used to assess the effectiveness of a fuel treatment. Guidelines exist for fire suppression capabilities based on FL and FI (Rothermel 1983) and are categorized as low (FL ≤ 1.2 m, FI ≤ 346 kW m^{-1}), moderate (FL > 1.2 m to 2.4 m, FI > 346 kW m^{-1} to 1730 kW m^{-1}), high (FL > 2.4 m to 3.4 m, FI > 1730 kW m^{-1} to 3459 kW m^{-1}) and extreme (FL > 3.4 m, FI > 3459 kW m^{-1}). Each category of fire behavior relates to a greater difficulty in controlling a wildland fire. Low and moderate fire behavior are typically surface fire, and high and extreme fire behavior are characteristic of crown fire with spotting fires (Rothermel 1983). Ideally, post-treatment predicted FL and FI would be characterized as low. Under 90th percentile windspeeds, all sites exhibit low FL and FI post-treatment. With gust windspeed, only one forest-treatment combination (SN-MT) is expected to have low fire behavior; the remaining four are predicted to have moderate to high fire behavior post-treatment. This elevated fire behavior often reduces the ability of fire suppression resources to extinguish a fire.

Although rate of spread does not have distinct categories as do flame length and fire line intensity, it can also be used to assess treatment effectiveness. Lower ROS coupled with lower FL and FI can result in smaller fire extent and affords fire suppression resources more opportunity to control a fire. Prescribed fire reduced ROS under both wind scenarios. The decrease of FL, FI, and ROS due to prescribed fire is not surprising given the reduction in surface fuels, which is similar to findings in past research (van Wagtendonk 1996, Knapp *et al.* 2005, Stephens and Moghaddas 2005a, Keifer *et al.* 2006, Vaillant *et al.* 2009). As with fire type, mechanical treatments had varied effects on ROS under both windspeeds. This mixed effect is likely due to the variety of mechanical treatments, their associated impact on surface and canopy fuels, and the assumptions used to characterize these changes when applying fire behavior models. Consequently, when evaluating the effectiveness of mechanical treatments, it is important to take into consideration the treatment prescription, the treatment objective, and the resultant impact on surface and canopy fuels.

When devising fuel treatments, land managers should consider the effect of the treatment on many factors, including potential wildfire behavior, fuels, vegetation, wildlife, aquatic systems, water, air, soils, cultural resources, and economics (Peterson and Johnson 2007). The decision between using mechanical methods and prescribed fire is not often straightforward. While prescription burning restores fire to the landscape and reduces surface fuel loads, issues such as smoke management, risk of fire escape, and difficulty of burn implementation can limit the ability to use prescribed fire (Stephens and Moghaddas 2005b, Stephens and Ruth 2005). Mechanical treatments have increased precision and do not create hazards associated with prescribed fire such as smoke and risk of escape (Stephens and Moghaddas 2005b, Huggett *et al.* 2008). However, mechanical treatments can cause soil disturbance (Neary *et al.* 1999), disruption to nutrient cycling (Jurgensen *et al.* 1997), and possible damage to trees left after treatment. Two of the many reasons mechanical treatments were chosen over prescribed fire for this study were proximity to homes and the need to alter forest and fuel structure before reintroducing fire to the treatment area.

This study showed that both prescribed fire and mechanical treatments were successful in reducing potential fire behavior with 90th percentile and gust windspeeds, which met the overriding clause in the National Fire Plan (USDA-USDI 2000), 10-Year Comprehensive Strategy (WGA 2001), and Healthy Forests Restoration Act (HFRA 2003). However, with a faster windspeed, four of the five forest-treatment combinations would benefit from more extensive or further treatment based on modeled fire type, FL, and FI. It must be stated that the fuel treatments were designed to withstand 90th percentile fire weather conditions, not the gust windspeeds modeled in this study. The fact that the treatments generally did not perform as well under the elevated windspeed raises the question of how managers might need to design fuel treatments to withstand the more extreme fire weather conditions projected for the future climate in California (Brown *et al.* 2004, Fried *et al.* 2008, Lenihan *et al.*

2008). Are the 90th percentile fire weather conditions of today going to be the 80th or 85th percentile of the near future? Do managers today need to start planning for tomorrow and implement treatments to withstand current 95th or 97.5th percentile conditions?

An additional goal of the National Fire Plan, the 10-Year Comprehensive Strategy, and the Healthy Forests Restoration Act was to target areas where the risk of negative impacts from wildland fire is the greatest. With 90th percentile windspeed, all forest-treatment combinations had low FL pre-treatment, and SN-MT and RF-MT had 100 % predicted surface fire. With gusting winds, all five forest-treatment combinations did have some plots with predicted crown fire pre-treatment, but SN-MT and LN-MT were only predicted to exhibit moderate pre-treatment fire behavior. With limited resources for implementing fuel treatments, it might be worth concentrating efforts in areas where fire behavior is predicted to be high or extreme as is the case with RF-MT, SN-PF, and LN-PF with gusting winds.

Another concern with fuel treatments is their effectiveness to maintain reduced potential fire behavior over time. The question of how frequent fuel treatments need to be retreated and with what methods is still relatively unknown (Agee *et al.* 2000, Graham *et al.* 2004, Finney *et al.* 2005, Huggett *et al.* 2008, Schmidt *et al.* 2008). Keifer *et al.* (2006) have shown that the majority of fuel accumulation occurs in the first 10 years after prescribed burning in the central and southern Sierra Nevada; however, the post-treatment fuel complex is different than the pre-treatment conditions. The alteration in fuel complex is likely due to the high proportion (>60 %) of trees killed from the treatment falling and contributing to the woody surface fuel loads (Keifer *et al.* 2006). The study by Keifer *et al.* (2006) is unique in the rich history of prescribed fire management, but their study did not include mechanical treatments. Our study presents an opportunity to continue long term monitoring of forest and fuel changes over time. This information could be used to better understand the longevity of fuel treatment effectiveness for three coniferous forest types and two treatment options for California.

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LITERATURE CITED

Agee, J.K., B.B. Bahro, M.A. Finney, P.N. Omi, D.B. Sapsis, C.N. Skinner, J.W. van Wagtendonk, and C.P. Weatherspoon. 2000. The use of shaded fuelbreaks in landscape fire management. Forest Ecology and Management 127: 55-66.

Agee, J.K., and C.N. Skinner. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management 211: 83-96.

Agee, J.K., and M.R. Lolley. 2006. Thinning and prescribed fire effects on fuels and potential fire behavior in and eastern Cascades forest, Washington, USA. Fire Ecology 2(2): 3-19.

Albini, F.A., and R.G. Baughman. 1979. Estimating windspeeds for predicting wildland fire behavior. USDA Forest Service Research Paper INT-221.

Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. USDA Forest Service General Technical Report INT-122.

Beaty, R.M., and A.H. Taylor. 2001 Spatial and temporal variation of fire regimes in a mixed conifer forest landscape, southern Cascades, California, USA. Journal of Biogeography 28: 955-966.

Brown, J.K. 1974. Handbook for inventorying downed woody material. USDA Forest Service General Technical Report INT-16.

Brown, J.K., R.D. Oberheu, and C.M. Johnson. 1984. Handbook for inventorying surface fuels and biomass in the interior west. USDA Forest Service General Technical Report INT-129.

Brown, T.J., B.L. Hall, and A.L. Westerling. 2004. The impact of twenty-first century climate change on wildland fire danger in the western United States, an applications perspective. Climate Change 62: 365-388.

Covington, W.W. 2000. Helping western forests heal, the prognosis is poor for US forest ecosystems. Nature 408: 135-136.

Crookston, N.L., and A.R. Stage. 1991. User's guide to the parallel processing extension of the prognosis model. USDA Forest Service General Technical Report INT-281.

Crosby J.S., and C.C. Chandler. 1966. Get the most from your windspeed observations. Fire Control News 27(4): 12-13.

Finney, M.A. 2006. An overview of FlamMap fire modeling capabilities. Pages 213-220 in: P.L. Andrews and B.W. Butler, compilers. Fuels management—how to measure success. USDA Forest Service Proceedings RMRS-P-41.

Finney, M.A., C.W. McHugh, and I.C. Grenfell. 2005. Stand- and landscape-level effects of prescribed burning on two Arizona wildfires. Canadian Journal of Forest Research 35: 1714-1722.

Fried, J.S., J.K. Gilless, W.R. Riley, T.J. Moody, C. Simon de Blas, K. Hayhoe, M. Moritz, S. Stephens, and M. Torn. 2008. Predicting the effect of climate change on wildfire behavior and initial attack success. Climate Change 87(Supplement 1): S251-S264.

Fry, D.L., and S.L. Stephens. 2006. Influence of humans and climate on the fire history of a ponderosa pine-mixed conifer forest in the southeastern Klamath Mountains, California. Forest Ecology and Management 223: 428-438.

Gill, S.J., S.G. Biging, and E.C. Murphy. 2000. Modeling conifer tree crown radius and estimating canopy cover. Forest Ecology and Management 126: 405-416.

Graham, R.T., S. McCaffrey, and T.B. Jain, technical editors. 2004. Science basis for changing forest structure to modify wildfire behavior and severity. USDA Forest Service General Technical Report RMRS-GTR-120.

Harrod, R.J, N.A. Povak, and D.W. Peterson. 2007. Comparing the effectiveness of thinning and prescribed fire for modifying structure in dry coniferous forests. Pages 1-18 in: B.W. Butler and W. Cook, compilers. The fire environment innovations, management, and policy. USDA Forest Service Proceedings RMRS-P-46CD.

HRFA [Healthy Forest Restoration Act]. 2003. HR 1904.

Huggett, R.J., K.L Abt, and W. Shepperd. 2008. Efficacy of mechanical fuel treatments for reducing wildfire hazard. Forest Policy and Economics 10: 408-414.

Kalabokidis, K.D., and P.N. Omi. 1998. Reduction of fire hazard through thinning/residue disposal in the urban interface. International Journal of Wildland Fire 8(1): 29-35.

Keifer, M., J.W. van Wagtendonk, and M. Buhler. 2006. Long-term surface fuel accumulation in burned and unburned mixed-conifer forests of the central and southern Sierra Nevada, CA (USA). Fire Ecology 2(1): 53-72.

Keyes, C.R., and K.L. O'Hara. 2002. Quantifying stand targets for silvicultural prevention of crown fires. Western Journal of Applied Forestry 17(2): 101-109.

Knapp, E.E., J.E. Keeley, E.A. Ballenger, and T.J. Brennan. 2005. Fuel reduction and coarse woody debris dynamics with early and late season prescribed fire in a Sierra Nevada mixed conifer forest. Forest Ecology and Management 208: 383-397.

Jurgensen, M.F., A.E. Harvey, R.T. Graham, D.D. Page-Dumroese, J.R. Torn, M.J. Larsen, and T.B. Jain. 1997. Impacts of timber harvesting on soil organic matter, nitrogen, productivity, and health of inland northwest forests. Forest Science 42: 234-251.

Lenihan, J.M., D. Banchelet, R.P. Neilson, and R. Drapek. 2008. Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California. Climatic Change 87(Supplement 1): S215-S230.

Martinson, J., and P.N. Omi. 2003. Performance of fuel treatments subjected to wildfires. Pages 7-13 in: P.N. Omi and L.A. Joyce, technical editors. Fire, fuel treatments, and ecological restoration. USDA Forest Service Proceedings RMRS-P-29.

McCulloch, C.E., and S.R. Searle. 2001. Generalized, linear, and mixed models. John Wiley & Sons, New York, New York, USA.

Millar, C.I., N.L. Stephenson, and S.L. Stephens. 2007. Climate change and forests of the future, managing in the face of uncertainty. Ecological Applications 17(8): 2145–2151.

Miller, J.D., H.D. Safford, M. Crimmins, and A.E. Thode. 2009. Quantitative evidence for increasing forest fire severity in the Sierra Nevada and southern Cascade Mountains, California and Nevada, USA. Ecosystems 12: 16-32.

Moghaddas, J.J., and L. Craggs. 2007. A fuel treatment reduces fire severity and increases suppression efficiency in a mixed conifer forest. International Journal of Wildland Fire 16: 673-678.

Moody, T.J., S.L. Stephens, and J. Fites-Kaufman. 2006. Fire history and climate influences from forests in the northern Sierra Nevada, USA. Fire Ecology 2(1): 115-141.

National Oceanic and Atmospheric Administration [NOAA]. 2007. National Weather Service climate data. < http://www.nws.noaa.gov/>. Accessed 12 February 2007.

National Park Service [NPS]. 2003. Fire monitoring handbook. Fire Management Program Center, National Interagency Fire Center, Boise, Idaho, USA.

Neary, D.G., C.C. Klopatek, L.F. DeBano, and P.F. Ffolliott. 1999. Fire effects on belowground sustainability, a review and synthesis. Forest Ecology and Management 122: 51-71.

Noonan-Wright, E.K., L. Wilson, and J. Fites-Kaufman. 2006. The calculation of canopy fuels and predicted fire behavior from the Region 5 prescribed fire and fuel treatment effectiveness and effects monitoring program. Proceedings of the 2006 Fire Ecology and Management Congress. Association for Fire Ecology, 13-17 November 2006, San Diego, California, USA.

Peterson, D.L., J.K. Agee, T. Jain, M. Johnson, D. McKenzie, and E. Reinhardt. 2003. Fuels planning, managing forest structure to reduce fire hazard. Proceedings of the 2nd International Wildland Fire Ecology and Fire Management Congress. Association for Fire Ecology, 16-20 November 2003, Orlando, Florida, USA.

Peterson, D.L., and M.C. Johnson. 2007. Science-based strategic planning for hazardous fuel treatment. Fire Management Today 67(3): 13-18.

Pollet, J., and P.N. Omi. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. International Journal of Wildland Fire 11: 1-10.

Raymond, C.L., and D.L. Peterson. 2005. Fuel treatments alter the effects of wildfire in a mixed-evergreen forest, Oregon, USA. Canadian Journal of Forest Research 35: 2981-2995.

Ritchie, M.W., C.N. Skinner, and T.A. Hamilton. 2007. Probability of tree survival after wildfire in an interior pine forest of northern California: effects of thinning and prescribed fire. Forest Ecology and Management 247: 200-208.

Reinhardt, E.D., and N.L. Crookston, technical editors. 2003. The fire and fuels extension to the forest vegetation simulator. USDA Forest Service General Technical Report RMRS-GTR-116.

Roccaforte, J.P., P.Z. Fulé, and W.W. Covington. 2008. Landscape-scale changes in canopy fuels and potential fire behavior following ponderosa pine restoration treatments. International Journal of Wildland Fire 17: 293-303.

Rothermel, R.C. 1983. How to predict the spread and intensity of forest and range fires. USDA Forest Service General Technical Report INT-143.

Schmidt, D.A., A.H. Taylor, and C.N. Skinner. 2008. The influence of fuels treatment and landscape arrangement on simulated fire behavior, southern Cascade range, California. Forest Ecology and Management 255(8-9): 3170-3184.

Scott, J.H. 1999. NEXUS, a system for assessing crown fire hazard. Fire Management Notes 59: 21-24.

Scott, J.H., and E.D. Reinhardt. 2001. Assessing crown fire potential by linking models of surface and crown fire behavior. USDA Forest Service Research Paper RMRS-RP-29.

Scott, J.H., and R.E. Burgan. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. USDA Forest Service General Technical Report RMRS-GTR-153.

Stephens, S.L. 1998. Evaluation of the effects of silvicultural and fuels treatments on potential fire behaviour in Sierra Nevada mixed-conifer forests. Forest Ecology and Management 105: 21-35.

Stephens, S.L., and B.M. Collins. 2004. Fire regimes of mixed conifer forests in the north-central Sierra Nevada at multiple spatial scales. Northwest Science 78(1): 12-23.

Stephens, S.L., and J.J. Moghaddas. 2005a. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. Forest Ecology and Management 215: 21-36.

Stephens, S.L., and J.J. Moghaddas. 2005b. Silvicultural and reserve impacts on potential fire behavior and forest conservation: twenty-five years of experience from Sierra Nevada mixed conifer forests. Biological Conservation 125: 369-379.

Stephens, S.L., and L.W. Ruth. 2005. Federal forest fire policy in the United States. Ecological Applications 15: 532-542.

Stephens, S.L., J.J. Moghaddas, C. Edminster, C.E. Fiedler, S. Haase, M. Harrington, J.E. Keeley, E.E. Knapp, J.D. McIver, K. Metlen, C.N. Skinner, and A. Youngblood. 2009. Fire treatment effects on vegetation structure, fuels, and potential fire severity in western US forests. Ecological Applications 19(2): 305-320.

Sugihara, N.G., J.W. van Wagtendonk, and J. Fites-Kaufman. 2006. Fire as an ecological process. Pages 58-74 in: N.G. Sugihara, J.W. van Wagtendonk, J. Fites-Kaufman, K.E. Shaffer, and A.E. Thode, editors. Fire in California's ecosystems. University of California Press, Berkeley, USA.

USDA-USDI. 2000. National fire plan, a report to the president in response to the wildfires of 2000. <http://www.forestsandrangelands.gov/NFP/index.shtml>. Accessed September 2008.

Vaillant, N.M. 2008. Sagehen Experimental Forest past, present and future: an evaluation of the fireshed assessment process. Dissertation, University of California, Berkeley, USA.

Vaillant, N.M., J. Fites-Kaufman, and S.L. Stephens. 2009. Effectiveness of prescribed fire as a fuel treatment in Californian coniferous forests. International Journal of Wildland Fire 18: 165-172.

van Wagtendonk, J.W. 1996. Use of a deterministic fire growth model to test fuel treatments. Pages 1155-1166 in: D.C. Erman, editor. Sierra Nevada ecosystems project, final report to congress, vol. II. Assessments and Scientific Basis for Management Options. University of California, Davis, Centers for Water and Wildland Resources Report 37.

van Wagtendonk, J.W., J.M. Benedict, and W.M. Sydoriak. 1996. Physical properties of woody fuel particles of Sierra Nevada conifers. International Journal of Wildland Fire 6: 117-123.

VanWagner, C.E. 1968. The line intercept method in forest fuel sampling. Forest Science 14: 20-26.

VanWagner, C.E. 1977. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research 7: 23-34.

Westerling, A.L., H.G. Hildago, D.R. Cayan, and T.W. Swetnam. 2006. Warming and earlier spring increases western US forest wildfire activity. Science 313: 940-943.

Western Regional Climate Center [WRCC]. 2007. Monthly wind data for California. <http://www.wrcc.dri.edu/>. Accessed 12 February 2007.

WGA [Western Governor's Association]. 2001. A collaborative approach for reducing wildland fire risks to communities and the environment: 10-year comprehensive strategy. <http://www.westgov.org/wga_reports.htm>. Accessed September 2008.

Zar, J.H. 1999. Biostatistical analysis. Fourth edition. Prentice-Hall, Upper Saddle River, New Jersey, USA.