Effectiveness of Prescribed Fire as a Fuel Treatment in Californian Coniferous Forests

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Abstract—*Effective fire suppression for the past century has altered forest structure and increased fuel loads. Prescribed fire as a fuels treatment can reduce wildfire size and severity. This study investigates how prescribed fire affects fuel loads, forest structure, potential fire behavior, and modeled tree mortality at 80th, 90th, and 97.5th percentile fire weather conditions on eight National Forests in California. Potential fire behavior and effects were modeled using Fuel Management Analyst. Prescription burning did not significantly change forest structure at most sites. Total fuel loads (litter, duff, 1, 10, 100, and 1000-hour) were reduced by 23 to 78 percent across the sites. This reduction in fuels altered potential fire behavior by reducing rate of spread, flame length, and fireline intensity. Increased torching index values coupled with decreased fuel loads reduced crown fire potential post-treatment in some stands. Predicted tree mortality decreased post-treatment as an effect of reduced potential fire behavior and fuel loads. With the vast forested areas classified at high risk for catastrophic wildland fire in California, it is most efficient to target stands that benefit the most from treatment.*

Introduction

In many coniferous forests, fire suppression has lead to higher tree densities (Biswell 1959), changes in species composition (Weaver 1943), and higher fuel loads (Dodge 1972), which have altered fire regimes (Beaty and Taylor 2001; Stephens and Collins 2004). A recent analysis of fire cause and extent on U.S. Forest Service (USFS) lands from 1940 to 2000 demonstrated that California experienced a significant increase in the total number of fires and had the most area burned relative to other regions in the United States (Stephens 2005). Although the area burned has not significantly increased from 1940 to 2000 in California (Stephens 2005), the wildland fire problem has only worsened as suppression has become more effective (Brown and Arno 1991).

Fuels treatments can be effective at reducing the severity (Pollet and Omi 2002; Agee and Skinner 2005; Finney and others 2005) and size of wildland fires (Stephens 1998; Piñol and others 2005). Reduction of surface fuels, and in some cases crown fuels, can reduce the likelihood of crown fires (van Wagner, 1977). Typically, mechanical methods are used to alter stand structure (i.e., reduce tree density, decrease basal area, increase the height to live crown base, and reduce canopy cover) (Keyes and O'Hara 2002; Pollet and Omi, 2002; Stephens and Moghaddas, 2005a,b). Prescribed fire alone can decrease surface and ladder fuels which reduce potential fire behavior and thus lower the risk of crown fire and spot fire ignition (van Wagtendonk 1996; Stephens 1998).

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The objective of this study is to determine how prescribed fire effects fuel loads, vegetation structure, and potential fire behavior and effects in eight National Forests in California. The null hypothesis investigated is that there will be no significant difference in vegetation structure, fuel load, fire behavior, and predicted tree mortality at each study site when comparing pre- and post-treatment characteristics. Information from this study could be used to assist in the development of forest management plans that use prescribed fire to reduce fire hazards.

Methods

Study Location

Nine project sites are located on eight National Forests: the Klamath (one on the eastern section, KNF E, and one on the western section, KNF W), Lassen (LNF), Los Padres (LPF), Modoc (MDF), Mendocino (MNF), Plumas (PNF), Shasta-Trinity (SHF) and Sierra (SNF) (fig. 1). LPF, MDF, MNF, and SNF are dominated by yellow pine [>80% of basal area is composed of ponderosa pine (*Pinus ponderosa* Laws) or Jeffrey pine (*Pinus jeffreyi* Grev.)] and KNF E, KNF W, PNF, and SHF are in mixed-conifer forests.

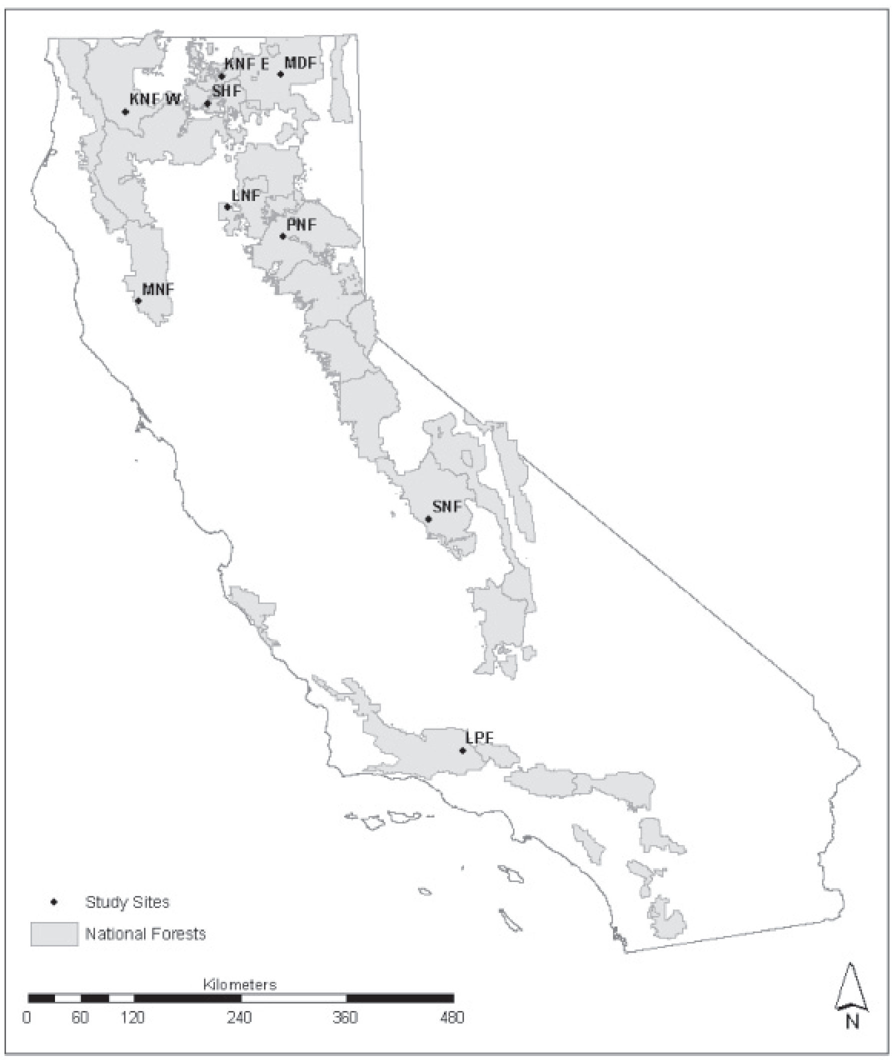

Figure 1—Location of study sites.

Climate in the study sites is Mediterranean with a summer drought period that extends into the fall. The majority of precipitation occurs during winter and spring. Tree species present include ponderosa pine, Jeffrey pine, sugar pine (*Pinus lambertiana* Dougl.), white fir (*Abies concolor* Gord. and Glend.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), incense-cedar (*Calocedrus decurrens* Torr.), western juniper (*Juniperus occidentalis* Hook.), California black oak (*Quercus kelloggii* Newb.), canyon live oak (*Quercus chrysolepis* Liebm.), and bigleaf maple (*Acer macrophyllum* Pursh).

The average elevation of the study sites ranges from approximately 1000 to 1600 m. Average slopes vary from three to 61 percent. Pre-treatment percent-cover of tree canopy, shrubs, and grasses varies between study locations.

Treatments

All of the study sites were treated with prescribed fire. The primary objectives of the prescribed burns were to reduce the potential for catastrophic stand replacing fire events and to reintroduce fire into the ecosystem. Each of the National Forests implemented their own prescribed fires. The prescribed fires occurred either in spring or fall depending on weather, available personnel, and funding, with the majority of prescribed fires taking place in the spring (six out of nine).

Vegetation Measurements

In each of the nine project sites, vegetation was measured using 0.2 ha randomly-placed, permanently-marked circular plots (26 total plots). Tree information was collected in two nested subplots; 0.1-ha for all trees greater than 15 cm diameter at breast height (d.b.h.), and 0.025 ha for trees 2.5 to 15 cm d.b.h. Tree measurements (species, d.b.h., height, height to live crown base (HTLCB), and tree crown position (dominant, codominant, intermediate or suppressed)) are recorded for live trees; for snags species, d.b.h., and total height was recorded. Canopy cover was measured every meter along two perpendicular 50 m transects using a Moosehorn sight tube (Gill and others 2000). Shrub measurements were also taken along the same transects in each of the plots to estimate percent shrub cover. An ocular estimate of percent cover by grasses was made along the shrub transect in a 1 m^2 frame every 10 m.

Ground and Surface Fuel Characteristics

Surface and ground fuels were measured with four transects in each of the plots using the line-intercept method (van Wagner 1968; Brown 1974). For each transect, one-hour (0 to 0.64 cm diameter) and 10-hour (0.64 to 2.54 cm diameter) fuels were sampled from 0 to 1.83 m, 100-hour fuels (2.54 to 7.62 cm diameter) from 0 to 3.66 m, and 1000-hour fuels (diameter >7.62 cm) from 0 to 15.24 m. Species, diameter, and decay status (rotten or sound) were recorded for all 1000-hour fuels. Litter, duff, and fuel bed depth (cm) measurements were taken every 1.52 m totaling 10 per transect. Surface and ground fuel loads were calculated using arithmetically-weighted coefficients specific to the California tree species based on the average basal area fraction of the individual sites (van Wagtendonk and others 1998; Stephens and Moghaddas 2005a).

Fire Modeling

Fire behavior and effects were modeled under upper 80^{th}, 90^{th}, and 97.5^{th} percentile fire weather conditions. Eightieth, 90^{th}, and 97.5^{th} percentile fire weather represent moderate, high, and extreme fire weather, respectively. Percentile weather was computed using Fire Family Plus (Main and others 1990). Forty-three years (1961 to 2004) of weather data from the most representative Remote Automated Weather Station (RAWS) for each site (NFAM 2004) were analyzed to determine percentile weather conditions.

Fuels Management Analyst (FMA) was used to model fire behavior and effects (rate of spread, flame length, fireline intensity, crowning index, torching index, and tree mortality) (Carlton 2005). Fire behavior predictions were made for stand and fuel structures before and after prescribed burning. A surface fuel model was assigned to each sampling plot based on stand structure, shrub cover, grass cover, and fuel loads (Scott and Burgan 2005).

Data Analysis

Paired t-tests were used to determine if significant differences ($p<0.1$) existed in vegetation (trees ha^{-1}, basal area ha^{-1}, tree height, HTLCB, canopy cover, crown bulk density (CBD)) and fuel loads (litter, duff, 1-hr, 10-hr, 100-hr, 1000-hr sound, 1000-hr rotten, total fuel load (1 to 1000-hr, litter and duff), and fuel depth) for each site pre- and post-prescribed fire (Zar 1999). The choice of $p<0.1$ was made due to high natural variation found between plots in each study site. The number of sample plots varied by site location due to the ability of the individual National Forests to burn the proposed units and because some prescribed fires did not burn the entire intended area.

Results

Forest Structure

The inventory plots in the nine study locations included 860 live trees greater than 2.5 cm d.b.h. pre-treatment and 801 post-treatment. No significant differences were found for any of the measured variables (basal area, trees ha^{-1}, d.b.h., tree height, HTLCB, canopy cover, CBD) at KNF W, MDF, SHF or SNF (table 1). At LNF, LPF, MNF and PNF some but not all of the variables were significantly different (table 1). All variables were significantly different at KNF E except HTLCB.

Fuels Characteristics

A total of 104 fuel transects were analyzed over the nine project sites to characterize surface and ground fuels pre- and post-prescribed burning. All locations had a significant difference post-treatment in at least one of the fuels parameters (table 2). All of the locations except PNF experienced a significant reduction in litter loads. Total fuel load was reduced at all sites; however, the difference was only significant at MNF and LPF.

Potential Fire Behavior

Rate of spread (ROS) increased for all sites with increasing percentile weather (table 3). Post-treatment ROS either decreased or experienced no change when compared to pre-treatment. Flame length (FL) increased with

Table 1—Average pre- and post-treatment vegetation structure for all trees greater than 2.5 cm d.b.h. by site location for nine stands in eight Californian National Forests.

Site	Basal area (m^2 ha^{-1})		Trees (ha^{-1})		DBH (cm)		Tree height (m)		HTLCB (m)		Canopy cover (percent)		CBD (kg m^{-3})	
	Pre	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*
KNF E	37.0[a]	36.0[a]	706.7[a]	533.3[a]	27.2[a]	29.6[a]	14.4[a]	15.6[a]	4.9	4.6	43.2[a]	35.3[a]	0.094[a]	0.091[a]
KNF W	48.2	42.6	585.0	420.0	33.7	34.5	15.0	17.1	3.4	8.9	76.3	70.6	0.054	0.050
LNF	51.9	48.8	490.0[a]	405.0[a]	34.7	36.2	21.0	21.4	8.9	9.4	96.6	93.1	0.046	0.044
LPF	28.1	27.3	600.0	306.7	27.3	37.1	14.3	13.3	3.6	3.2	24.0[a]	19.8[a]	0.049[a]	0.044[a]
MDF	26.9	24.3	313.3	263.3	33.3	34.1	14.3	15.1	3.8	4.8	29.4	30.2	0.057	0.050
MNF	27.3	27.2	520.0	516.0	27.3	26.6	14.0	14.0	4.2	4.2	69.0[a]	50.7[a]	0.090	0.089
PNF	38.1	35.9	423.3	360.0	33.9	35.3	19.3[a]	21.0[a]	7.8[a]	11.3[a]	64.7	62.1	0.069	0.067
SHF	34.4	33.8	163.3	120.0	52.5	58.6	27.9	31.4	10.4	11.7	30.5	27.6	0.034	0.033
SNF	40.7	40.8	525.0	525.0	36.2	36.2	19.1	19.1	7.1	7.1	51.0	44.2	0.074	0.071

HTLCB= height to live crown base, CBD= crown bulk density, [a]=significantly different pre- versus post-treatment.

Table 2—Average fuel loads (metric t ha^{-1}) pre- and post-treatment by site location.

Site	Duff		Litter		1-hr		10-hr		100-hr		1000-hr sound		1000-hr rotten		1-1000-h plus litter, duff		Fuel depth (cm)	
	Pre	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*
KNF E	21.4	2.2	11.1[a]	4.4[a]	1.5	0.9	2.7	1.3	2.8	2.5	3.5	6.5	39.7	0.0	82.7	17.8	28.2[a]	7.7[a]
KNF W	33.2	7.4	18.5[a]	3.0[a]	1.4	0.3	6.1	1.4	5.9	1.3	9.7	6.9	61.4	33.7	136.0	53.9	25.6	12.3
LNF	17.0	9.2	18.9[a]	3.5[a]	2.1	0.6	7.7	3.8	4.5	2.7	7.4	0.8	7.4	29.8	65.1	50.3	14.7	11.5
LPF	22.3[a]	10.0[a]	4.4[a]	1.7[a]	0.6	0.2	1.0	0.8	2.8	4.1	0.0	4.6	13.2	0.0	44.3[a]	21.3[a]	9.7	3.4
MDF	13.6	5.2	5.6[a]	3.8[a]	0.5[a]	0.2[a]	1.2	0.9	1.7[a]	2.8[a]	1.2	0.0	12.0	3.6	35.6	16.5	7.9	3.5
MNF	16.7	14.8	12.9[a]	3.0[a]	0.3	0.4	2.5	1.6	3.6	4.8	2.7	7.3	64.7[a]	12.2[a]	103.5[a]	44.1[a]	67.0[a]	8.3[a]
PNF	22.5	9.0	4.3	10.0	1.3	0.6	2.0	2.1	5.1	3.9	13.8	0.2	25.2	15.3	74.2[a]	41.0[a]	16.2[a]	10.3[a]
SHF	28.9[a]	6.9[a]	5.4[a]	1.9[a]	0.9[a]	0.2[a]	3.4[a]	1.0[a]	7.6	3.1	0.4[a]	9.5[a]	17.6	7.6	64.3	30.2	11.1[a]	7.4[a]
SNF	15.4	8.5	12.1[a]	2.7[a]	0.9	0.5	2.3	0.8	5.3	3.7	1.5	2.5	6.0	2.6	43.6	21.3	51.3	8.1

[a]=significantly different pre- versus post-treatment .

Table 3—Average modeled fire behavior under 80th, 90th, and 97.5th percentile weather by site location.

Site	ROS			FL			FI			TI			CI		
	80th	90th	97.5th	80th	90th	97.5th	80th	90th	97.5th	80th	90th	97.5th	80th	90th	97.5th
Pre	- - ($m\ min^{-1}$) - -			- - - - (m) - - - -			- - - - - - ($kW\ m^{-1}$) - - - - - -			- - - - - - ($km\ h^{-1}$) - - - - - -			- - - - ($km\ h^{-1}$) - - - -		
KNF E	2.9	7.2	15.7	0.6	0.7	6.6	75.5	153	49286.6	152.8	119.5	109.7	41.5	37.2	33.2
KNF W	2.0	12.6	24.9	0.9	4.3	5.2	213.3	10476.3	16751.5	76.1	26.9	24.0	51.6	47.0	41.3
LNF	1.4	1.8	2.1	0.7	0.8	0.9	160.3	201.8	248.6	595.2	462.7	417.3	60.6	56.0	51.4
LPF	3.6	4.6	12.5	1.4	1.5	2.8	570.8	685.4	2950.5	35.3	26.2	23.2	75.9	67.0	60.6
MDF	1.2	1.6	2.9	0.8	1.0	1.2	185.5	245.9	379.3	135.9	104.5	88.5	73.1	68.4	60.8
MNF	6.4	8.3	16.0	3.2	3.7	7.1	5430.0	8500.2	44942.9	48.3	37.6	34.2	34.1	31.4	28.6
PNF	1.5	1.6	1.8	0.6	0.7	0.7	100.8	111.3	129.9	770.3	612.8	560.1	44.2	38.8	32.5
SHF	0.4	0.5	0.7	0.3	0.4	0.4	25.3	30.2	40.4	1894.2	1491.6	1401.0	80.6	75.1	70.4
SNF	1.8	4.5	5.4	0.9	1.4	1.5	22.9	578.4	685.9	212.2	140.1	117.7	45.6	29.8	24.7
Post															
KNF E	0.7	0.9	15.4	0.4	0.4	6.3	33.9	42.6	46828.1	434.7	347.0	321.2	42.8	38.4	34.2
KNF W	0.5	0.7	0.9	0.3	0.3	0.3	15.6	19.7	24.2	3023.2	2422.0	2218.5	58.0	53.0	46.8
LNF	0.5	0.7	0.8	0.3	0.3	0.3	15.9	19.9	21.9	2167.4	1766.4	1650.3	61.8	57.2	52.7
LPF	0.7	0.7	4.6	0.4	0.4	0.5	31.2	33.9	53.4	299.6	238.2	217.8	84.6	74.8	67.8
MDF	0.4	0.5	0.7	0.2	0.3	0.3	12.1	15.9	24.2	619.0	521.8	466.9	85.6	85.9	71.2
MNF	2.4	2.6	3.9	1.2	1.2	1.5	408.4	451.3	659.7	104.7	83.2	76.2	34.3	31.6	28.8
PNF	1.5	1.7	2.0	0.6	0.7	0.7	94.4	107.2	125.4	981.9	782.0	715.1	51.2	45.1	38.1
SHF	0.4	0.5	0.6	0.2	0.3	0.3	12.1	14.5	19.7	2677.8	2134.9	2012.2	82.9	77.2	72.4
SNF	0.6	0.7	0.7	0.3	0.3	0.3	17.7	21.9	21.9	1299.2	1052.0	968.1	47.2	40.4	38.1

ROS-rate of spread; FL-flame length; FI-fireline intensity; TI-torching index; CI-crowning index.

respect to higher percentile fire weather pre-treatment except at PNF and SHF where no change occurred between the 90th and 97.5th percentiles (table 3). FL was shorter post-treatment as compared to pre-treatment in all locations except PNF where it did not change. Modeled fireline intensity (FI) increased as percentile weather increased both pre- and post-treatment for all site locations except SNF (table 3). FI decreased post-treatment as compared to pre-treatment for all site locations. Torching index (TI) decreased as percentile weather increased pre- and post-treatment (table 3). Crowning index (CI) decreased with increasing percentile weather except at MDF where it only increased between the 80th and 90th percentile. CI increased slightly post-treatment for all locations, following the decreasing trend with respect to increasing severity of fire weather.

Fire type (FT) remained 100 percent surface fire in the LNF, PNF, SHF, and SNF sites pre- and post-treatment for all weather scenarios (table 4). Prescribed fire changed predicted FT in the KNF E, KNF W, LPF, MDF, and MNF sites by either decreasing the likelihood of crown fire or decreasing the severity of crown fire. At 80th and 90th percentile fire weather conditions, all post-treatment sites experienced only surface fire.

Predicted Tree Mortality

Probability of mortality was modeled for four diameter classes (2.5 to 25, 25 to 51, 51 to 76, >76 cm d.b.h.) as well as for all trees at each study site pre- and post-treatment (table 5). For all sites, a higher percentage of trees was predicted to die prior to treatment than after treatment. A higher amount of

Table 4—Modeled fire type under 80th, 90th, and 97.5th percentile weather by site location.

Site	80th	90th	97.5th
Pre			
KNF E	33%PCF,66%SF	33%PCF,66%SF	33%ACFWD, 66%SF
KNF W	33%PCF,66%SF	33%SF, 66%PCF	33%SF,33%PCF,33%ACFPD
LNF	100%SF	100%SF	100%SF
LPF	33%PCF,66%SF	33%PCF,66%SF	33%SF, 66%PCF
MDF	100%SF	100%SF	33%PCF, 66%SF
MNF	40%PCF, 60%SF	40%PCF, 60%SF	20%PCF, 20%ACFPD, 60%SF
PNF	100%SF	100%SF	100%SF
SHF	100%SF	100%SF	100%SF
SNF	100%SF	100%SF	100%SF
Post			
KNF E	100%SF	100%SF	33%ACFWD, 66%SF
KNF W	100%SF	100%SF	100%SF
LNF	100%SF	100%SF	100%SF
LPF	100%SF	100%SF	33%PCF, 66%SF
MDF	100%SF	100%SF	100%SF
MNF	100%SF	100%SF	100%SF
PNF	100%SF	100%SF	100%SF
SHF	100%SF	100%SF	100%SF
SNF	100%SF	100%SF	100%SF

SF=surface fire; PCF=passive crown fire; ACFWD=active crown fire wind driven; ACFPD=active crown fire plume dominated.

mortality was predicted in smaller diameter classes (2.5 to 25 cm and 25 to 51 cm d.b.h.) regardless of location, weather condition, or treatment status. An increase in mortality with respect to increasing predicted fire weather conditions occurred in most study sites prior to prescribed fire; the trend was not the same post-treatment (table 5).

Table 5—Average pre- and post-prescribed burn percent predicted mortality by diameter class and site location for three percentile weather conditions.

	DBH range (cm)	KNF E	KNF W	LNF	LPF	MDF	MNF	PNF	SHF	SNF
Pre										
80th	2.5-25	62.7	90.6	56.1	99.4	86.0	95.4	64.3	65.5	58.7
	25-51	21.9	52.1	24.1	70.5	27.5	79.6	17.5	20.4	17.3
	51-76	6.9	8.0	7.3	6.0	8.4	•	6.4	5.2	4.9
	>76	•	4.6	2.0	2.8	•	•	2.0	3.6	2.0
	All	30.5	38.8	22.4	44.7	40.6	87.5	22.5	23.7	20.7
90th	2.5-25	66.5	98.1	57.8	99.6	92.4	96.9	64.7	65.5	77.5
	25-51	26.7	84.1	25.0	79.6	32.6	85.7	17.5	20.4	28.8
	51-76	8.2	50.0	8.0	8.9	12.1	•	6.4	5.2	5.4
	>76	•	48.3	2.0	3.8	•	•	2.0	3.6	2.0
	All	33.8	70.1	23.2	48.0	45.7	91.3	22.6	23.7	28.4
97.5th	2.5-25	69.5	99.1	59.2	99.6	97.8	99.2	66.0	65.5	83.8
	25-51	46.6	87.9	26.6	89.0	44.0	95.5	17.6	20.4	37.2
	51-76	35.6	64.0	9.3	39.4	20.6	•	6.4	5.2	6.5
	>76	•	58.6	2.0	5.5	•	•	2.0	3.6	2.0
	All	50.6	77.4	24.3	58.4	54.1	97.3	23.0	23.7	32.4
Post										
80th	2.5-25	52.3	58.9	46.0	52.4	53.6	81.7	52.2	40.2	48.0
	25-51	21.1	23.1	23.2	22.5	17.2	58.8	17.8	18.6	13.9
	51-76	6.9	5.6	8.6	7.1	5.0	•	6.3	5.2	4.3
	>76	•	2.9	2.0	2.4	•	•	2.0	3.6	2.0
	All	26.8	22.6	19.9	18.3	25.2	70.2	19.6	16.9	17.1
90th	2.5-25	52.3	58.9	46.0	52.4	53.6	85.7	52.2	40.2	48.0
	25-51	21.1	23.1	23.2	22.5	17.2	67.2	17.8	18.6	13.9
	51-76	6.9	5.6	8.6	7.1	5.0	•	6.3	5.2	4.3
	>76	•	2.9	2.0	2.4	•	•	2.0	3.6	2.0
	All	26.8	22.6	19.9	18.3	25.2	76.5	19.6	16.9	17.1
97.5th	2.5-25	65.7	58.9	46.0	56.9	53.9	87.6	52.3	40.2	48.0
	25-51	46.7	23.1	23.2	31.0	17.9	78.0	17.8	18.6	13.9
	51-76	35.6	5.6	8.6	16.6	5.2	•	6.3	5.2	4.3
	>76	•	2.9	2.0	2.4	•	•	2.0	3.6	2.0
	All	49.3	22.6	19.9	18.8	25.7	82.8	19.6	16.9	17.1

• = no trees in this diameter class for this location.

Discussion

Topography, weather, and fuels all play a role in the hazard and severity of wildland fire. Altering the fuel load is the most feasible and important factor to decrease hazard and severity of wildland fire. The vertical and horizontal continuity of surface fuels (litter and downed woody debris), ladder fuels (shrubs and small trees), and/or canopy fuels (large trees) must be broken to reduce fire severity. Reduction in surface fuels can reduce FI, increasing HTLCB can reduce the risk of torching, and reduction in crown density can limit tree-to-tree spread of crown fires (Agee 2002; Hessberg and Agee 2003; Agee and Skinner 2005).

Many studies in ponderosa pine and mixed-conifer forests document the effectiveness of prescribed fire in reducing future fire severity (Weaver 1943; Biswell and others 1973; Kauffman and Martin 1989; van Wagtendonk 1996; Stephens 1998; Miller and Urban 2000; Pollet and Omi 2002; Finney and others 2005; Knapp and others 2005; Stephens and Moghaddas 2005a,b). Prescribed fire effectively reduces surface fuel loads as well as kills shrubs and small diameter trees which reduce ladder fuels. Understory burning can also raise the height to live crown base through scorching of lower branches. One unifying goal of the prescribed burns analyzed in this work was to reduce the risk of stand-replacing catastrophic fire.

Stand characteristics did not significantly change in four of the nine site locations after treatment. This is consistent with many of the studies mentioned above. However, KNF E did experience a significant change in basal area, trees ha^{-1}, d.b.h., tree height, canopy cover, and CBD post-prescribed fire. This may be partially due to a tree blowdown event between plot readings (Kit Jacoby, personal communication). In the rest of the sites there were few differences in stand structure pre- and post-treatment. TI and CI moderately increased at all sites post-treatment, which indicates the need for an increase in wind speed to initiate and maintain crown fire. Overall, the modeled outputs document a reduced percentage of crown fires post-treatment; five treatments had a component of passive crown fire pre-treatment and two post-treatment (table 4).

If the primary goal of the prescribed fire treatment is to reduce the potential of stand replacing catastrophic wildfires, then TI and CI might be of particular interest. CI only increased slightly for all sites post-treatment indicating that the prescribed fire treatments did not effect the overstory (CBD or tree canopy cover). Under the 80^{th} percentile fire weather condition, the untreated sites are unlikely to initiate crown fire due to high TI (table 3). For the 90^{th} and 97.5^{th} percentile fire weather conditions, pre-treatment values of TI and CI make the KNF W, LPF, and MNF sites more vulnerable to active crown fire (table 3). The reduction in likelihood of crown fire is due to a combination of changes in stand structures and surface fuel loads. Crown fire is not solely linked to canopy characteristics; surface fuel loads also play a critical role in active crown fire initiation and spread. If surface fireline intensity exceeds the critical level needed to initiate an active crown fire, the canopy is likely to burn as long as high surface fuel loads are present.

Fuel bed depth was significantly reduced at the KNF E, MNF, PNF and SHF sites; however, fuel bed depth was reduced by at least 20 percent at the remaining five sites, but was not statistically significant. Total fuel loads (surface and ground) were reduced significantly at LPF, MNF and PNF. The relatively high consumption of ground and surface fuels is consistent with past studies (Kilgore and Sando 1975; Kauffman and Martin 1989; Stephens and Finney 2002; Knapp and others 2005). Prescribed fire without crown thinning has been shown to greatly reduce fireline intensity relative to no treatment (van Wagtendonk 1996; Stephens 1998). A reduction in surface fuel loads generally results in decreased fire severity, ROS, FL, and FI. Altered stand structures also contributed to the increase of surface fires versus crown fires post-treatment. Smaller diameter trees killed by prescribed fire are initially standing dead fuel. Eventually these trees will fall and contribute to the surface fuel loads (Stephens 1998; Agee 2003), necessitating future prescribed fires to keep hazards low.

Predicted tree mortality was higher pre-treatment than post-treatment for all locations under low, moderate, and extreme fire weather. Probability of tree mortality is primarily based on percent crown scorched which is derived from crown ratio, species tree height, and tree diameter (Reinhardt and others 1997). Predicted tree mortality was greatest in the smallest diameter class (2.5 to 25 cm d.b.h.) and decreased with increasing diameter classes (table 5). Increases in percentile fire weather post-treatment did not increase the likelihood of overall tree mortality at five sites (KNF W, LNF, PNF, SHF, SNF), it only slightly increased tree mortality in two sites (LPF and MDF), and it greatly increased tree mortality in two sites (KNF E and MNF). Predicted mortality almost doubled for all diameters at KNF E between the 90th and 97.5th percentile conditions post-treatment where fire type also changed; however, mortality was still lower relative to pre-treatment conditions (tables 4 and 5).

If reduction of potential stand replacing fires is the primary goal of prescribed fire treatments, selection of treatment locations must consider the existing fire hazards. Four of the nine study sites examined here only experienced modeled surface fire in pre-treatment conditions, including extreme fire weather conditions (table 4). Post-treatment potential fire behavior (ROS, FL, FI) was reduced, but these stands were not at risk of crown fire before treatment. On the other hand, three of the nine sites were at an elevated risk of crown fire (low TI and CI) pre-treatment at 97.5th percentile weather conditions (table 3). For the sites that would experience only surface fire, treatment is not warranted based on the reduction of potential fire behavior and effects. Sites experiencing low TI and CI values may benefit from a mechanical treatment (such as thinning from below) prior to prescribed fire to further reduce the risk of active crown fire.

In addition to the reduced potential for stand replacing catastrophic wildland fires, reintroduction of fire into the ecosystem was a primary goal of these prescribed fire treatments. Seasonality of prescribed fire is important from an ecological and fuels consumption standpoint. Fire history data from the southern Cascades in California document that prehistoric fires occurred mostly during the dormant season (starting as early as August and ending in October) in both pine dominated and mixed conifer forests (Taylor 2000; Beaty and Taylor 2001). In mixed conifer forests of the north-central, south-central, and southern Sierra Nevada, fires occurred most frequently just before dormancy in latewood growth (Stephens and Collins 2004). If reintroducing ecological processes is an important goal of a prescribed burn, it would be best if the burns took place in a time consistent with the fire history records.

Managers must consider many facets when choosing a location for treatment. With the amount of land rated at high hazard in California it would be wise to target stands which would benefit the most from treatment. If reintroduction of fire into the ecosystem is the primary goal and fuel reduction the secondary goal, then choosing treatment locations could include both stands with high and low fire hazards. Unfortunately, there is no one size fits all for fuel treatments in California; managers must consider many factors when implementing a forest restoration plan.

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