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Effectiveness of prescribed fire as a fuel treatment in Californian coniferous forests

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Abstract. Effective fire suppression and land use practices over the last century have altered forest structure and increased fuel loads in many forests in the United States, increasing the occurrence of catastrophic wildland fires. The most effective methods to change potential fire behavior are to reduce surface fuels, increase the canopy base height and reduce canopy bulk density. This multi-tiered approach breaks up the continuity of surface, ladder and crown fuels. Effectiveness of fuel treatments is often shown indirectly through fire behavior modeling or directly through monitoring wildland fire effects such as tree mortality. The present study investigates how prescribed fire affected fuel loads, forest structure, potential fire behavior, and modeled tree mortality at 90th and 97.5th percentile fire weather conditions on eight National Forests in California. Prescription burning did not significantly change forest structure at most sites. Total fuel loads (litter, duff, 1, 10, 100, and 1000-h) were reduced by 23 to 78% across the sites. The reduction in fuel loads altered potential fire behavior by reducing fireline intensity and increasing torching index and crowning index at most sites. Predicted tree mortality decreased after treatment as an effect of reduced potential fire behavior and fuel loads. To use limited fuel hazard reduction resources efficiently, more effort could be placed on the evaluation of existing fire hazards because several stands in the present study had little potential for adverse fire effects before prescribed fire was applied.

Additional keywords: fire behavior modeling, fire hazard, fire risk, Fuels Management Analyst, wildfire.

Introduction

The Forest Reserves System was established in 1891 and, in 1905, it became the United States Forest Service (USFS) (Pyne 1982). From the beginning, one of the primary objectives of the USFS was timber production, and fire therefore was viewed as detrimental to this management objective. As a result, a policy of complete fire suppression was adopted (Pyne 1982; Stephens and Ruth 2005). However, it was not until 1924 when the federal Clarke–McNary Act was created that national fire suppression became national policy (Stephens and Ruth 2005). With the release of the Leopold report, which documented the negative impacts of fire suppression on wildlife, federal fire policy started to change (Leopold *et al.* 1963). Prior research demonstrated adverse effects of fire exclusion on forest structure, species composition, and fuel loads (Chapman 1926; Weaver 1943; Biswell 1961), but the negative connotation with fire remained until the late 1960s. In 1968, the US National Park Service changed their fire policy to include the use of management-ignited and prescribed natural fire in the western US (Kilgore and Briggs 1972). In 1974, the USFS also changed their policy from complete suppression to fire management where naturally caused fires were allowed to burn in a few wilderness areas (van Wagtendonk 2007; Collins *et al.* 2009). Although this represented a major change in USFS fire policy, suppression is still dominant within the agency (Franklin and Agee 2003).

With the onset of fire suppression, harvesting, and livestock grazing, forests in the western US started to change into what they are today. Past management has led to higher tree densities (Biswell 1959), changes in species composition (Weaver 1943) and higher fuel loads (Dodge 1972) in many coniferous forests altering their fire regimes (Taylor 2000; Beaty and Taylor 2001; Stephens and Collins 2004; Fry and Stephens 2006; Moody *et al.* 2006). A recent analysis of fire cause and extent on USFS lands from 1940 to 2000 (Stephens 2005) 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 US. Although the relative area burned has not significantly increased from 1940 to 2000 in California (Stephens 2005), the wildland fire problem has only persisted as suppression has become more efficient (Brown and Arno 1991) and as climate has changed (Westerling *et al.* 2006; Miller *et al.* 2009).

The most effective method to change potential wildland fire behavior is to alter fuel structures. Effective fuel treatments reduce flame length, fireline intensity and the occurrence of crown fire. Under most weather conditions, fuel treatments modify fire behavior; however, under the most extreme weather conditions, fuels treatments can become much less effective (Pollet and Omi 2002; Finney *et al.* 2003). Mechanical or manual thinnings of various intensities, mastication, whole tree removal and prescribed fire are the most common fuels treatments used

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in the western US. Fuel treatments that alter more than one component of forests or use more than one treatment type are frequently more effective (i.e. Agee and Skinner 2005; Stephens and Moghaddas 2005*a*; Schmidt *et al*. 2008; Stephens *et al.*, in press).

The most successful methods to change potential fire behavior are to reduce surface fuels, increase the canopy base height, and reduce canopy bulk density, in order of effectiveness. This multi-tiered approach breaks the continuity of surface, ladder and crown fuels (i.e. Van Wagner 1977; Agee *et al*. 2000; Scott and Reinhardt 2001; Agee and Skinner 2005). 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 2005*a*, 2005*b*; Stephens *et al.*, in press). Prescribed fire alone can decrease surface and ladder fuels, which reduces potential fire behavior and thus lowers the risk of crown fire and spot fire ignition (van Wagtendonk 1996; Stephens 1998; Stephens and Moghaddas 2005*a*). Effectiveness of fuel treatments is often shown indirectly through fire behavior modeling or directly through monitoring wildland fire effects such as tree mortality. Stand-level treatments have been shown to effectively reduce fire severity, reduce fire size and aid in suppression efforts in real wildfires (Agee *et al*. 2000; Martinson and Omi 2003; Finney *et al*. 2005; Moghaddas and Craggs 2007).

The objective of the present study is to determine how prescribed fire affects fuel loads, vegetation structure, and potential fire behavior and effects in stands from eight National Forests in California. The null hypothesis investigated is that there will be no significant difference in vegetation structure, fuel load, modeled fire behavior, and predicted tree mortality at each study site when comparing pre- and post-treatment characteristics. Information from the present 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). Climate across the study sites is Mediterranean with a summer drought period that extends into the fall. The majority of precipitation occurs during winter and spring. The average elevation of the study sites ranges from ~1000 to 1600 m (Table 1). Average slopes vary from 3 to 61%. Pretreatment percentage cover of tree canopy, shrubs, and grasses varied between study locations (Table 1).

California Wildlife Habitat Relationships vegetation types were used to classify dominant vegetation among the nine sites (FRAP 2008). KNF E, PNF and SHF are Sierran mixed conifer (Table 1). KNF W is characterized as Klamath mixed conifer. LNF, LPF, MDF, and SNF are dominated by yellow pines, ponderosa pine and Jeffrey pine (*Pinus ponderosa* Laws. and *Pinus jeffreyi* Grev., respectively). LNF and SNF are in the ponderosa pine forest type, MDF is eastside pine and LPF is classified as Jeffrey pine. Finally, MNF is montane hardwood–conifer (Table 1). Tree species present in these forest stands include ponderosa pine, Jeffrey pine, sugar pine (*Pinus lambertiana* Dougl.), white fir (*Abies concolor* Gord. & 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.).

Vegetation measurements

In each of the nine projects sites, vegetation structure and fuel characteristics were measured using 0.2-ha randomly placed, permanently marked circular plots (26 total plots, Table 1). Each stand had between two and five plots installed initially and remeasured after treatment (Table 1). Tree measurements were collected in two nested subplots; 0.1 ha for all trees greater than 15 cm diameter at breast height (DBH), and 0.025 ha for trees 2.5 to 15 cm DBH. Tree measurements (species, DBH, height, height-to-live-crown base (HTLCB), and tree crown position (dominant, co-dominant, intermediate or suppressed)) were recorded for all live trees. For snags species, DBH and total height were recorded. Canopy cover was measured every metre along two perpendicular 50-m transects using a sight tube (Gill *et al*. 2000). Shrub measurements were also taken along the same transects in each of the plots to estimated percentage shrub cover. An ocular estimate of percentage cover by grasses was made along the shrub transect in a 1-m^2 frame every 10 m. Data were collected before and after treatment on the same plots at each site.

Fuels Management Analyst (FMA) was used to calculate average canopy characteristics (canopy base height, canopy bulk density, and canopy height) for each stand (Carlton 2005). FMA uses information from field measurements (i.e. tree species, DBH, tree crown ratio, tree crown position and tree height) to estimate average canopy base height and canopy bulk density (Reinhardt *et al*. 2000; Reinhardt and Crookston 2003). Canopy bulk density is calculated using a running mean along the height of the canopy. Canopy base height is determined as the height above the ground where the first canopy layer has sufficient density to support the vertical movement of fire (Carlton 2005).

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). Fuels data were recorded before and after treatment along the same transects at each site. For each transect, 1-h (0- to 0.64-cm diameter) and 10-h (0.64- to 2.54-cm diameter) fuels were sampled from 0 to 1.83 m, 100-h fuels (2.54- to 7.62-cm diameter) from 0 to 3.66 m, and 1000-h fuels (diameter >7.62 cm) from 0 to 15.24 m. Species, diameter and decay status (rotten or sound) were recorded for all 1000-h 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 based on average basal area fraction of tree species

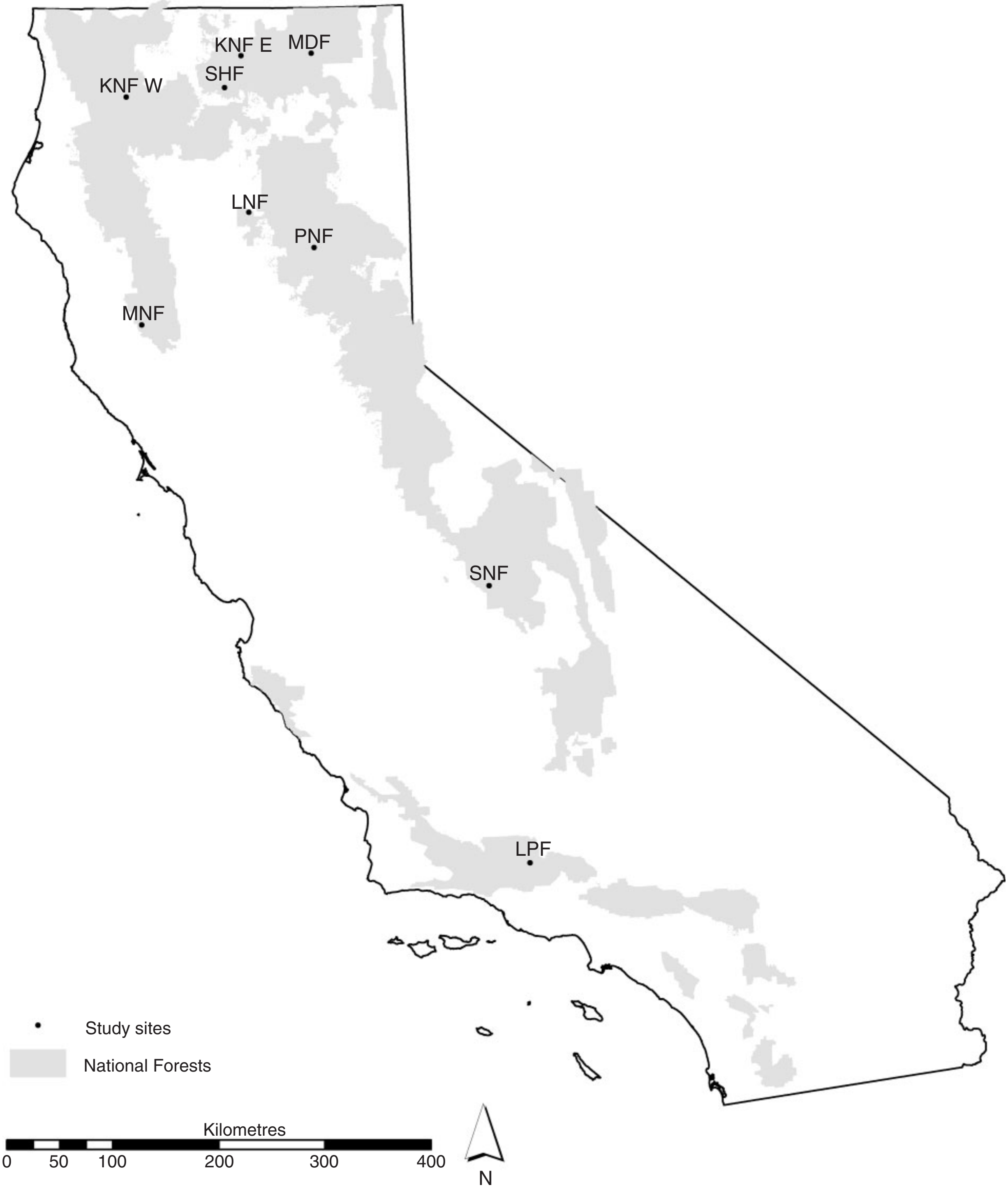

Fig. 1. Location of study sites in eight National Forests in California.

present at the individual sites (van Wagtendonk *et al*. 1998; Stephens 2001).

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 secondarily 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.

Table 1. Detailed description of study site locations for nine stands in eight Californian National Forests

Site	No. of plots	California Wildlife Habitat Relationship[A]	Avg. elevation (m)	Avg. slope (%)	Avg. canopy cover (%)[B]	Avg. shrub cover (%)	Avg. grass cover (%)
KNF E	3	Sierran mixed conifer	1532	8	45	53	33
KNF W	2	Klamath mixed conifer	1576	40	70	110	0
LNF	2	Ponderosa pine	1005	31	95	126	0
LPF	3	Jeffrey pine	2073	26	24	50	35
MDF	3	Eastside pine	1501	3	29	32	33
MNF	5	Montane harwood–conifer	1239	26	69	95	33
PNF	3	Sierran mixed conifer	1187	61	65	126	7
SHF	3	Sierran mixed conifer	1127	5	31	36	38
SNF	2	Ponderosa pine	1463	26	57	83	0

[A] California Wildlife Habitat Relationship is a system used to designate vegetation groups by the California Department of Forestry and Fire Protection.
[B] Overlapping shrub measurements allow for $>100\%$ cover.

Table 2. Pre- and post-treatment fuel model selection by site for nine stands in eight Californian National Forests

Fuel model designations are from Scott and Burgan (2005)

Site	Pre-treatment fuel model	Post-treatment fuel model
KNF E	TL3, TL3, TL4	TL1, TL3, TL1
KNF W	TU5, TL5	TL1, TL1
LNF	TU1, TL3	TL1, TL1
LPF	SH1, TL8, TL8	TL3, GS1, TL1
MDF	TU1, TU1, TL8	TL1, TL1, TL1
MNF	TL8, TL8, TL3, TL3, TL8	TL8, TL8, TL3, TL1, TL8
PNF	TL4, TL3, TL4	TL3, TL3, TL3
SHF	TL3, TL3, TL1	TL1, TL1, TL1
SNF	TU1, TU1	TL1, TL1

Fire behavior modeling

Fire behavior and effects were modeled under upper 90th and 97.5th percentile fire weather conditions. Ninetieth and 97.5th percentile fire weather represent high and extreme fire weather, respectively. 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 (wind speed, temperature, relative humidity, and fuel moistures) using Fire Family Plus (Main *et al.* 1990).

Fuels Management Analyst was also used to model fire behavior and effects (fireline intensity, crowning index, torching index, and tree mortality) (Carlton 2005). FMA incorporates established published methodologies for computing predicted fire fireline intensity (FI) (Albini 1976), fire type (Van Wagner 1977; Alexander 1988; Van Wagner 1993), torching index (TI) and crowning index (CI) (Scott and Reinhardt 2001) and predicted tree mortality (Reinhardt *et al.* 1997). A surface fuel model was assigned to each sampling plot based on the presumed carrier of fire (grass, grass-shrub, shrub, timber-understorey, timber-litter or slash-blowdown) using understorey composition, stand composition, and calculated surface fuel loads (Table 2) (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, canopy base height (CBH), canopy cover, canopy bulk density (CBD)) and fuel loads (litter, duff, 1-h, 10-h, 100-h, 1000-h sound, 1000-h rotten, total fuel load (1 to 1000-h, litter and duff)), and fuel depth for each site before and after prescribed fire (Zar 1999). The choice of $P < 0.1$ was made owing to high natural variation found between plots in each study site (Tables 3 and 4). The number of sample plots varied by site location owing 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 (Table 1).

Average values for modeled fire behavior metrics (FI, TI and CI), and percentages of fire type and expected mortality by diameter class are presented to compare pre- and post-treatment effectiveness. Owing to the number of assumptions associated with fire behavior models, statistically testing of model outputs was not done (Stephens and Moghaddas 2005*b*).

Results

Forest structure

Measurements were taken on 859 live trees greater than 2.5 cm DBH before treatment and 797 after treatment in the 26 sampling plots. At KNF E, post-treatment DBH and tree height were significantly larger, and tree density and canopy cover were significantly lower (Table 3). At KNF W, post-treatment basal area was significantly lower. For LNF, tree density was significantly lower after treatment. Canopy cover and canopy bulk density were significantly lower after treatment at LPF and canopy cover also significantly decreased at MNF. At MDF, canopy bulk density was significantly lower after treatment. At PNF, tree height was significantly higher after treatment. No significant differences were found for any of the measured variables (basal area, trees ha^{-1}, DBH, tree height, CBH, canopy cover, CBD) at SHF or SNF (Table 3).

Fuels characteristics

A total of 104 fuel transects were analyzed over the nine project sites to characterize surface and ground fuels before and after

Table 3. Average (standard error) pre- and post-treatment vegetation structure for all trees greater than 2.5 cm diameter at breast height (DBH) by site location for nine stands in eight Californian National Forests

DBH, diameter at breast height; CBH, canopy base height; BA, basal area; CBD, canopy bulk density

	Site	DBH (cm)	CBH (m)	Canopy height (m)	BA (m^2 ha^{-1})	Trees (ha^{-1})	Canopy (%)	CBD (kg m^{-3})
Pre-treatment	KNF E	27.2 (2.5)$^{\text{A}}$	4.4 (1.5)	14.4 (2.4)$^{\text{A}}$	37.0 (10.4)	707 (62)$^{\text{A}}$	44 (6)$^{\text{A}}$	0.092 (0.019)
	KNF W	32.9 (5.8)	3.4 (0.3)	15.0 (2.8)	49.1 (2.9)$^{\text{A}}$	620 (220)	76 (13)	0.049 (0.001)
	LNF	34.7 (1.3)	8.9 (0.5)	21.0 (1.0)	51.9 (0.1)	490 (70)$^{\text{A}}$	97 (0)	0.042 (0.009)
	LPF	36.4 (5.4)	3.2 (0.4)	12.9 (2.0)	28.4 (2.0)	317 (78)	24 (4)$^{\text{A}}$	0.048 (0.019)$^{\text{A}}$
	MDF	33.3 (3.1)	3.8 (1.1)	14.3 (2.1)	26.9 (9.4)	310 (107)	29 (12)	0.057 (0.026)$^{\text{A}}$
	MNF	26.6 (1.6)	4.2 (0.2)	14.0 (0.6)	27.0 (1.6)	514 (66)	69 (3)$^{\text{A}}$	0.090 (0.010)
	PNF	33.9 (1.4)	11.3 (4.3)	19.3 (1.0)$^{\text{A}}$	38.5 (8.7)	443 (111)	65 (11)	0.066 (0.015)
	SHF	52.5 (3.6)	14.6 (4.1)	27.9 (2.5)	34.4 (2.6)	163 (13)	30 (6)	0.034 (0.004)
	SNF	36.9 (12.4)	7.3 (2.4)	19.2 (6.3)	40.6 (5.5)	535 (305)	51 (6)	0.076 (0.025)
Post-treatment	KNF E	29.6 (2.6)$^{\text{A}}$	4.6 (1.6)	15.6 (2.6)$^{\text{A}}$	35.8 (10.0)	530 (26)$^{\text{A}}$	35 (4)$^{\text{A}}$	0.091 (0.020)
	KNF W	35.8 (3.3)	8.9 (3.1)	17.1 (4.3)	46.1 (3.0)$^{\text{A}}$	430 (50)	71 (16)	0.052 (0.017)
	LNF	36.1 (2.0)	9.4 (0.3)	21.4 (0.2)	48.8 (1.3)	405 (75)$^{\text{A}}$	93 (4)	0.044 (0.006)
	LPF	37.1 (6.9)	3.2 (0.5)	13.3 (2.4)	27.1 (1.7)	297 (85)	20 (4)$^{\text{A}}$	0.044 (0.019)$^{\text{A}}$
	MDF	34.1 (3.6)	4.8 (1.7)	15.1 (2.4)	24.3 (10.0)	263 (109)	30 (13)	0.051 (0.027)$^{\text{A}}$
	MNF	26.6 (1.6)	4.2 (0.2)	14.0 (0.6)	26.8 (1.4)	512 (68)	51 (5)$^{\text{A}}$	0.089 (0.010)
	PNF	35.3 (0.9)	11.3 (0.9)	21.0 (0.8)$^{\text{A}}$	35.9 (10.6)	360 (110)	62 (12)	0.068 (0.020)
	SHF	58.6 (7.4)	11.7 (1.4)	31.4 (4.5)	33.8 (2.5)	120 (21)	23 (3)	0.033 (0.004)
	SNF	36.9 (12.3)	7.1 (2.5)	19.2 (6.3)	40.6 (5.5)	535 (305)	44 (10)	0.071 (0.022)

$^{\text{A}}$Denotes a significant difference ($P < 0.1$) before and after treatment using a pairwise t-test for that given metric.

Table 4. Average (standard error) fuel loads (t ha^{-1}) and fuel depth before and after treatment by site location for nine stands in eight Californian National Forests

	Site	Duff	Litter	1-h	10-h	100-h	1000-h	Total fuel load	Fuel depth (cm)
Pre	KNF E	21.4 (9.9)	11.1 (1.0)$^{\text{A}}$	1.5 (0.4)	2.7 (0.7)	2.8 (1.8)	43.2 (28.9)	82.7 (41.9)	28.2 (5.2)$^{\text{A}}$
	KNF W	33.2 (9.2)	18.5 (2.4)$^{\text{A}}$	1.4 (0.0)	6.1 (1.5)	5.9 (4.6)	71.1 (64.8)	136.0 (82.5)	25.6 (1.6)
	LNF	17.0 (6.4)$^{\text{A}}$	18.9 (8.5)	2.1 (1.2)	7.7 (5.2)	4.5 (0.3)	14.8 (0.2)	65.1 (5.0)	14.7 (1.6)
	LPF	22.3 (1.6)$^{\text{A}}$	4.4 (0.0)$^{\text{A}}$	0.6 (0.2)	1.0 (0.2)	2.8 (2.4)	13.2 (6.6)	44.3 (8.7)$^{\text{A}}$	9.7 (2.9)
	MDF	13.6 (4.1)	5.6 (1.1)$^{\text{A}}$	0.5 (0.1)$^{\text{A}}$	1.2 (0.4)	1.7 (0.8)$^{\text{A}}$	13.2 (8.9)	35.6 (10.8)	7.9 (1.7)
	MNF	16.7 (1.9)	12.9 (1.3)$^{\text{A}}$	0.3 (0.1)	2.5 (1.1)	3.6 (0.9)	67.4 (19.2)$^{\text{A}}$	103.5 (22.8)$^{\text{A}}$	67.0 (6.3)$^{\text{A}}$
	PNF	22.5 (6.5)	4.3 (1.5)	1.3 (0.7)	2.0 (0.2)	5.1 (0.9)	39.0 (5.3)$^{\text{A}}$	74.2 (10.9)$^{\text{A}}$	16.2 (3.2)$^{\text{A}}$
	SHF	28.9 (4.4)$^{\text{A}}$	5.4 (1.1)$^{\text{A}}$	0.9 (0.4)	3.4 (0.8)$^{\text{A}}$	7.6 (1.2)	18.0 (5.9)	64.3 (13.3)	11.1 (2.3)$^{\text{A}}$
	SNF	15.4 (13.4)	12.1 (0.5)$^{\text{A}}$	0.9 (0.1)	2.3 (0.9)	5.3 (2.8)	7.5 (1.8)	43.6 (19.3)	51.3 (25.4)
Post	KNF E	2.2 (0.8)	4.4 (0.1)$^{\text{A}}$	0.9 (0.1)	1.3 (0.6)	2.5 (1.3)	6.5 (4.7)	17.8 (2.4)	7.7 (2.1)$^{\text{A}}$
	KNF W	7.4 (0.6)	3.0 (1.7)$^{\text{A}}$	0.3 (0.2)	1.4 (0.1)	1.3 (1.3)	40.6 (39.0)	53.9 (42.9)	12.3 (7.0)
	LNF	9.2 (5.3)$^{\text{A}}$	3.5 (0.2)	0.6 (0.2)	3.8 (1.9)	2.7 (1.3)	30.6 (20.8)	50.3 (29.7)	11.5 (4.0)
	LPF	10.0 (2.0)$^{\text{A}}$	1.7 (0.9)$^{\text{A}}$	0.2 (0.0)	0.8 (0.4)	4.1 (2.1)	4.6 (4.6)	21.3 (5.1)$^{\text{A}}$	3.4 (1.0)
	MDF	5.2 (0.9)	3.8 (0.9)$^{\text{A}}$	0.2 (0.0)$^{\text{A}}$	0.9 (0.3)	2.8 (0.6)$^{\text{A}}$	3.6 (1.0)	16.5 (2.9)	3.5 (0.6)
	MNF	14.8 (2.3)	3.0 (0.5)$^{\text{A}}$	0.4 (0.1)	1.6 (0.5)	4.8 (1.3)	19.5 (4.9)$^{\text{A}}$	44.1 (7.4)$^{\text{A}}$	8.3 (1.6)$^{\text{A}}$
	PNF	9.0 (1.3)	10.0 (2.4)	0.6 (0.2)	2.1 (0.5)	3.9 (0.2)	15.4 (8.7)$^{\text{A}}$	41.0 (10.5)$^{\text{A}}$	10.3 (2.4)$^{\text{A}}$
	SHF	6.9 (2.0)$^{\text{A}}$	1.9 (0.2)$^{\text{A}}$	0.2 (0.0)	1.0 (0.1)$^{\text{A}}$	3.1 (1.9)	17.1 (6.1)	30.2 (6.4)	7.4 (1.3)$^{\text{A}}$
	SNF	8.5 (5.4)	2.7 (0.5)$^{\text{A}}$	0.5 (0.2)	0.8 (0.2)	3.7 (2.1)	5.1 (0.6)	21.3 (7.7)	8.1 (3.7)

$^{\text{A}}$Denotes a significant difference ($P < 0.1$) before and after treatment using a pairwise t-test for that given metric.

prescribed burning. All locations had a significant difference after treatment in at least one of the fuel parameters (duff, litter, 1-h, 10-h, 100-h, 100-h sound, 1000-h rotten or total fuel load, and fuel depth) (Table 4). MNF and SHF experienced the greatest significant reduction in post-treatment fuel loads and fuel depth out of the nine sites. KNF W, LNF and SNF experienced the fewest number of significant changes in fuel loads after treatment.

Potential fire behavior

Pretreatment modeled potential fire type (FT) for the 90th and 97.5th percentile fire weather conditions are shown in Fig. 2. Before treatment, LPF and MNF experienced passive crown fire activity for the 90th percentile fire weather condition. Under the 97.5th percentile fire weather conditions, six (KNF E, KNF W, LPF, MDF, MNF, and SNF) of the sites experience crown fire (Fig. 2). Of those six sites experiencing crown fire, only KNF

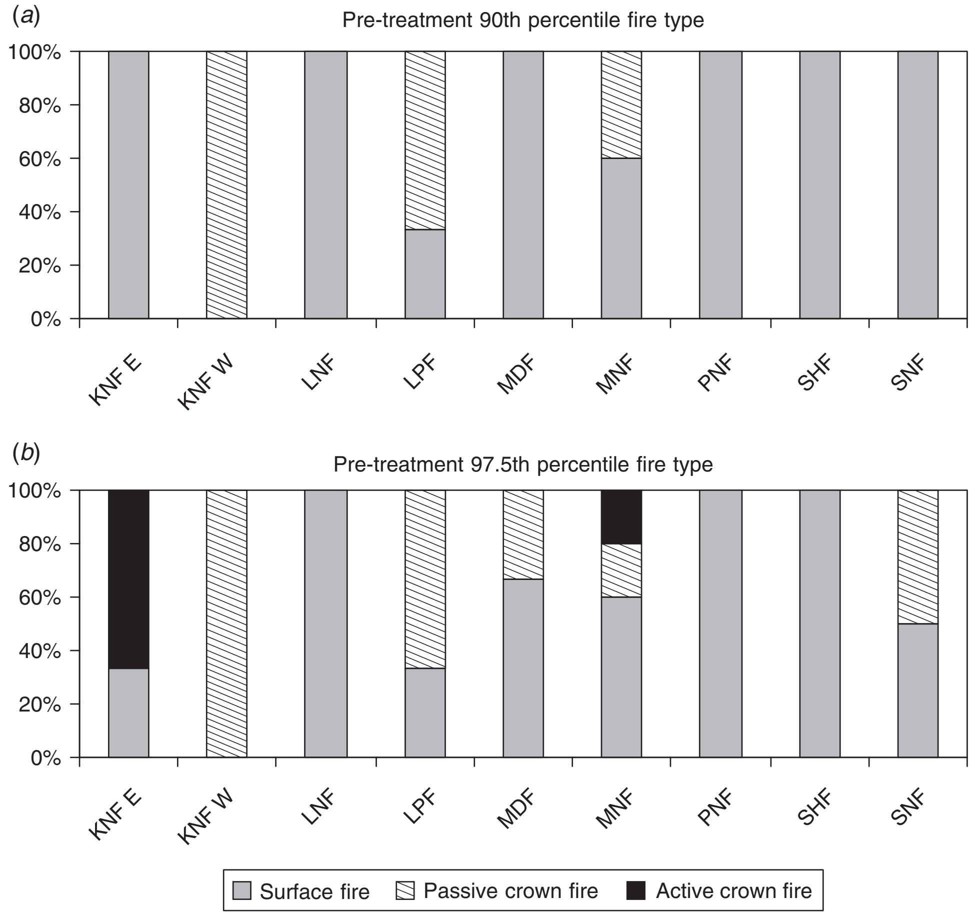

Fig. 2. Pretreatment modeled fire type for nine sites at eight National Forests in California.

Table 5. Average pre- and post-treatment modeled fire behavior under 90th and 97.5th percentile weather scenarios by site location for nine stands in eight Californian National Forests

	Site		90th percentile			97.5th percentile	
		Fireline intensity (kW m^{-1})	Torching index (km h^{-1})	Crowning index (km h^{-1})	Fireline intensity (kW m^{-1})	Torching index (km h^{-1})	Crowning index (km h^{-1})
Pre	KNF E	50	86	38	>1730	86	34
	KNF W	>1730	0	51	>1730	0	44
	LNF	137	>160	59	154	>160	54
	LPF	1191	22	69	>1730	20	63
	MDF	189	54	66	332	47	57
	MNF	>1730	43	31	>1730	38	29
	PNF	96	>160	43	110	>160	36
	SHF	30	>160	75	40	>160	70
	SNF	578	70	29	767	56	24
Post	KNF E	10	110	38	13	101	34
	KNF W	9	>160	52	12	>160	46
	LNF	9	>160	57	9	>160	53
	LPF	24	>160	75	31	>160	68
	MDF	8	>160	84	10	>160	69
	MNF	210	151	32	269	138	29
	PNF	75	>160	44	86	>160	37
	SHF	9	>160	77	12	>160	72
	SNF	16	>160	40	14	>160	38

E and MNF experienced active crown fire. Post-treatment fire type was 100% surface fire for both fire weather scenarios for all nine sites.

Reported values for modeled fireline intensity, torching index and crowning index were truncated for the present study (Table 5). Values above 1730 kW m^{-1} for fireline intensity are associated with fire behavior that may present serious control problems and attempts to control the head fire will probably be ineffective (Rothermel 1983). Torching and crowing indexes were curtailed at 160 km h^{-1}, because wind speeds greater than this rarely occur. Modeled FI decreased after treatment compared with before treatment for all site locations (Table 5). TI decreased as percentile weather increased before and after treatment except at KNF E and KNF W, where there was no change between the 90th and 97.5th percentile before treatment (Table 5). CI increased slightly after treatment for all locations except KNF E and LNF.

Predicted tree mortality

Probability of mortality was modeled for six diameter classes (2.5 to 14.9, 15 to 29.9, 30 to 44.9, 45 to 59.9, 60 to 74.9, and $\geq$75 cm DBH) for all trees at each study site before and after treatment (Figs 3 and 4). For all sites, a higher percentage of trees were predicted to die before treatment compared with after treatment except for the smallest-diameter class at PNF (Figs 3 and 4). A higher amount of mortality was predicted in smaller-diameter classes (2.5 to 14.9, 15 to 29.9, and 30 to 44.9 cm DBH), except for the 45 to 59.9 cm DBH class at MNF. An increase in mortality with respect to increasing fire weather conditions occurred at all study sites except SHF (Figs 3 and 4).

Discussion

Several studies in ponderosa pine and mixed-conifer forests document the effectiveness of prescribed fire in reducing future fire severity (Weaver 1943; Biswell *et al.* 1973; Kilgore and Sando 1975; Kauffman and Martin 1989; van Wagtendonk 1996; Stephens 1998; Miller and Urban 2000; Pollet and Omi 2002; Finney *et al.* 2005; Knapp *et al.* 2005; Stephens and Moghaddas 2005*a*, 2005*b*; Stephens *et al.*, in press). Most prescribed fires in the current study reduced surface fuel loads, as well as killed shrubs and small-diameter trees, effectively reducing ladder fuels, confirming the assertions made in the previous studies. Understorey burning can also raise canopy base height by scorching lower branches and needles. Stand characteristics did not significantly change in two (SHF and SNF) 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 more of the stand characteristics than the other sites, which may be due to a tree blowdown event before the post-treatment remeasurement (K. Jacoby, pers. comm., 2006). In the rest of the sites, there were few differences in stand structure before and after treatment (Table 3). TI and CI modestly increased at most sites after 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 after treatment; six sites (KNF E, KNF W, LPF, MDF, MNF and SNF) had a component of crown fire before treatment and zero after treatment (Fig. 2).

If the primary goal of the prescribed fire treatment is to reduce the potential of stand-replacing catastrophic wildfires, then TI and CI could be of particular interest. CI only increased slightly for all sites after treatment, indicating that the prescribed fire treatments did not affect the overstorey (Tables 3 and 5). For the 90th and 97.5th percentile fire weather conditions, pre-treatment values of TI and CI at KNF W, LPF, MDF and MNF make these sites more vulnerable to active crown fire (Table 5). Ladder fuels were reduced at seven of the nine sites in the present study by reducing smaller-diameter tree density, resulting in lower average tree densities and larger average tree DBHs (Table 3). Smaller-diameter trees killed by prescribed fire are initially standing dead fuel. Eventually these trees will fall and contribute to surface fuel loads (Stephens 1998; Agee 2003), necessitating future prescribed fires to keep hazards low. The post-treatment reduction in likelihood of crown fire is due to a combination of changes in stand structures and surface fuel loads.

Active crown fire is not solely linked to canopy characteristics; surface fuel loads also play a critical role in active crown fire initiation and spread. In addition to the changes in stand structure, pre- and post-treatment fuel loads differed for all the sites (Table 4). Fuel bed depth was significantly reduced at the KNF E, MNF, PNF and SHF sites (Table 4). Post-treatment fuel bed depth was reduced by at least 20% 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 at these three sites is consistent with past studies (Kilgore and Sando 1975; Kauffman and Martin 1989; Stephens and Finney 2002; Knapp *et al.* 2005). Prescribed fire without crown thinning has been shown to greatly reduce fireline intensity relative to no treatment (van Wagtendonk 1996; Stephens 1998). Predicted tree mortality was higher before treatment than after treatment for all locations under the 90th and 97.5th percentile fire weather conditions. Probability of tree mortality is primarily based on percentage crown scorched, which is derived from crown ratio, species, tree height, and tree diameter (Reinhardt *et al.* 1997). Predicted tree mortality was greatest in the smallest-diameter class (2.5 to 14.9 cm DBH) and decreased with increasing diameter classes, except at MNF (Figs 3 and 4). Increases in percentile fire weather after treatment did not increase the likelihood of overall tree mortality at seven sites; it only slightly increased tree mortality in the remaining two sites (MNF and PNF).

If reduction of potential stand-replacing fires is the primary goal of prescribed fire treatments, selection of treatment locations should consider existing fire hazards. Three of the nine sites (KNF W, LPF, and MNF) were at an elevated risk of crown fire (low TI and CI) before treatment at 90th and 97.5th percentile weather conditions (Table 5). Four of the nine sites (KNF W, LPF, MDF, and SNF) experienced passive crown fire, one a mixture of passive and active crown fire (MNF), and one (KNF E) active crown fire under the 97.5th percentile fire weather condition. Sites experiencing low TI and CI values may benefit from a mechanical treatment (such as thinning from below) before prescribed fire to further reduce the risk of crown fire. Three of the nine study sites examined here (LNF, PNF, and SHF) experienced only modeled surface fire in pretreatment conditions, including extreme fire weather conditions (Fig. 2).

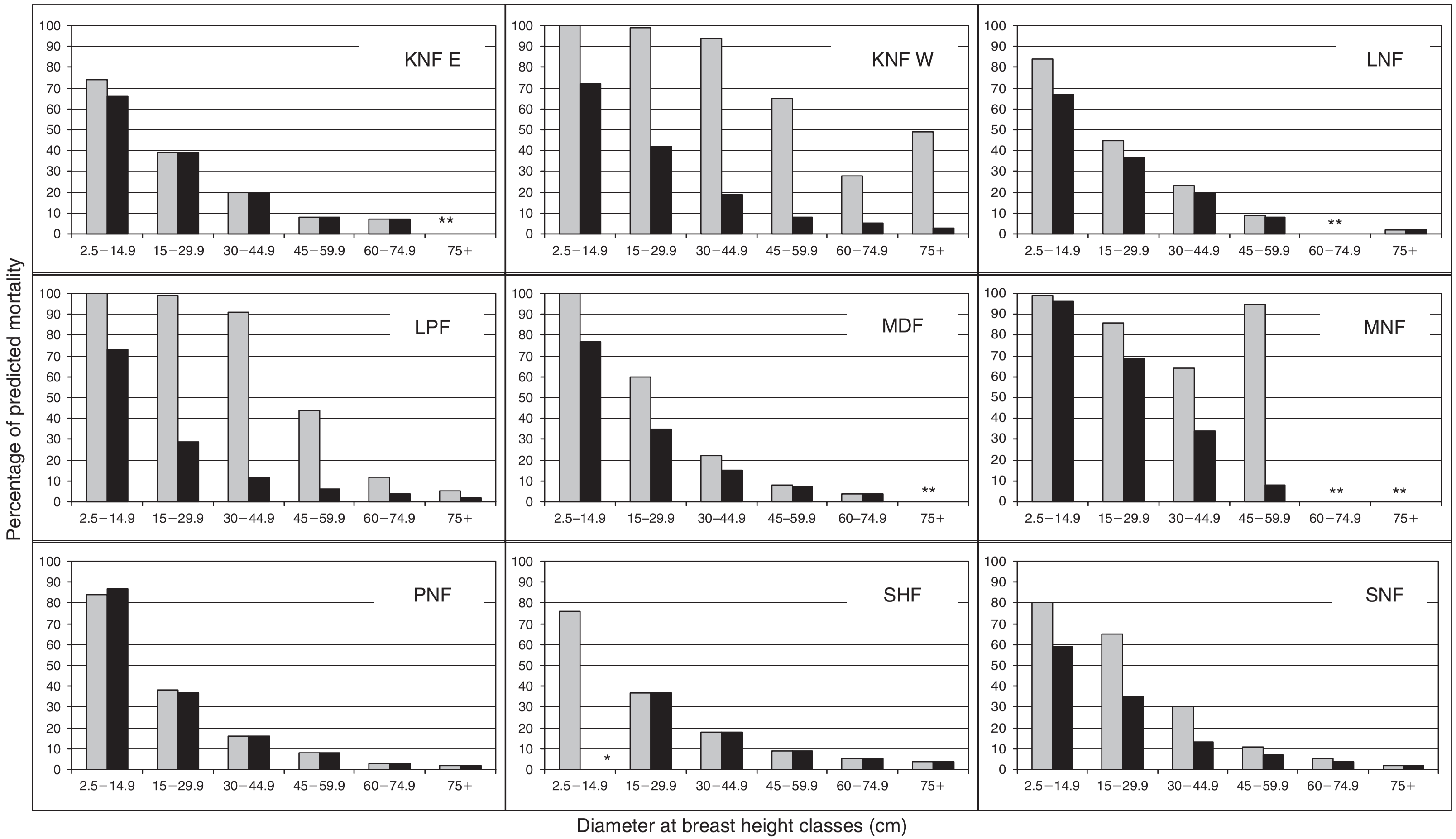

Fig. 3. Pre- and post-treatment predicted tree mortality by diameter class for the 90th percentile fire weather scenario for nine sites at eight National Forests in California. Stars (*) denote no trees present in the given diameter class.

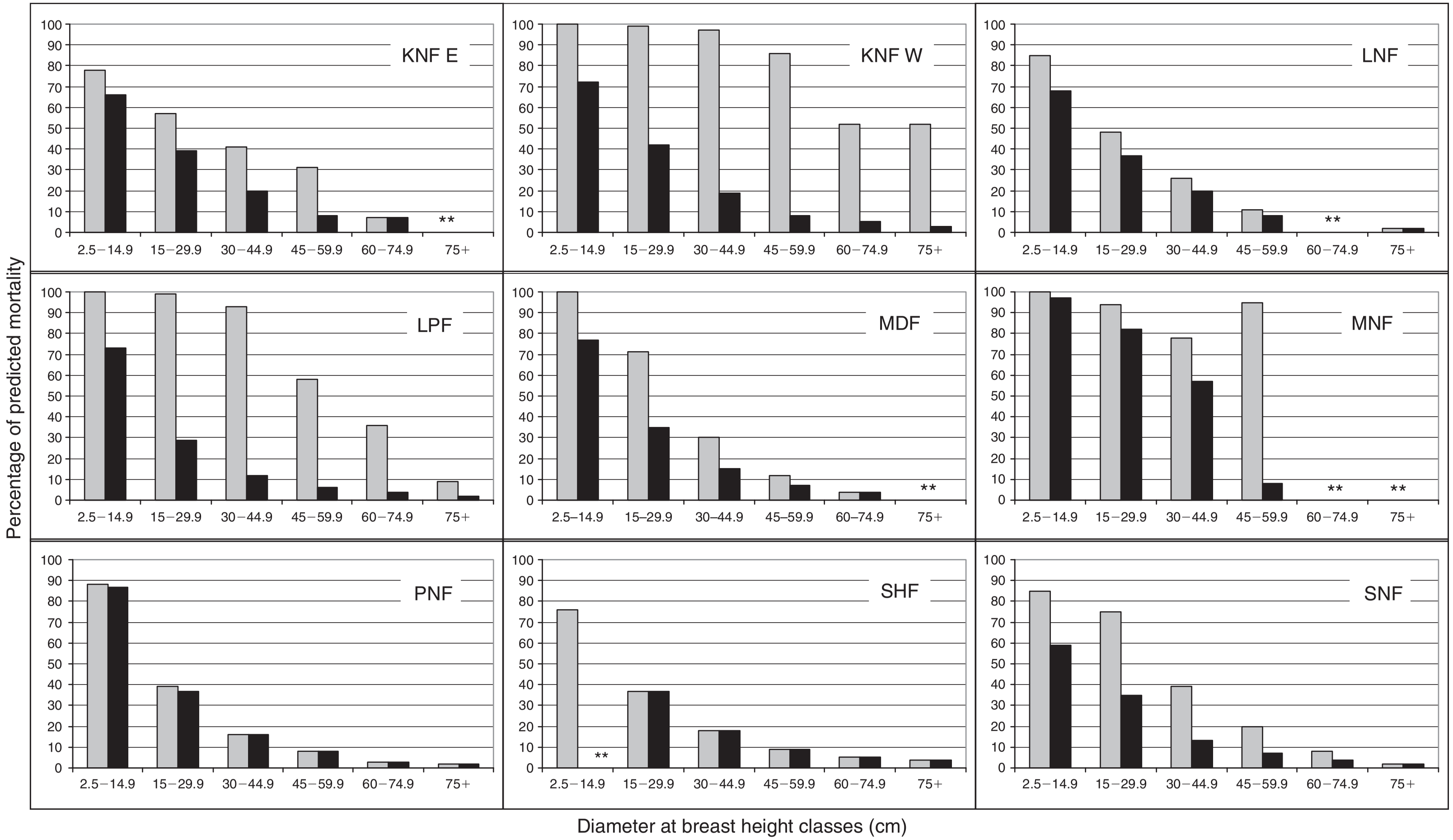

Fig. 4. Pre- and post-treatment predicted tree mortality by diameter class for the 97.5th percentile fire weather scenario for nine sites at eight National Forests in California. Stars (*) denote no trees present in the given diameter class.

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 that 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 management plan.

Conclusions

Prescription burning did not significantly change forest structure at most sites in spite of reducing tree densities up to 31%. Total fuel loads (litter, duff, 1-, 10-, 100-, and 1000-h) were reduced significantly in three sites but no significant differences were recorded in the six other sites. Four of the nine sites examined were at an elevated risk of crown fire (low TI and CI combined with high fuel loads) before treatment at 90th and 97.5th percentile weather conditions. Increased TI coupled with decreased fuel loads (surface and ladder) reduced crown fire potential after treatment at all of the sites, although some sites had low fire hazards before treatment. The primary objective of the prescribed fires examined was to reduce the potential for stand-replacing fire events. With this being the primary objective of conducting fuel treatments, it might be more valuable to select sites with an elevated hazard before treatment.

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