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Fire treatment effects on vegetation structure, fuels, and potential fire severity in western U.S. forests

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Abstract. Forest structure and species composition in many western U.S. coniferous forests have been altered through fire exclusion, past and ongoing harvesting practices, and livestock grazing over the 20th century. The effects of these activities have been most pronounced in seasonally dry, low and mid-elevation coniferous forests that once experienced frequent, low to moderate intensity, fire regimes. In this paper, we report the effects of Fire and Fire Surrogate (FFS) forest stand treatments on fuel load profiles, potential fire behavior, and fire severity under three weather scenarios from six western U.S. FFS sites. This replicated, multisite experiment provides a framework for drawing broad generalizations about the effectiveness of prescribed fire and mechanical treatments on surface fuel loads, forest structure, and potential fire severity. Mechanical treatments without fire resulted in combined 1-, 10-, and 100-hour surface fuel loads that were significantly greater than controls at three of five FFS sites. Canopy cover was significantly lower than controls at three of five FFS sites with mechanical-only treatments and at all five FFS sites with the mechanical plus burning treatment; fire-only treatments reduced canopy cover at only one site. For the combined treatment of mechanical plus fire, all five FFS sites with this treatment had a substantially lower likelihood of passive crown fire as indicated by the very high torching indices. FFS sites that experienced significant increases in 1-, 10-, and 100-hour combined surface fuel loads utilized harvest systems that left all activity fuels within experimental units. When mechanical treatments were followed by prescribed burning or pile burning, they were the most effective treatment for reducing crown fire potential and predicted tree mortality because of low surface fuel loads and increased vertical and horizontal canopy separation. Results indicate that mechanical plus fire, fire-only, and mechanical-only treatments using whole-tree harvest systems were all effective at reducing potential fire severity under severe fire weather conditions. Retaining the largest trees within stands also increased fire resistance.

Key words: fire hazard; fire policy; fire suppression; fire resistance; fuel management; fuel treatment; mixed conifer; ponderosa pine; wildfire.

INTRODUCTION

Forest structure and species composition in many western U.S. coniferous forests have been altered through fire exclusion, past and ongoing harvesting practices, and livestock grazing. The effects of these activities have been most pronounced in seasonally dry, low and mid-elevation, coniferous forests that once experienced frequent, low to moderate intensity fire

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regimes (Agee and Skinner 2005, Stephens and Fulé 2005). Increased stand density, decreased overall tree size, and increased surface fuel loads are well documented for many forests of this type (Kilgore and Taylor 1979, Parsons and DeBenedetti 1979, Arno 1980, Skinner and Chang 1996, Taylor 2000, Fulé et al. 2002, Heyerdahl et al. 2002, Hessburg et al. 2005). These changes concern fire managers because the increased fuel loads and altered forest structure have made many forests vulnerable to fire severities outside of desired conditions. Changing climates in the next several decades may further complicate fire management by increasing temperatures and fire season length (McKenzie et al. 2004, Westerling et al. 2006).

Currently over 10 million hectares of coniferous forests in the western United States are in moderate or high fire hazard condition classes and pose a significant problem for management (Stephens and Ruth 2005). Because of these conditions, modification of potential fire behavior has become a central management focus in most coniferous forests in the western United States. Several recent fire policies and initiatives such as the U.S. National Fire Plan, Ten-Year Comprehensive Strategy, and Healthy Forest Restoration Act have been enacted to address the national wildfire problem in the United States (Stephens and Ruth 2005, Moritz and Stephens 2008).

Fuel reduction methods for modifying fire behavior are practiced by many managers (Pollet and Omi 2002, Agee and Skinner 2005, Peterson et al. 2005), although much remains to be done to more precisely quantify fuel treatment effects on potential wildfire severity under different fire weather scenarios and stand conditions (Fernandes and Botelho 2003). In addition, there is relatively little understanding of the ecological effects of fuel treatments, in particular the extent to which mechanical treatments might emulate natural ecological processes such as fire (Sierra Nevada Ecosystem Project 1996, McIver et al. 2009). Creating forest structures that can reduce fire severity at a landscape level may decrease the need for an aggressive suppression response and could eventually reduce the costs of fire suppression.

Debate over the efficacy of treatments utilized to modify vegetation structure and fuel loads in ways that alter fire behavior is ongoing at local, state, and national levels. Though there have been qualitative and comparative studies on the effectiveness of various fuel treatments, controlled empirical studies using modern fuel reduction techniques are relatively rare (Fulé et al. 2001, Pollet and Omi 2002, Fiedler et al. 2004, Stephens and Moghaddas 2005*a*, Agee and Lolley 2006, Schmidt et al. 2008, Youngblood et al. 2008), especially studies that are replicated and represent multiple regions of the U.S. Researchers have modeled the impacts of different fuel treatments on potential fire behavior in western coniferous forests (van Wagtendonk 1996, Stephens 1998, Miller and Urban 2000) but these analyses are constrained by model assumptions and a limited number of study locations.

The Fire and Fire Surrogate Study (FFS) was funded by the U.S. Joint Fire Science Program to provide information on the effects of using different silvicultural techniques to reduce fire hazard in common forest types that once experienced frequent, low to moderate intensity fire regimes across the continental United States (Weatherspoon and McIver 2000, McIver et al. 2009; see Plate 1). This study fills an important gap in our understanding of how fuel reduction treatments affect a range of ecological factors in these forest types. Initial effects of FFS treatments on a number of response variables, including vegetation, soils, insects, wildlife, fire behavior, and social responses to treatments have been reported at the site level by several authors (e.g., Metlen et al. 2004, Gundale et al. 2005, Knapp et al. 2005, Apigian et al. 2006, Youngblood et al. 2006, McCaffrey et al. 2008, Moghaddas and Stephens 2008, Schmidt et al. 2008). However, comparative treatment effects on potential fire severity across multiple FFS sites have not been analyzed and are the focus of this work.

The overriding goal of the fuel treatments was to increase stand resistance to the severe effects of wildfire and not to emulate historical, pre-European settlement, forest conditions. The primary fuel treatment objective was to alter stand conditions so that projected fire severity would result in at least 80% of the dominant and codominant residual trees surviving a wildfire under the 80th percentile fire weather conditions (the "80-80" rule). This standard (80-80 rule) was only a minimum requirement and stricter agency or local standards were commonly implemented across sites. While recognizing this minimum standard would likely not appreciably reduce tree mortality or significantly enhance fire suppression capabilities under more severe fire weather conditions, it may facilitate more widespread use of wildland fire use (WFU) and appropriate management response (AMR) (USDA and USDI 2005) to manage fires. Increasing resistance in forests can also moderate expected climate change impacts (Millar et al. 2007).

In this paper, we report the effects of FFS forest stand structure treatments on fuel load profiles and potential fire behavior and severity under three weather scenarios from six western FFS sites. This replicated, multisite experiment provides a framework for drawing broad generalizations about the effectiveness different fuel treatments in dry, low to mid-elevation coniferous forests in the western United States.

Methods

Study sites

The FFS study is a multidisciplinary project implemented at 12 sites nationwide (for map, see Schwilk et al. [2009]). Treatments varied somewhat between sites, and the data collection methods used two designs; however, similarities in how the experiment was conducted did facilitate comparison of results across

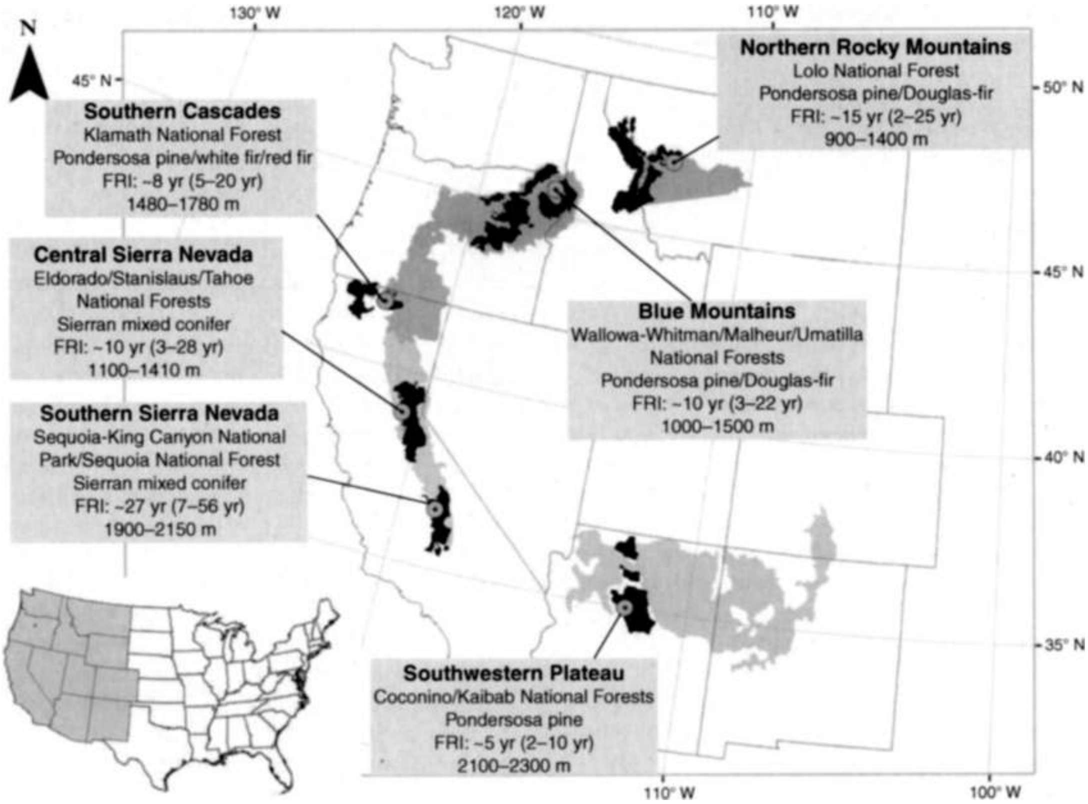

FIG. 1. Location, forest type, fire return interval (FRI, mean with range in parentheses), and elevation of the six western United States Fire and Fire Surrogate sites used in this work.

sites. This paper focuses on fuel treatment effects for a subset of six sites that are representative of the most common dry coniferous forest types in the western United States (Fig. 1). The FFS sites were selected to represent forests originally characterized by fire regimes of frequent, low-moderate intensity. The six sites included in this study are (1) Southern Cascades, within the Klamath National Forest in northern California; (2) Central Sierra Nevada, within the El Dorado National Forest in east-central California; (3) Southern Sierra Nevada, within Sequoia National Park in the southern Sierras of California; (4) Blue Mountains, within the Wallowa-Whitman National Forest in northeastern Oregon; (5) Northern Rocky Mountains, within the Lolo National Forest in western Montana; and (6) Southwestern Plateau, within the Coconino and Kaibab National Forests in northern Arizona (Table 1, Fig. 1, Appendix).

The forests represented by these sites span a latitudinal range of more than 12 degrees and contain forests that experience both summer rain and summer drought. Historical mean fire return intervals of the six sites ranged from 5 to 30 years and all sites have experienced a century of near total fire exclusion (Table 1, Appendix). Sites represented a diversity of past land management practices; five had been harvested repeatedly with the sixth being an unharvested old-growth forest at Sequoia National Park (Appendix).

Treatments

Site level treatments included an unmanipulated control, prescribed fire only (in the fall, spring, or both), mechanical treatment only, and a mechanical plus prescribed fire treatment (in the fall or spring). Regional variations in treatment implementation were reflective of local mechanical treatment and prescribed burning practices. All mechanical treatments included removal of commercial material composed of stud logs and saw logs (trees greater than 20–25 cm diameter at breast height [dbh]) and some sites removed biomass or pulp trees (trees 5–25 cm dbh). In all mechanical treatments, removal of saw logs was completed using whole-tree, cut-to-length, or standard chainsaw and skidder or forwarder systems (Appendix). Within mechanical plus fire and fire-only treatments, prescribed burns were implemented in the fall with the exception of the Northern Rocky Mountains, which applied spring burns, a local prescribed burning preference (Appendix). In the Southern Sierra Nevada, mechanical treatments were not used; instead fall and spring prescribed burns were implemented to compare differences in burn seasonality. While most prescribed fires were designed

TABLE 1. Characteristics of the six western United States Fire and Fire Surrogate Study sites.

Fire surrogate study site, name, and location	Replicates per treatment	Latitude and longitude	Elevation range (m)
Central Sierra Nevada, Blodgett Forest Research Station, California	3	38° N, 120° W	1100–1410
Northern Rocky Mountains, Lubrecht Experimental Forest, Montana	3	47° N, 113° W	900–1400
Southern Cascades, Goosenest Adaptive Management Area, California	3	41.5° N, 122° W	1480–1780
Blue Mountains, Hungry Bob, Wallowa-Whitman National Forest, Oregon	4	45°30′ N, 117° W	1000–1500
Southwestern Plateau, northern Arizona	3	35° N, 112° W	2100–2300
Southern Sierra Nevada, Sequoia National Park, California	3	36.5° N, 119° W	1900–2150

as low intensity understory burns, achieving the 80-80 objective required mixed fire severities on some sites.

All treatments were replicated at least three times at each FFS site (Table 1). Experimental units were at least 10 ha each with a central measurement area used for field measurements to reduce edge effects. Treatments were assigned to experimental units randomly, except at the Southwestern Plateau, where one experimental block required specific arrangements of burn units for safety reasons.

Assessment of stand structure and fuels

At the Central Sierra Nevada and Blue Mountains, vegetation was measured with the use of 0.04-ha circular plots installed in each experimental unit (20 and 25 plots, respectively, in each experimental unit). Plots were placed on a systematic grid with a random starting point. Tree species, dbh, tree height, height to live crown base, and crown position in the forest canopy (dominant, codominant, intermediate, suppressed) were recorded for all trees greater than 10 cm dbh on each plot. Similar information was also recorded for all trees greater than 1.37 m tall on a 0.004 ha nested subplot in each of the 0.04-ha circular plots. Canopy cover was measured at 25 points (5×5 m grid) on each 0.04-ha plot using a sight tube (Jennings et al. 1999). Surface and ground fuels were sampled using the line-intercept method (van Wagner 1968, Brown 1974) along two randomly chosen azimuths at each of the 0.04-ha plots. Duff and litter depth (cm) were measured at two points along each transect; surface fuel depth (cm) was measured at three points along each transect. At the Blue Mountains, destructive plot-based sampling was used to sample 1-hour ($<$0.064 cm diameter) and 10-hour (0.064–2.54 cm diameter) woody fuels.

At the other four FFS sites, 0.1-ha (20×50 m) rectangular plots were randomly located in each experimental unit at ten of 36 points in a 6×6 grid (50 m intervals between grid points). These modified Whittaker (Keeley and Fotheringham 2005) plots were used to sample live and dead vegetation, and fuels. Plots were oriented randomly at some sites or oriented in one of the four cardinal directions (0°, 90°, 180°, 270°, randomly chosen) at other sites. Diameter at breast height of all trees with dbh $>$ 10 cm was measured and status (alive, standing dead, dead and down) were recorded. Saplings (dbh $<$ 10 cm and height $>$ 1.37 m) were sampled on half of each 0.1-ha plot. Saplings were not individually tagged, but the same data were recorded as for trees. Percentage canopy cover was estimated at grid points or at the corner of the 0.1-ha plots. Surface fuels were measured using two transects (20 m in length) placed at each of the 36 grid points within each experimental unit; litter and duff depth measurements were taken at three locations along these transects.

At all sites, ground fuel loads were calculated using either published equations (Brown 1974, van Wagtendonk et al. 1996, 1998) or site-specific fuel depth to weight relationships developed from destructive sampling of the forest floor. Data analyzed in this study were one year posttreatment, except at Blue Mountains, which were two years posttreatment.

Modeling potential fire behavior and severity

In western U.S. coniferous forests, fire managers often use a stricter standard than the FFS 80th percentile weather conditions for designing fuels treatments (i.e., 90th or 97.5th percentile). Therefore, we simulated fire behavior and effects under upper 80th (moderate), 90th (high), and 97.5th (extreme) percentile fire weather conditions based on archived remote access weather station (RAWS) data. Weather data from the RAWS station (data *available online*)[12] closest to each FFS site were analyzed with Fire Family Plus (Main et al. 1990) to determine percentile fire weather conditions (Table 2). Each RAWS station had a weather record of at least 25 years and these data were used to generate percentile fire weather.

Fuels Management Analyst Plus (FMA) was used to estimate potential fire behavior, crowning index, torching index, and tree mortality (Carlton 2004). Torching and crowning indices are the wind speed (measured at 6.1 m above ground) required to initiate torching (passive crown fire) or to sustain a crown fire (active crown fire) within a stand, respectively (Scott and Reinhardt 2001). Higher values of torching and crowning indices are desirable. FMA uses information from field measurements (tree species, dbh, tree crown ratio, tree crown position, percentage canopy cover, surface and ground fuel loads, slope) and fire weather to simulate fire behavior and fire effects at the stand scale.

[12] ⟨http://www.raws.dri.edu/⟩

TABLE 1. Extended.

Tree species (mean ages of dominant and codominant trees)	Fire return interval (mean and range) (yr)
Pinus ponderosa, *Pinus lambertiana*, *Calocedrus decurrens*, *Pseudotsuga menziesii* (90–100 yr)	10 (3–28)
Pinus ponderosa, *Pseudotsuga menziesii* (80–90 yr)	15 (2–25)
Pinus ponderosa, *Abies concolor* (70–80 yr)	8 (5–20)
Pinus ponderosa, *Pseudotsuga menziesii* (70–100 yr)	10 (3–22)
Pinus ponderosa (70–90 yr)	5 (2–10)
Abies concolor, *Abies magnifica*, *Calocedrus decurrens*, *Pinus jeffreyi*, *Pinus ponderosa*, *Pinus lambertiana* (300–500 yr)	27 (7–56)

FMA incorporates published methodologies for computing crown bulk density, fire behavior, and predicted mortality by species. See Stephens and Moghaddas (2005*a*, *b*) for summaries of the methodologies used for these computations. The fuel models (Rothermel 1983, Carlton 2004, Burgan and Scott 2005) used for estimating fire behavior for each treatment and site are given in Table 3; fuel models were selected by scientists associated with each of the individual FFS sites.

Acknowledgement is given to the fact that the fuel and fire behavior models used in this assessment are simplified representatives of real fuel conditions (Burgan and Scott 2005) and fire behavior (Pastor et al. 2003). Further, the models have not all been field validated because of the difficulty of doing so (Scott and Reinhardt 2001). Crown fire behavior is notably complex and is controlled by several interacting, highly variable elements such as weather, crown characteristics, and surface fuels, which the models tend to homogenize. That said, these models still represent the best available compilation of fire behavior science, whether empirically or theoretically derived (Pastor et al. 2003), and therefore, results of modeled crown fire behavior can be particularly useful for relative comparisons between treatments. However, predictions should be used with caution for estimating absolute values of model outputs (Scott 2006), particularly torching index. High values of torching index, those that are multiple times the magnitude of any possible wind speed at an individual site, should be interpreted as a characteristic of a forest structure that is extremely resistant to passive crown fire. Potential tree mortality (fire severity) is the most appropriate metric to compare the results of the FFS fuel treatments in this study.

Data analysis

An analysis of covariance (ANCOVA) (Zar 1999) was performed for each FFS site using the posttreatment fuel and stand structure measurements as response variables with the pretreatment values used as the covariate. Several variables were separately analyzed at all sites including vegetation (trees/ha, canopy cover) and surface fuel (1-, 10-, and 100-h time lag fuel loads/ha) characteristics. No pretreatment data were collected at the Southern Cascades site; therefore an ANOVA was completed on the post treatment data only. At all sites, Bonferroni multiple pairwise comparisons (Zar 1999) were evaluated at the mean value of the covariate to determine if significant differences ($P < 0.05$) existed in the vegetation and fuels variables analyzed. Potential for crown fire (torching index, crowning index) and fire severity (predicted tree mortality) were computed for each fire weather combination (Table 2) and fuel conditions created by each treatment type (Table 3). The JMP statistical software package (Sall et al. 2001) (this product is not endorsed by the authors of this study) was used in all analyses. All statistical comparisons were made between treatment types and controls, separately, by site.

RESULTS

Surface fuels and stand structure

The combined 1-, 10-, and 100-h surface fuel loads (fuels with diameter 0–7.5 cm) in mechanical-only treatments were significantly greater than in the controls at three of five FFS sites (Table 4). The mechanical plus fire treatment significantly reduced 1-, 10-, and 100-h surface fuels at only the Central Sierra Nevada site. Fire alone, when used in the fall, significantly reduced 1-, 10-, and 100-h surface fuels at two of five FFS sites (Table 4). Fire used in the spring significantly reduced 1-, 10-, and 100-h surface fuels at one of two FFS sites. At the Southern Sierra Nevada, where burns were conducted in both seasons, there was a significantly greater reduction in these fuels with fall burning. Fire alone, in either fall or spring, significantly reduced 1-, 10-, and 100-h fuels compared to three of five FFS sites utilizing mechanical-only treatments and one site with the mechanical plus fire treatment.

Canopy cover was significantly lower than controls at three of five FFS sites with mechanical-only treatments and all five FFS sites with the mechanical plus fire treatment (Table 5). Fire alone had no significant effect on canopy cover at five of the six FFS sites; canopy cover was significantly reduced by fall burning but not by spring burning at the Southern Sierra Nevada site (Table 5).

Compared to controls, density of the smallest trees (2.5–25 cm dbh) was significantly lower in mechanical-only treatments at three of five FFS sites and in mechanical plus fire treatments at all five FFS sites tested (Table 6). Fall burning significantly reduced tree density between 2.5 and 25 cm dbh at four of five FFS

TABLE 2. Upper 80th, 90th, and 97.5th percentile fire weather conditions for the six western United States Fire and Fire Surrogate sites.

Weather parameter	Central Sierra Nevada, Bald Mountain			Northern Rocky Mountains, Missoula			Southern Cascades, Van Bremmer			Blue Mountains, Roberts Butte		
Weather percentile	80	90	97.5	80	90	97.5	80	90	97.5	80	90	97.5
Probable maximum 1-min wind speed (km/hr) (Crosby and Chandler 1966)	22	27	31	13	16	16	18	16	21	13	13	14
Dry-bulb temperature (°C)	29	32	33	30	33	34	29	31	33	31	33	35
Relative humidity (%)	25	17	15	26	19	17	17	14	11	15	13	10
1-h fuel moisture (%)	3.9	3	1.8	4.5	4.8	4	3.5	2.5	2.2	3	2.8	1.5
10-h fuel moisture (%)	5.2	2.7	2.3	5.5	6.4	4.9	3.9	2.7	2.7	3.7	3.4	2.2
100-h fuel moisture (%)	7.7	6.6	4.2	9.5	10	8.2	6.8	5.8	5.6	6.2	6	5
Herbaceous fuel moisture (%)	62	30	30	57	42	47	39	40	36	88	91	95
Woody fuel moisture (%)	101	47	41	99	80	76	59	60	52	15	13	10
Foliar fuel moisture (%)	100	80	75	100	80	75	100	80	75	100	80	75

sites using this treatment. Spring burning significantly reduced the density of trees between 2.5 and 25 cm dbh at the Northern Rocky Mountains. Tree density from 25 to 51 cm dbh was significantly reduced in mechanical-only treatments at four of five FFS sites (all except the Blue Mountains) and in mechanical plus fire treatments at all five FFS sites that used this treatment (Table 6). In the fire-only treatment (fall or spring), density of trees between 25 and 51 cm dbh was reduced only at the Southern Sierra Nevada with a fall burn. Tree density of the 51–76 cm dbh size class was significantly reduced in the mechanical-only and mechanical plus fire treatment at only the Central Sierra Nevada site. Density of the largest trees (dbh > 76 cm) was not significantly reduced by any treatment (Table 6).

Potential crown fire and tree mortality

The mechanical treatment alone had a variable effect on torching index; two FFS sites showed either a decrease (Northern Rockies) or little improvement (Central Sierra) in the torching index, compared with controls, while large increases in the torching index were noted at the other three FFS sites (Fig. 2). For the combined treatment of mechanical plus fire, all five FFS sites with this treatment had a substantially lower likelihood of passive crown fire as indicated by the very high torching indices.

Across all FFS sites using mechanical treatments, the relative potential for active crown fire (as measured by the crowning index) was lowest in mechanical plus fire treatments, followed by the mechanical-only treatments, closely followed by fire-only treatments (fall or spring), and highest in the controls (Fig. 3). The relative potential for passive and active crown fires from fall/spring burn-only treatments at the Southern Sierra Nevada site was lower than most active treatments at all other sites (Figs. 2 and 3).

Predicted tree mortality (all tree size classes) from a potential wildfire at all percentile weather conditions was lowest for the mechanical plus fire treatment, followed by the fire-only treatment (Figs. 4–6). The mechanical-only treatment resulted in an effective reduction of potential tree mortality across all diameter classes compared to controls except at the Northern Rockies where potential mortality increased in mechanical-only treatments for all weather scenarios and at the Central Sierra Nevada where it was largely unchanged (Figs. 4–6). The mechanical-only treatment at the Central Sierra slightly increased predicted mortality for trees up to 51 cm dbh under 80th percentile weather conditions.

DISCUSSION

Quantitatively evaluating the source of fire hazard from surface, ladder, and crown fuels, or their combination, will help managers design more effective fuel treatments. Fire hazard also can pose a risk to other resources that are targeted for protection, including human development, wildlife habitat, water quality, recreation areas, wood fiber, and other values (McKelvey et al. 1996, Agee 2003, Hessburg et al. 2005, Spies et al. 2006). More effective strategies are likely to be

TABLE 3. Fuel models used for fire behavior and effects modeling at the six western United States Fire and Fire Surrogate sites.

Location	Control	Mechanical only	Mechanical plus fire	Fire only
Central Sierra Nevada	10A[2]	11MC[2]	8A[2]	8A[2]
Northern Rocky Mountains	TL-05[3]	SB-02[3]	TL-01[3] (S)	TL-01[3] (S)
Blue Mountains	2[1]	11AC[2]	9[1]	9[1]
Southwestern Plateau	9[1]	11CB[2]	9[1]	9[1]
Southern Cascades	10M[2]	11CC[2]	8A[2]	8A[2]
Southern Sierra Nevada	10[1]	NA	NA	8[1] (S)

Notes: Burning treatments were in the fall except where specified spring (S). Fuel models used are from the references cited. NA, not applicable: this site did not include these treatments.

References (indicated by superscript numbers): 1, Rothermel (1983); 2, Carlton (2004); 3, Burgan and Scott (2005).

Table 2. Extended.

Southwestern Plateau, Tusayan			Southern Sierra Nevada, Dinkey Creek and Park Ridge		
80	90	97.5	80	90	97.5
18	23	16	15	16	15
26	28	31	27	28	29
12	10	7	27	20	18
2.7	3.2	2.5	5.2	4.5	4.2
3.8	3.6	2.9	6.8	5.6	5.0
5.1	5.1	4.4	10.0	8.8	7.6
30	30	30	41	30	21
50	50	7	83	75	65
100	80	75	100	80	75

developed through assessments that span stand and landscape scales as appropriate for the area being treated. Net treatment costs and reduction in fire risk are critical considerations when determining the feasibility of any fuel treatment (Fiedler et al. 2004, Finney 2005, Hartsough et al. 2008).

The effectiveness of mechanical thinning for reducing passive and active crown fire potential was largely dependent on the type of harvest system used, and whether the harvest system left activity fuels in the unit. The Southern Cascades utilized a whole-tree harvest system that resulted in no significant increase in 1-, 10-, and 100-h surface fuels after mechanical treatment. The Central Sierra Nevada site used a lop and scatter treatment of limbs and tree tops followed by mastication of approximately 90% of the standing live and dead trees from 2.5 to 25 cm dbh. The Northern Rocky Mountains, Southwestern Plateau, and Blue Mountains used cut-to-length systems that left tree limbs and tree tops in the experimental units. These mechanical-only treatments significantly increased combined 1-, 10-, and 100-h surface fuels. It is important to note that at these sites, residual surface fuels exceeded 15 Mg/ha (Table 4), but the Central Sierra Nevada and Southwestern Plateau still had slightly reduced crown fire potential because of reduced small tree density (Table 6) and higher canopy base heights. At the Northern Rockies site, high surface fuel loads combined with low canopy base heights from the large number of trees remaining in the 2.5–25 cm dbh size class contributed to decreased effectiveness in reducing torching potential and predicted tree mortality when compared to the untreated forest (controls).

Mechanical treatments reduced active crown fire potential when compared to controls at all five sites that included this treatment (Fig. 3). These sites utilized low thinning, and sometimes improvement or selection cutting to remove commercial and sub-merchantable materials, and this resulted in increased horizontal and vertical separation of canopy fuels (Fiedler et al. 2003, Graham et al. 2004, Agee and Skinner 2005, Peterson et al. 2005, Youngblood et al. 2008). Silvicultural treatments that remove commercial material yet retain high levels of biomass (trees with dbh < 25 cm) do not improve resistance to high-severity fire. Mechanical treatments followed by prescribed burning or pile burning were the most effective treatment for reducing crown fire potential and predicted tree mortality.

The use of whole-tree harvesting has been previously recommended to minimize activity fuels (Agee and Skinner 2005); the findings reported in our study provide quantitative evidence supporting this recommendation. Whole-tree removal systems were the most effective mechanical system analyzed in this study and may be preferred where wood-chip or biomass markets are available to forest managers. Where trees are too small for sawn products and cannot be economically chipped and transported to a processing facility, subsidizing treatment or hauling costs should be considered if the corresponding decrease in fire hazard warrants the additional expenditure. Whole-tree removal systems are also advantageous when managers plan to prescribe burn after tree removals because only surface fuels existing pretreatment need to be consumed (a few activity fuels will be left on site).

Of all active treatments, spring burning alone resulted in the fewest significant changes to stand and fuel structures. At the Southern Sierra Nevada site, both fall and spring fire-only treatments were still effective at removing surface fuels. Whereas the fall fire treatment was more effective at reducing the density of trees up to 25 cm dbh; spring burning resulted in greater retention of large woody debris (Knapp et al. 2005). While treatments involving fall burns resulted in greater surface fuel reduction, broad generalizations about the effect of burning season on modeled fire behavior and

Table 4. Mean posttreatment 1-, 10-, and 100-hour combined fuel loads (Mg/ha, with SE in parentheses) by treatment for six western United States Fire and Fire Surrogate sites.

Location	Control	Mechanical only	Mechanical + fire, fall	Mechanical + fire, spring	Fire only, fall	Fire only, spring
Central Sierra Nevada	14.2^{a} (1.1)	17.1^{b} (0.8)	4.8^{c} (0.2)	†	4.4^{c} (1.0)	†
Northern Rocky Mountains	8.2^{a} (1.2)	21.1^{b} (2.0)	†	7.6^{a} (0.9)	†	2.6^{a} (0.2)
Blue Mountains	4.1 (1.0)	5.6 (1.5)	3.0 (0.7)	†	1.7 (0.1)	†
Southwest Plateau	5.7^{bc} (1.2)	15.5^{a} (0.7)	8.6^{c} (0.9)	†	3.7^{b} (0.2)	†
Southern Cascades	6.3 (1.3)	7.1 (0.9)	3.6 (0.3)	†	3.7 (0.6)	†
Southern Sierra Nevada	8.5^{a} (0.1)	†	†	†	0.6^{b} (0.2)	2.6^{c} (0.0)

Note: Mean values in a row with different superscript letters are significantly different ($P < 0.05$).
† No treatment of this type at given site.

TABLE 5. Mean (with SE in parentheses) percentage canopy cover by treatment for six western United States Fire and Fire Surrogate Study sites.

Location	Control	Mechanical only	Mechanical + fire, fall	Mechanical + fire, spring	Fire only, fall	Fire only, spring
Central Sierra Nevada	75^{a} (5)	51^{b} (1)	58^{b} (4)	†	65^{ab} (3)	†
Northern Rocky Mountains	70^{a} (2.5)	44^{b} (3.1)	†	36^{b} (2.6)	†	69^{a} (0)
Blue Mountains	63^{a} (3.8)	60^{a} (7.2)	39^{b} (4.2)	†	51^{a} (8)	†
Southwester Plateau	63^{a} (3)	39^{b} (2)	36^{b} (4)	†	61^{a} (0)	†
Southern Cascades	59^{a}	39^{ab}	28^{b}	†	44^{ab}	†
Southern Sierra Nevada	56^{ab} (7)	†	†	†	50^{b} (1)	61^{a} (4)

Note: Mean values in a row followed by the same superscript letter are not significantly different ($P < 0.05$).
† No treatment of this type at given site.

effects are not possible here because burns in both seasons were only conducted at one site, and too few sites used spring burning. However, our results are consistent with other recent reports of greater change (fuel consumption and tree mortality) with late-season burns in western U.S. forest ecosystems (Thies et al. 2005, Perrakis and Agee 2006).

An important difference between the fire-only and mechanical plus fire treatment is the residual standing dead material left after the fire-only treatment (Skinner 2005). Previous studies in the Central Sierra Nevada site found a significantly higher total standing volume of snags up to 15 cm dbh in the fire-only treatment when compared with the mechanical plus fire treatment

TABLE 6. Mean posttreatment live tree density (trees/ha with SE in parentheses) by treatment for six western United States Fire and Fire Surrogate sites.

Size class (dbh)	Control	Mechanical only	Mechanical + fire, fall	Mechanical + fire, spring	Fire only, fall	Fire only, spring
Central Sierra Nevada						
2.5–25	851.3^{a} (77.7)	286.9^{b} (139.8)	100.0^{b} (19.7)	†	223.9^{b} (21.4)	†
25–51	175.4^{a} (15.6)	61.3^{b} (4.7)	66.7^{b} (15.4)	†	137.1^{a} (11.7)	†
51–76	62.6^{a} (5.4)	56.4^{b} (6.6)	47.8^{b} (3.2)	†	65.0^{a} (1.1)	†
>76	19.8 (4.0)	23.9 (3.0)	24.3 (6.1)	†	15.2 (1.8)	†
All	1109.0^{a} (84.1)	428.5^{b} (139.4)	238.8^{b} (20.9)	†	441.3^{b} (32.1)	†
Northern Rockies						
2.5–25	2406.4^{a} (403.0)	1051.2^{bc} (131.6)	†	221.7^{c} (81.3)	†	1966.6^{b} (824.6)
25–51	154.5^{a} (20.8)	83.0^{b} (7.4)	†	69.2^{b} (15.0)	†	145.2^{a} (21.7)
51–76	14.5 (7.7)	6.3 (0.9)	†	5.9 (3.5)	†	7.2 (2.4)
>76	0.0 (0.0)	0.0 (0.0)	†	0.0 (0.0)	†	0.0 (0.0)
All	2575.4^{a} (381.6)	1140.5^{c} (132.2)	†	296.8^{bc} (90.8)	†	2119.1^{ac}(808.3)
Blue Mountains						
2.5–25	244.8^{a} (45.9)	248.5^{a} (47.8)	73.5^{b} (25.0)	†	115.6^{b} (29.8)	†
25–51	137.8^{a} (9.1)	105.1^{ab} (3.7)	91.0^{b} (10.2)	†	124.6^{ab} (24.4)	†
51–76	10.8 (0.0)	6.0 (0.0)	3.2 (0.0)	†	4.5 (0.0)	†
>76	0.6 (0.7)	0.0 (0.0)	0.3 (0.3)	†	0.0 (0.0)	†
All	394.0^{ac} (49.0)	359.7^{c} (49.6)	167.9^{bc} (33.9)	†	244.7^{ac} (23.4)	†
Southwestern Plateau						
2.5–25	442.6 (155.3)	97.5 (33.1)	67.2 (16.1)	†	353.4 (178.6)	†
25–51	186.1^{a} (26.6)	64.2^{b} (13.3)	55.0^{b} (15.8)	†	188.7^{a} (12.9)	†
51–76	7.6 (0.3)	17.1 (5.4)	14.8 (3.0)	†	10.2 (3.7)	†
>76	0.3 (0.3)	0.3 (0.3)	0.7 (0.7)	†	0.3 (0.3)	†
All	636.9^{a} (147.4)	179.2^{c} (24.0)	137.7^{bc} (18.1)	†	552.6^{ab} (163.2)	†
Southern Cascades						
2.5–25	1741.9^{a} (113.3)	27.1^{c} (11.1)	16.2^{c} (3.4)	†	413.6^{b} (62.7)	†
25–51	242.4^{a} (22.4)	113.6^{b} (4.7)	76.4^{b} (17.2)	†	240.4^{a} (23.4)	†
51–76	36.2 (5.9)	39.8 (4.4)	26.3 (4.9)	†	32.3 (10.6)	†
>76	1.3 (0.7)	2.6 (1.7)	1.3 (0.3)	†	0.0 (0.0)	†
All	2021.8^{a} (128.6)	183.2^{c} (8.4)	120.2^{c} (24.9)	†	686.3^{b} (86.0)	†
Southern Sierra Nevada						
2.5–25	462.5^{a} (85.9)	†	†	†	73.6^{b} (5.7)	224.9^{ab} (31.1)
25–51	87.3^{a} (1.7)	†	†	†	42.5^{b} (16.3)	82.3^{ab} (12.0)
51–76	38.5 (6.9)	†	†	†	24.4 (1.3)	38.9 (7.3)
>76	41.2 (3.4)	†	†	†	37.2 (2.0)	37.9 (2.0)
All	629.4^{a} (85.0)	†	†	†	177.7^{b} (19.9)	383.9^{ab} (24.0)

Note: Mean values in a row followed by different superscript letters are significantly different ($P < 0.05$).
† No treatment of this type at given site.

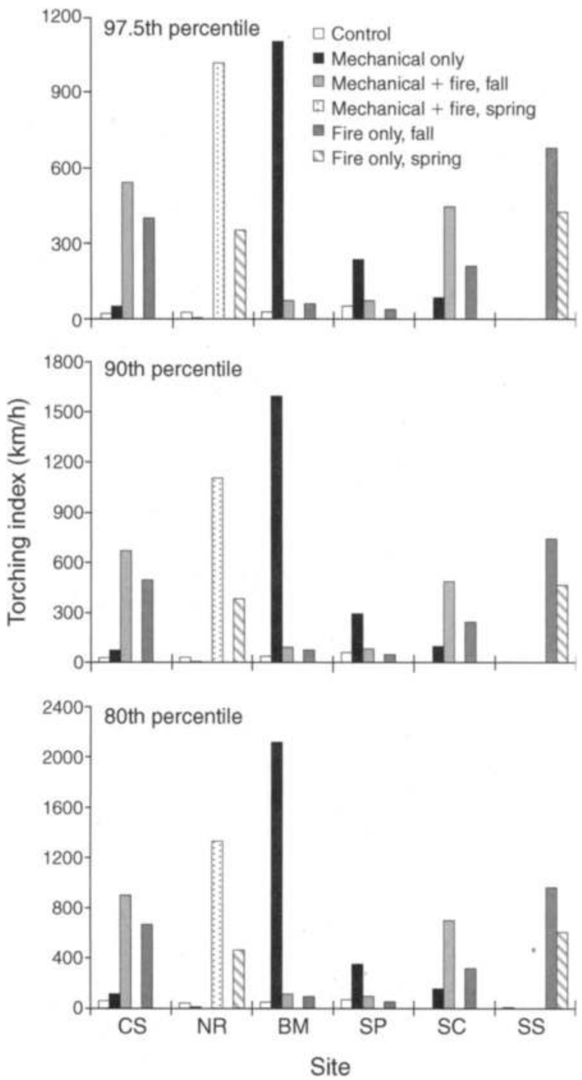

FIG. 2. Modeled posttreatment torching index (km/h) under 80th, 90th, and 97.5th weather percentiles at six western United States Fire and Fire Surrogate sites. If there is no bar, a treatment was not implemented at that site. Site names are abbreviated as: Central Sierra (CS), Northern Rockies (NR), Blue Mountains (BM), Southwestern Plateau (SP), Southern Cascades (SC), and Southern Sierra (SS). High values of torching index, those that are multiple times the magnitude of any possible windspeed at a site, should be interpreted as a characteristic of a forest structure that is extremely resistant to passive crown fire.

(Stephens and Moghaddas 2005*c*). This standing dead material will eventually fall to the ground and can exacerbate fire effects when the site burns again, although high fire hazard areas will likely be patchy. While additions of this woody debris may be considered desirable for habitat value or stabilizing erosive soils, it will increase future surface fuel loads and shorten the longevity of the fuel treatment. It is expected that several fire-only treatments (two to three) would be needed to achieve a desired condition regarding potential fire behavior and effects in these forests.

The potential for active crown fire was reduced by both mechanical and mechanical plus burning treatments but not appreciably by the fire-only treatment. However, the fire-alone and fire plus mechanical treatments greatly increased the torching index and this effectively reduced the vulnerability of these stands to individual or groups of trees torching. This is supported by empirical studies of actual and projected fire effects on sites with similar treatments (Graham 2003, Skinner et al. 2004, Skinner 2005, Ritchie et al. 2007).

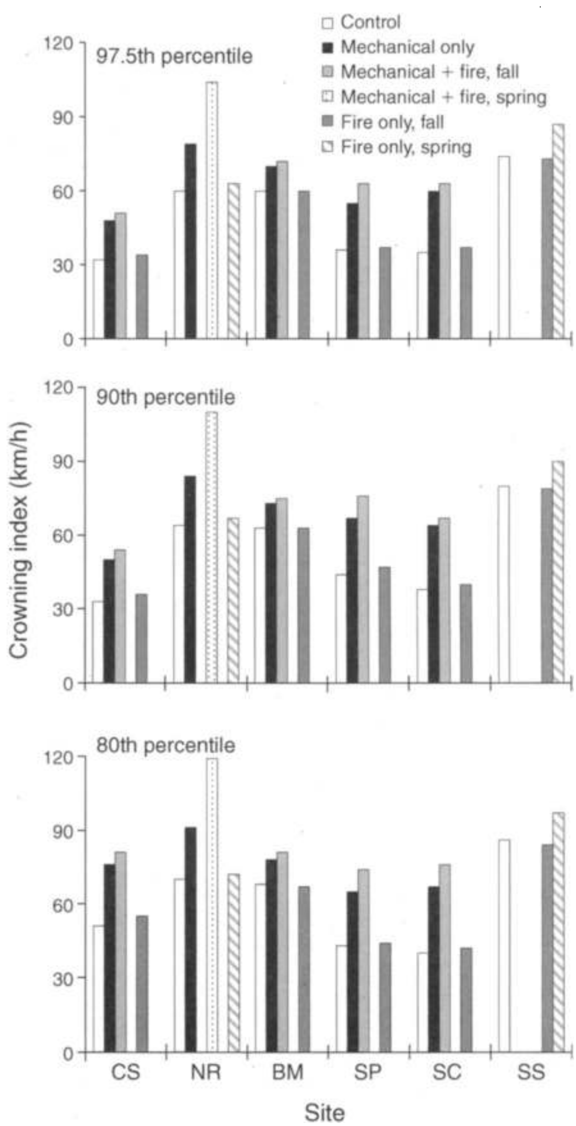

FIG. 3. Modeled posttreatment crowning index (km/h) under 80th, 90th, and 97.5th weather percentiles at six western United States Fire and Fire Surrogate sites. If there is no bar, a treatment was not implemented at that site. Site names are abbreviated as: Central Sierra (CS), Northern Rockies (NR), Blue Mountains (BM), Southwestern Plateau (SP), Southern Cascades (SC), and Southern Sierra (SS).

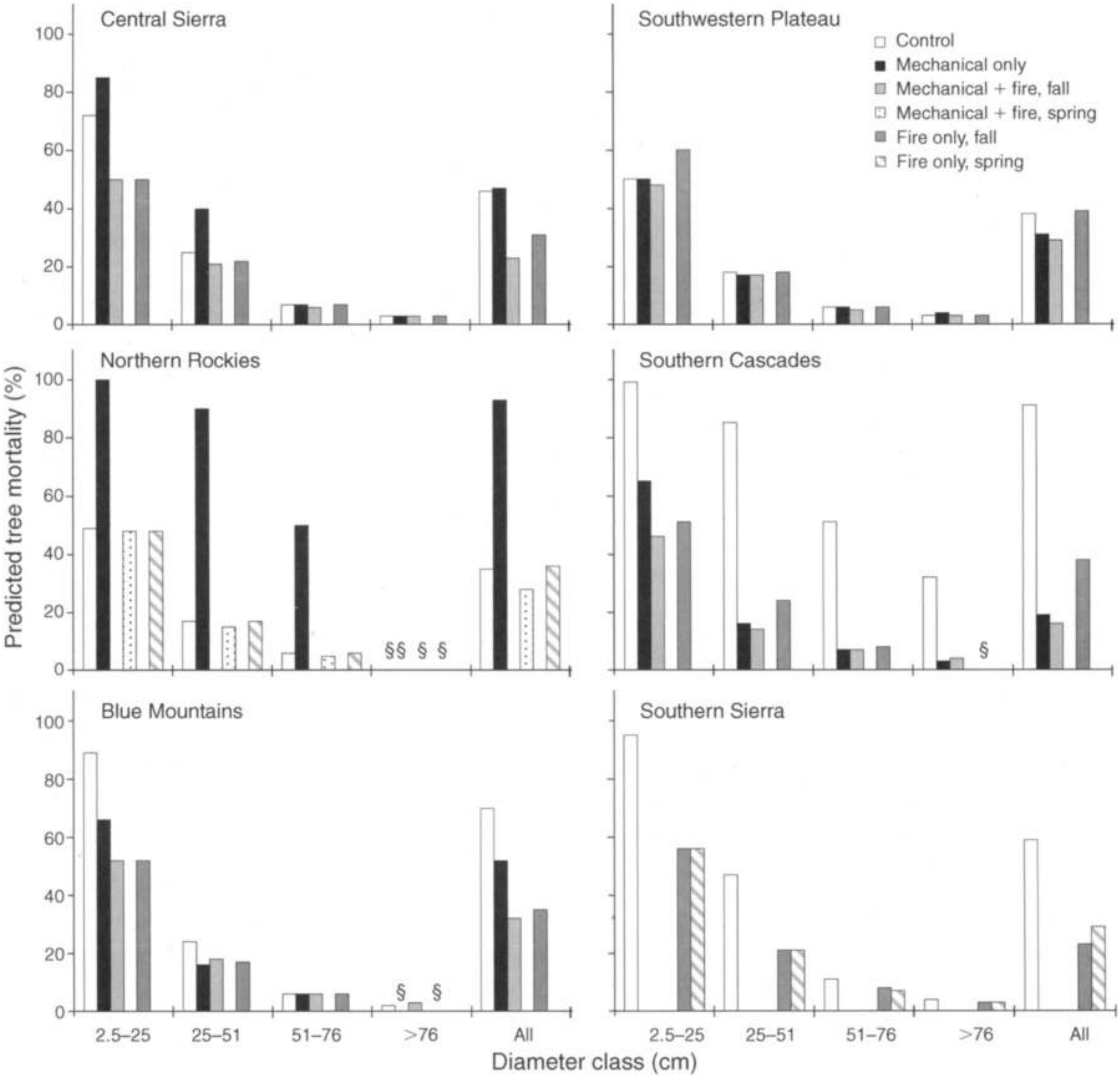

FIG. 4. Modeled postfire tree mortality by dbh class under 80th percentile weather conditions for trees remaining at six western United States Fire and Fire Surrogate sites after treatments. When no trees were present in a given treatment, this absence of a given size class is denoted by §. If there is no bar, a treatment was not implemented at that site.

The controls were the most susceptible to active and passive crown fire and had the highest predicted tree mortality except in the Northern Rockies site, where the mechanical-only treatments had the highest potential severity over all weather scenarios. The high fire severity in the Northern Rockies site is due to high surface fuel depositions from the use of a cut-to-length harvest system (Table 4). The overall effectiveness of the fire-only treatment at reducing potential fire severity at the Southern Sierra Nevada site was influenced by the larger tree sizes found in this old-growth forest when compared with the other five FFS sites, coupled with a significant reduction in surface and ladder fuels from burning. National Park managers in the Southern Sierras did not choose to implement a mechanical treatment; fire was therefore the only tool available to modify forest structure and this probably resulted in higher intensity prescriptions to achieve their desired results.

These results highlight the effectiveness of reducing surface fuels, thinning from below, and retaining the larger dominant and co-dominant trees in residual stands for reducing fire severity and increasing forest resistance (Agee and Skinner 2005). Conversely, thinning from above, or overstory removal of dominant and co-dominant trees, decreases fire resistance (Stephens and Moghaddas 2005*b*). Removing trees through a low thinning, and removing some low-vigor and more abundant shade-tolerant trees (if present) from the main canopy through improvement/selection cutting can also reduce fire hazards and create more sustainable forest conditions (Fiedler et al. 2001).

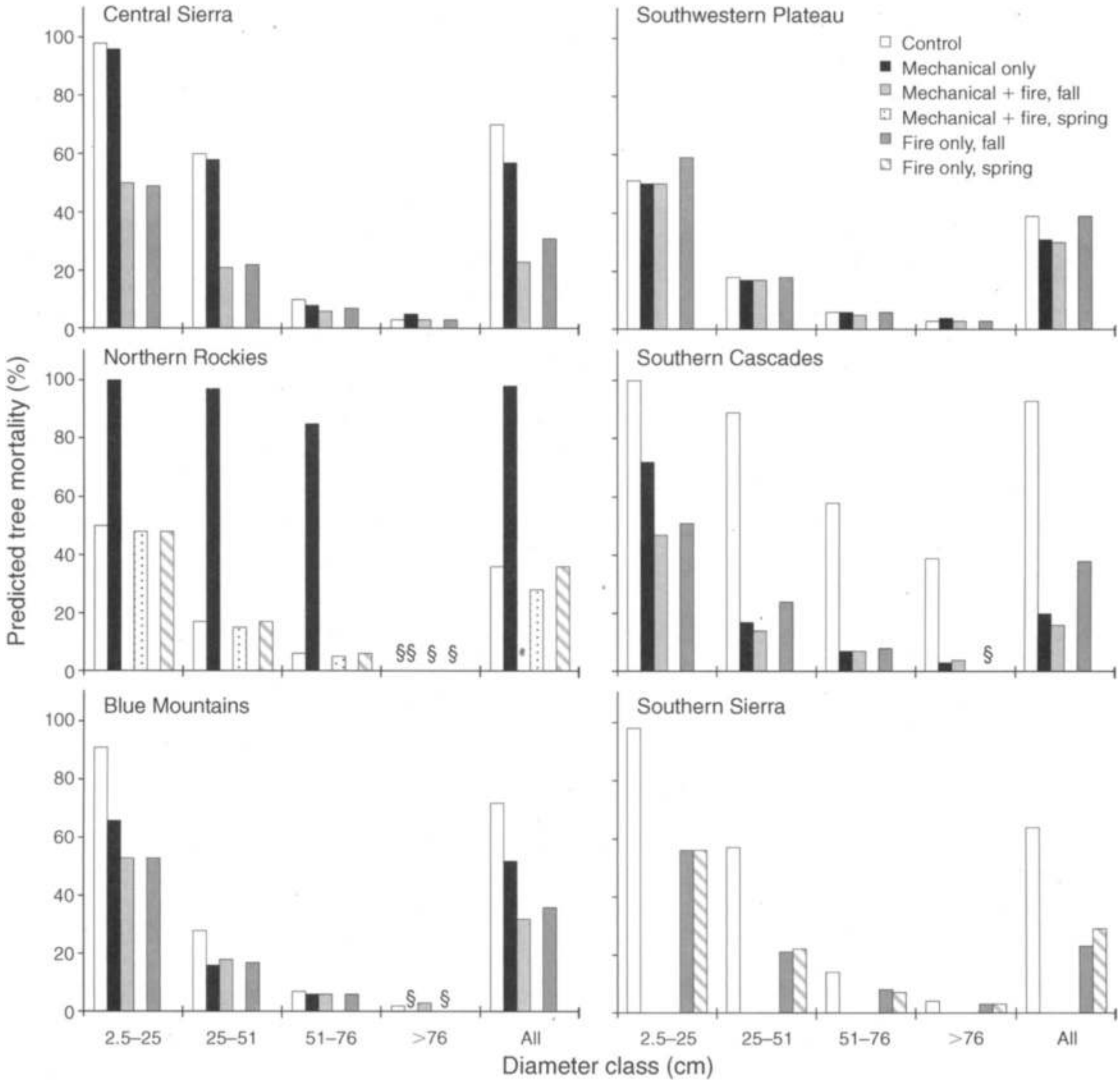

FIG. 5. Modeled postfire tree mortality by dbh class under 90th percentile weather conditions for trees remaining at six western United States Fire and Fire Surrogate sites after treatments. When no trees were present in a given treatment, this absence of a given size class is denoted by §. If there is no bar, a treatment was not implemented at that site.

This analysis did not include the FFS site in Washington. In contrast to the six FFS analyzed here, the Washington FFS site is remote and not accessible from a road network (Agee and Lolley 2006). It therefore used a skyline yarding system and limits imposed on prescribed fire operations resulted in fuel reduction objectives not being obtained. Reducing fire hazards in remote forests is challenging and the use of WFU or AMR may be an option in these locations (Collins and Stephens 2007, Stephens et al. 2007; Collins et al. 2008).

Effectiveness of fuel treatments during actual wildfires

Mechanical plus fire treatments were effective in reducing fire severity in the Cone Fire (Skinner et al. 2004, Ritchie et al. 2007), the Rodeo Chediski Fire (Strom 2005), and the Biscuit fires (Raymond and Peterson 2005) as well as other wildfires (Omi and Martinson 2004) in the western United States. In addition, fire-only treatments were effective at reducing fire severity on the Hayman Fire (Graham 2003), the Rodeo-Chediski Fire (Finney et al. 2005), and other fires (Biswell 1989), though effectiveness of prescribed burn treatments will likely decline more rapidly over time as surface fuels accumulate (Finney et al. 2005, Skinner 2005).

Results of wildfire impacts on areas treated only with mechanical methods are mixed. In post-wildfire studies, stands treated mechanically with no surface fuel treatments burned with higher severity than those where mechanical treatments were followed by prescribed fire, though with lower severity than untreated controls (Skinner et al. 2004, Cram et al. 2006, Schmidt et al. 2008). Others (Raymond and Peterson 2005) found

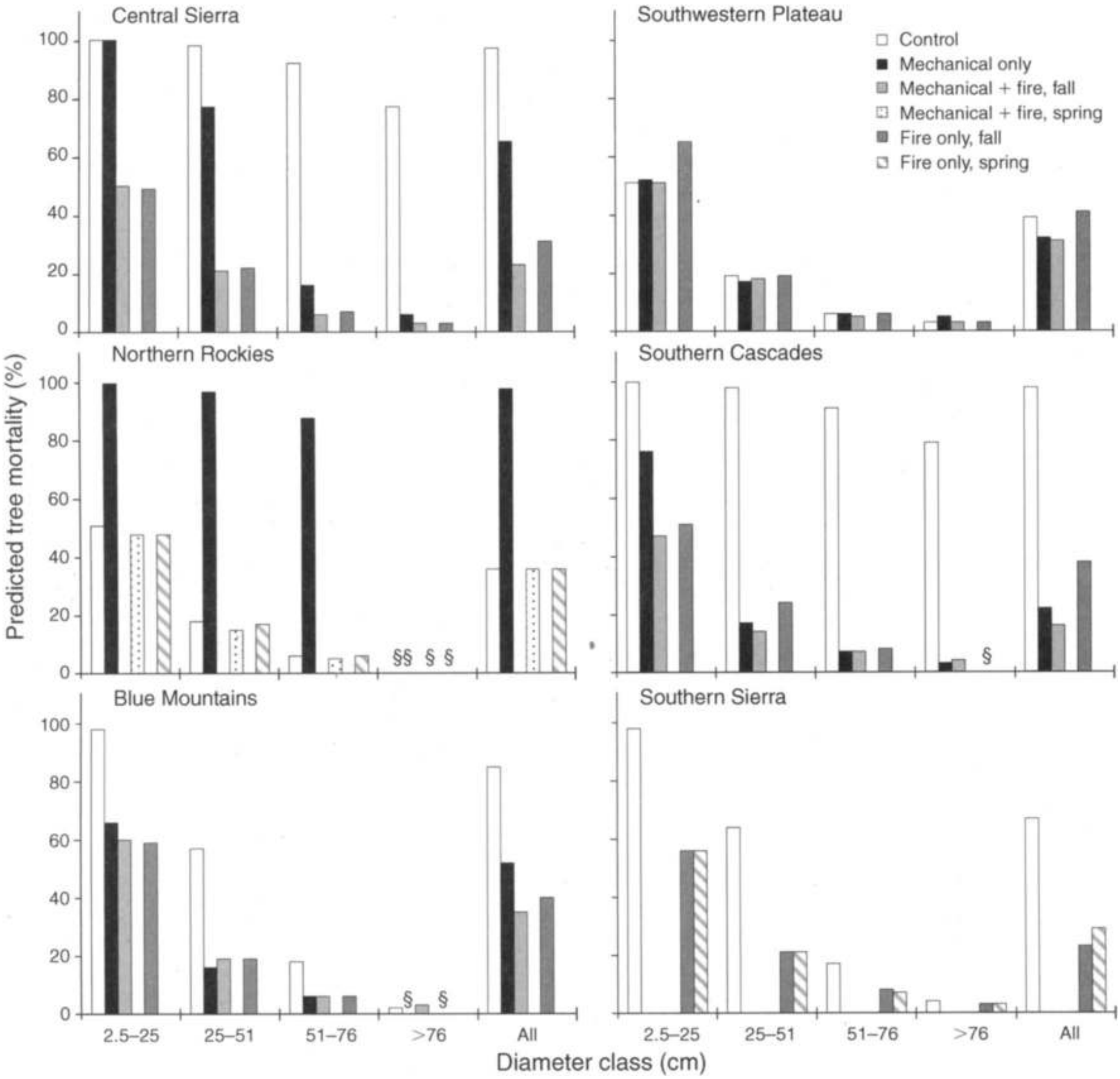

FIG. 6. Modeled postfire tree mortality by dbh class under 97.5th percentile weather conditions for trees remaining at six western United States Fire and Fire Surrogate sites after treatments. When no trees were present in a given treatment, this absence of a given size class is denoted by §. If there is no bar, a treatment was not implemented at that site.

areas treated with mechanical-only treatments burned with higher severity than untreated areas. It is important to note that in the latter study (Raymond and Peterson 2005), the 10- and 100-hour fuel loads exceeded 15 Mg/ha and are higher than sites in our study that used a whole-tree harvest system (Southern Cascades). These results are consistent with our findings that, although mechanically treating stands may enhance suppression capabilities by reducing crown fire potential, fire effects in these stands may be severe (Figs. 4–6), primarily due to high residual surface fuel loads (Table 4). Other factors influencing fire severity are topographic location, average tree size, species composition, and actual fire weather and fuel moistures within the stand.

Thinning from below, with subsequent surface fuel reduction by fire, was the most effective treatment when the goal was to reduce potential fire behavior and severity. However this treatment may not be sufficient in some Rocky Mountain stands with dense mid- and upper canopies and significant proportion of shade-tolerant species because of high vertical fuel continuity (Fiedler and Keegan 2003, Fiedler et al. 2003).

Implications for management

Analysis of our data supports the assertion that "no treatment" or "passive management" (Agee 2003, Stephens and Ruth 2005) perpetuates the potential for high fire severity in forests similar to those in this study. Results indicate that mechanical plus fire, fire-only, and

PLATE 1. Ignition of a Southern Cascades mechanical plus fire experimental unit by Phil Weatherspoon in October 2001. Phil was the original team lead for the Fire and Fire Surrogate Study. Photo credit: C. N. Skinner.

mechanical-only treatments using whole-tree harvest systems were all effective at reducing potential fire severity under extreme fire weather conditions. It is important for managers to apply the results of this study within similar forest types, site classes, and stands with similar management histories and topography (Dibble and Rees 2005). In addition, other management goals such as wildlife habitat, water quality, public safety, smoke production, and biodiversity (Dombeck et al. 2004) also need to be considered in decisions of what type of management is locally most appropriate.

Although the FFS study has provided quantitative data on the modeled stand level effects of fuel treatments on potential fire behavior, it is important for managers to consider the landscape context when planning fuel management strategies (Schmidt et al. 2008). Currently, two dominant paradigms, the use of shaded fuel breaks (Agee et al. 2000, Hessburg et al. 2005) and strategically placed area treatments (SPLATs) (Finney 2001), are put forward as foundational approaches for treating fuels at a landscape level. Regardless of the approach or combination of approaches taken, land managers should consider implementing the array of fuel treatments that best meets their objectives within economic constraints and acceptable levels of risk. The more effective strategies will likely be those that combine approaches by adjusting them to fit the local topography and vegetation (Weatherspoon and Skinner 1996). Fuel treatment strategies are likely to be more effective if they integrate knowledge of fire managers who have wildfire experience in the areas under consideration for treatment. This information can be integrated into long-range fuel treatment planning through frameworks such as the FIRESHED (Husari et al. 2006, Bahro et al. 2007) or other collaborative planning process.

CONCLUSION

The current condition of many coniferous forests across the western United States leaves them susceptible to high-severity wildfire. This is particularly true in pine (*Pinus* spp.) dominated and mixed conifer forests that were once characterized by fire regimes of frequent, low to moderate intensity such as those that were analyzed in this study. Managing these types of forests without fuel management will maintain or even increase hazard over the coming decades.

The challenge of reducing fire hazards in millions of ha of forests in the western United States is formidable because of treatment costs, access, and the spatial scale of the needed operations. With such a large undertaking we recommend that a full suite of potential fuel treatments be implemented including prescribed fire, mechanical-only, and mechanical followed by fire, along with taking advantage of expanded opportunities for using WFU and AMR fire management. Moving beyond stand level treatments to landscape-level strategies should improve overall fuels management effectiveness (Arno and Fiedler 2005, Finney 2005). It is crucial to maintain the initial effectiveness of fuel treatments by implementing successive, appropriate maintenance and additional treatments into the future.

It should be emphasized that the FFS treatments were not primarily designed to restore forest structure to presettlement conditions (i.e., before 1850). The goal of the treatments was to achieve a specific proportion of mid- and upper-canopy trees to survive wildfires under a stated set of fire weather conditions (increase forest resistance). The weather information analyzed to assess potential fire behavior and severity covered the last two to three decades in the 20th century. While we believe this analysis provides a sound approach, information for current conditions may not be appropriate for changing climates.

Present global climate models do not provide enough accuracy or precision to enable us to project fire weather conditions into the future at even moderate spatial scales (Millar et al. 2007). If this capability becomes available, we recommend that a similar analysis to that presented here be undertaken to estimate the resistance of forest structures to wildfires of the future. Designing more fire resistant stands and landscapes will likely create forests more resistant to changes imposed on them by changing climates. For this reason, it is more appropriate to design and test a range of specific forest structures to learn about their resistance and vulnerabilities, rather than restoring them to a presettlement condition that may not be appropriate for the future.

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APPENDIX

Characteristics of past management and treatments in the six western United States Fire and Fire Surrogate Study sites (*Ecological Archives* A019-013-A1).