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## Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests

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**Abstract.** Fire exclusion policies have affected stand structure and wildfire hazard in north American ponderosa pine forests. Wildfires are becoming more severe in stands where trees are densely stocked with shade-tolerant understory trees. Although forest managers have been employing fuel treatment techniques to reduce wildfire hazard for decades, little scientific evidence documents the success of treatments in reducing fire severity. Our research quantitatively examined fire effects in treated and untreated stands in western United States national forests. Four ponderosa pine sites in Montana, Washington, California and Arizona were selected for study. Fuel treatments studied include: prescribed fire only, whole-tree thinning, and thinning followed by prescribed fire. On-the-ground fire effects were measured in adjacent treated and untreated forests. We developed *post facto* fire severity and stand structure measurement techniques to complete field data collection. We found that crown fire severity was mitigated in stands that had some type of fuel treatment compared to stands without any treatment. At all four of the sites, the fire severity and crown scorch were significantly lower at the treated sites. Results from this research indicate that fuel treatments, which remove small diameter trees, may be beneficial for reducing crown fire hazard in ponderosa pine sites.

*Additional keywords:* *Pinus ponderosa*; Montana; Washington; California; Arizona; fuel treatment; crown fire.

### Introduction

Ponderosa pine (*Pinus ponderosa*) is the most widely distributed forest type in the western United States and covers millions of hectares (Van Hooser and Keegan 1988). Fires in ponderosa pine forests are becoming a growing concern (Arno and Brown 1991; Covington and Moore 1994): Colorado's Buffalo Creek Fire in 1996, for example, burned over 4000 ha in approximately 6 h, mostly as a crown fire (Orozco 1998). Millions of dollars were spent controlling the Buffalo Creek Fire, replacing burned structures, rehabilitating the site, and in consequent flood damages. Such wildfires have focused attention on controlling fire costs and damages (Gale 1977; Gonzalez-Caban *et al.* 1995).

Fires in ponderosa pine forests often differ dramatically from those observed by early settlers. Many of today's fires are stand-destroying crown fires as opposed to much lower intensity surface fires (Arno and Brown 1991; Agee 1993; Covington and Moore 1994; Mutch 1994). In addition to changes in fire behavior, stand structure in ponderosa pine forests also has been altered in the last century. Historical accounts describe large, park-like and open stands (Weaver

1943; Mutch *et al.* 1993; Covington and Moore 1994) that can be compared to the densely packed areas currently undergoing stand conversion as shade-tolerant trees out-compete ponderosa pine regeneration. These changes may be attributed to effective fire exclusion efforts over the past 100 years.

Forest managers have long contended that stand structural changes can be linked to more extreme wildfire behavior (Weaver 1943; Biswell 1960; Cooper 1960; Dodge 1972; Van Wagner 1977; Rothermel 1991; McLean 1993; Fiedler *et al.* 1995; Williams 1998). For example, shade-tolerant species and dense regeneration may serve as ladder fuels to move fire into the tree crowns (Weaver 1943; Dickman 1978; Laudenslayer *et al.* 1989; MacCleery 1995). (Ladder fuels provide vertical continuity between the surface fuels and crown fuels, increasing the likelihood of torching and crowning.) Fuel treatments such as prescribed fire and mechanical thinning are offered as ways to reduce or retard wildfire spread and intensity in ponderosa pine forests (Weaver 1961; Biswell *et al.* 1968; Babbitt 1995).

Many scientists and land managers assume that fuel treatments reduce wildfire hazard, but few studies have

**Table 1. Candidate fires that were considered but not selected for this study during 1992–1995 (Omi 1997)**

This table provides anecdotal evidence supporting the benefits of fuel treatments in mitigating wildfire spread and related damages

Fire name	Year	Size	Location	Description
Cleveland	1992	n/a	Eldorado National Forest, CA	Ponderosa pine plantations previously underburned survived a wildfire when suppression crews were able to backfire from the treated areas. This site was not selected due to suppression activities near the treatment boundary.
Paddock	1992	12 ha	Lakeview, OR	Fire spread into ponderosa pine that was underburned 3 years prior to wildfire. The fire had potential to reach 2000 ha and spread on to private land. Land managers felt that the treatment limited the wildfire size, resource damage and suppression costs. This site was not selected because it did not have mechanical fuel treatment. We later limited studied fuel treatments to some type of mechanical treatment.
Star Gulch	1992	12 000 ha	Boise National Forest, ID	Ponderosa pine plantations that were thinned and underburned survived a wildfire. Untreated plantations experienced high mortality. The time lapse between the wildfire and study notification was too long for this study to be included since there was much deterioration of fire effects evidence.
Aspen	1994	664 ha	Salyer National Wildlife Refuge, SD	An escaped prescribed fire in aspen–grassland–shrubland became controllable in an aspen clear-cut. Ponderosa pine was not a dominant species.
Henry Peaks	1994	3240 ha	Flathead Reservation, MT	An area thinned 20 years prior to the wildfire by uneven-aged logging (whole tree skidding with pile burning) experienced significantly lower fire severity and mortality compared to adjacent forest. The length of time since treatment precluded this site's selection.
LeClair	1994	13 355 ha	Warm Springs Reservation, OR	Dozer line and prescribed burning 1 year prior to wildfire in sagebrush–grass held the fire at a subdivision boundary. Clear-cutting as a fuel treatment did not meet the study's objectives.
Robinson	1994	3400 ha	Yellowstone National Park, WY	Beetle-killed lodgepole pine (self-thinned to lower density) experienced significantly lower fire severity compared to adjacent burned areas. The dominant vegetation was not ponderosa pine and it was a naturally thinned stand, not a mechanical fuel treatment.
Wind	1995	40 ha	Deschutes National Forest, OR	Fire behavior became more controllable in a grass and rabbitbrush area treated by prescribed fire in 1987. This enabled a dozer line to contain the wildfire. The dominant vegetation was not ponderosa pine.

analysed on-the-ground fire effects in treated versus untreated stands. Much of the evidence supporting the effectiveness of fuel treatments in mitigating wildfire damages has been inferred from informal observation, non-systematic inquiry or computer modeling (Omi and Kalabokidis 1991; Edminster and Olsen 1995; Fiddler *et al.* 1995; Fiedler 1996; Kalabokidis and Omi 1998; Scott 1998a, 1998b; Stephens 1998). Only two studies have examined field wildfire effects in stands with fuel manipulations. First, Vihanek and Ottmar (1993) measured more severe post-wildfire effects in areas where slash was left compared to less severe effects in slash-treated areas. Another study attempted to quantify fire damage to ponderosa pine tree crowns by examining post-fire aerial photos and available databases (Weatherspoon and Skinner 1995). Weatherspoon and Skinner found that sites with harvest treatments that included complete slash removal had lower fire severity, but they did not complete field verification of the results. In contrast to these previously mentioned studies, our study systematically and quantitatively examines field observations following wildfire in treated versus untreated ponderosa pine stands.

Our hypothesis is that fuel treatments reduce fire severity and crown scorch. Fire severity, for the purpose of this study,

refers to fire's effect on the ecosystem and is directly related to post-fire vegetation survival (Ryan and Noste 1985). Study objectives were to compare crown scorch and crown consumption in untreated versus treated stands; and to develop a methodology for making *post-facto* comparisons of fire severity in untreated versus treated ponderosa pine stands.

### Methods

The best methods for assessing fire severity require observing an active fire's behavior or by immediate post-fire observation. Due to the unpredictable nature of wildfire occurrence, it was impossible for this study to take real-time fire behavior measurements or make immediate post-fire observations. Delays of 1 year or more occurred between the wildfire and field sampling. Other studies analysing similar questions surrounding effectiveness of fuels treatments for mitigating wildfire effects have relied on computer simulation (Kalabokidis and Omi 1998; Scott 1998; Stephens 1998). Computer modeling avoids problems associated with a *post-facto* field study, but computer simulation is not always a good substitute for actual fire behavior.

Methods for study site selection and field data collection are described below. Both site selection and data collection were tailored to assure study integrity, i.e. eliminate intentional or unintentional bias.

#### Site selection

We began field searching for suitable wildfires in 1995 and ended our search in 1998. During that time, 12 sites were considered for inclusion in this study. Of those, only four wildfires met our selection criteria:

Webb Fire in Montana; Tye fire in Washington; Cottonwood Fire in California; and Hochderffer Fire in Arizona. Table 1 summarizes the 8 fires that were considered for this study, but not selected. Table 1 also provides anecdotal observations on the effectiveness of fuel treatments.

Sites were selected in ponderosa pine forests that had adjacent untreated and treated stands and that were burned in wildfires. The following criteria were used to select sites for the study:

- Stands where ponderosa pine was the major species;
- Adjacent treated and untreated stands exposed to the same recent wildfire;
- Stands that had accurate treatment records (i.e. maps, timber sale inventories); and
- Stands that were treated within 15 years prior to wildfire.

Due to the relatively short fire return interval in ponderosa pine forests, stands that were treated greater than 15 years prior to wildfire may have out-grown the effects of the fuel treatment. Stands from each category were adjacent to each other to facilitate comparisons. We avoided selecting sites with confounding influences such as roads, wide streams or constructed firelines that may have had a significant effect on fire behavior. Since slash resulting from logging operations increases fire hazard, at least in the short run (Fahnestock 1968; Vihaneck and Ottmar 1993), only thinned stands where slash residues were effectively removed prior to wildfire incidence were considered. Sites with accurate pre-fire fuel treatment maps and records were favored for selection.

#### Field data collection

Selected ponderosa pine stands were categorized as either 'treated' or 'untreated'. We consulted with agency officials and reviewed forest records to determine the fitness of sites. Adjacent untreated and treated stands were assumed to be equivalent prior to the treatment. By selecting stands that were adjacent to each other and with similar topography, we minimized the differences in weather and topography between the untreated and treated areas.

The first site, Webb, had a prescribed-fire-only fuel treatment. After sampling on that site, we limited fuel treatments to some type of mechanical tree removal, with or without subsequent prescribed fire. We focused the three later sites on mechanical fuel treatments since prescribed fire was already known to mitigate fire effects (Wagle and Eakle 1979) and we wanted to narrow the focus of this study. With thinning, stumps leave a record and an indication of biomass removal, where there is no such record with prescribed burning.

Plots located along transects captured the variability in the untreated and treated areas. We sampled an equal number of plots in the untreated and treated areas. Transect locations were located based on terrain and topography, and on the treatment and wildfire boundaries. Depending on the site, three to four transects spanned the treated and untreated areas and were situated parallel 150 m apart. Six to eight plots per transect were located 150 m apart. By selecting plot transect locations prior to any field visits, we avoided locating plots in areas that would possibly introduce bias. Prior to field sampling, we mapped transects and plot locations on a 7½ minute topographic map that delineated the treated and untreated stands.

We studied modifications of stand structure and canopy characteristics that are known to mitigate fire hazard. To determine the fuel treatment's effect on stand characteristics, three variables describing stand structure were measured: stand density (trees/ha), basal area (m<sup>2</sup>/ha) and average diameter (cm) of trees on the plot. Sample trees were selected using variable plot sampling with a 'cruiser's crutch' angle gauge.

Crown characteristics, especially crown bulk density and height to the live crown, are known to affect crown fire initiation and propagation

(Van Wagner 1977; Rothermel 1991). Since crown bulk density estimates cannot be determined accurately from simple field measurements, crown weight was used as a substitute for crown bulk density (Brown 1978). Formulas developed by Brown (1978) were used to determine the crown weight (kg) for the Webb, Tye and Cottonwood sites and incorporated the diameter at breast height (DBH), ratio of crown to tree height, and crown position. DBH was measured with a metric diameter tape, and crown length and tree height were calculated from clinometer measurements. Crown position, whether dominant, co-dominant or intermediate, was recorded for each tree in the plot. At the Hochderffer site, time constraints precluded crown weight measurements. By eliminating crown weight data, we could sample more plots over a shorter period of time. In addition, we collected ample data from the three previous wildfire sites to test any relationships between crown weights and severity measurements.

Crown scorch percentage was estimated visually for each tree, and a weighted mean was computed for each plot. Methods for determining crown scorch percentage were adapted from Peterson (1985), Ryan and Noste (1985) and Wyant *et al.* (1986). We did not complete a fire severity estimate from the soil/forest floor organic layer perspective because the elapsed time since the fire to sampling resulted in deterioration of much of that evidence. In addition to crown scorch percentages, one estimate of fire severity rating per plot was also visually determined based mostly on the condition of the aerial fuels (Wagener 1961). The following severity rating classes were adapted from Omi and Kalabokidis (1991):

- Unburned, fire did not enter the stand (rating=1);
- Light, surface burn without crown scorch (rating=2);
- Spotty, irregular crown scorch (rating=3);
- Moderate, intense burn with complete crown scorch (rating=4);
- Severe, high intensity burn with crowns totally consumed (rating=5).

We used multivariate response permutation procedures (MRPP) for statistically testing differences between the untreated and treated groups in this study (Mielke 1986; Good 1994). Non-parametric tests, such as MRPP, have several advantages compared to using more well-known parametric procedures. While *t*-tests are frequently used for two-sample comparisons, the validity of the assumptions of the *t*-test are questionable in this study. The various data sets in this study were relatively small and contained several outliers. MRPP techniques may be superior to *t*-tests when the sample size is small, if the assumption of normally distributed populations is not reasonable (i.e. samples contain extreme values or outliers), and if multivariate comparisons are desired. For other examples of MRPP used in forestry studies, see Huckaby and Moir (1995) and Reich (1991).

#### Selected study site descriptions

The four sites we sampled all met the selection criteria, but each site was unique in terms of stand characteristics, treatment type, and wildfire behavior. Table 2 summarizes general descriptions for the four wildfires and treatment types.

Figures 1, 2, 3 and 4 show the adjacent treated and untreated stands at the four sampling sites.

## Results

Table 3 shows that post-fire basal area is higher in the untreated plots for all sites except Cottonwood (see below for further explanation). Slightly higher basal areas in the treated stands may be explained by understanding that a stand with many small trees may have similar basal area to a stand with few large trees.

**Table 2. Description of sampling sites at the Webb, Tyee, Cottonwood and Hochderffer wildfires**

	Webb	Tyee	Fire Cottonwood	Hochderffer
Treatment type	Broadcast burn in 1989	Precommercial thinning in 1970s with underburn for slash removal in 1983	Whole-tree thinning in 1989, 1990	Thinning in 1970s with broadcast burn in 1995
Date of fire	September 1994	August 1994	August 1994	June 1996
Date sampled	July 1995	October 1995	September 1996	October 1997
Size of fire	1415 ha	56 780 ha	18 620 ha	6640 ha
Elevation	1067 m	762 m	2012 m	2408 m
Aspect	S	W	W	N
National Forest location	Kootenai NF, MT	Wenatchee NF, WA	Tahoe NF, CA	Coconino NF, AZ

The number of trees per hectare is much higher in the untreated stands at all four sites; the untreated Tyee site was especially dense with 1244 trees/ha. The average diameter of trees on the plots is higher for the treated stands, which shows that the fuel treatment removed smaller diameter trees. The crown scorch percentage and fire severity rating are higher for untreated stands at all four sites. The treated stands had higher crown weights. The formulas for estimating crown weights (Brown 1978) are most influenced by diameter. Thus larger diameter trees, such as those found in the treated stands, will produce greater crown weights.

Some differences in topography are evident between the untreated and treated sites. Due to generally more active fire behavior in west-facing sites compared to north-west aspects, one may expect more severe fire effects on western aspects. However, at the Tyee site, higher fire severity was found in plots with a north-west aspect. Further, inspection of the slope data showed that for two sites the treated areas had steeper slopes and for the other two sites the untreated area had steeper slopes.

At first glance, the basal area differences for the Cottonwood site seem peculiar. The two means are almost identical (30.0 versus 30.3 m<sup>2</sup>/ha) but are significantly different. Examining the Cottonwood site's density and tree diameters, the slightly higher basal area in that treated stand may be attributed to that stand having fewer but larger trees. There are many outliers at the Cottonwood site and the data ranges are very different between the untreated and treated plots. Basal areas in the treated areas ranged from 21 to 39 m<sup>2</sup>/ha compared to the untreated range of 4 to 60 m<sup>2</sup>/ha. Only 16% (2 observations) of the observations for the untreated area fell within the range of the treated area. The likelihood that such extreme values (i.e. basal area <20 m<sup>2</sup>/ha or basal area >40 m<sup>2</sup>/ha) would be observed in the treated plots is very small. Therefore, the two plots have significantly different basal areas even though their means are almost identical.

Statistical analysis provided additional insights into structural differences between treated versus untreated stands. Univariate and multivariate stand structure

comparisons between untreated and treated plots are analysed (Tables 4 and 5). Differences in fire severity rating and percentage crown scorch in untreated versus treated plots are presented statistically using MRPP (Table 6). Lastly, a correlation matrix (Table 7) shows associations between independent variables (density, basal area, diameter of trees on the plot, crown weight and slope) and the dependent variables (fire severity rating and crown scorch).

Results indicate that the untreated and treated stands are significantly different for the Webb, Tyee and Cottonwood sites. The lack of significant differences among the univariate and multivariate stand characteristic comparisons for the Hochderffer site is particularly noteworthy (Tables 4 and 5). Notice, however, the significant differences at that site for fire severity rating and crown scorch (Table 6). Something other than stand structure factors likely contributed to the differences in fire severity. Surface fuel loading or differences in fuel moistures rather than stand structure may have been the fire severity driver at this site.

Table 7 presents the correlation coefficients showing trends and relationships among the independent and dependent variables. Relationships among the independent and dependent variables are the most interesting and meaningful to this study. Density, basal area, diameter and crown weight all are significantly correlated with plot severity rating and percentage crown scorch. The highest correlation coefficient ( $r=0.57$ ,  $r^2=0.32$ ) between the independent and dependent variables is among density and fire severity rating. Thus 32% of the variation in fire severity rating can be explained by the variation in density. Slope does not appear to be related to fire severity or percentage crown scorch.

## Discussion

The treated plots in this study have lower fire severity ratings and less crown scorch than the untreated plots. The null hypothesis ( $H_0$ ), that both fire severity and crown scorch each do not differ significantly among untreated and treated plots, is rejected in favor of the research hypothesis ( $H_a$ ), that fire severity and crown scorch are higher in untreated plots.



Fig. 1. Untreated (a) and treated (b) stands at the Webb Fire site at adjacent locations.



Fig. 2. Untreated (a) and treated (b) at the Tye Fire site at adjacent locations.

**Table 3. Key site characteristics for the four wildfires**

Standard deviations are in parentheses. Identical superscripts indicate that the untreated and treated sites are not significantly different using univariate MRPP,  $\alpha=0.05$  (Good 1994). —, not measured

	Sample size	Aspect	Slope (%)	Basal area (m <sup>2</sup> /ha)	Density (stems/ha)	Av. diameter (cm)	Fire severity rating	Crown scorch (%)	Crown weight (kg)
Webb									
Untreated	9	S	29 <sup>a</sup> (13)	23.0 <sup>a</sup> (13.9)	637 <sup>a</sup> (498)	24.1 <sup>a</sup> (10.5)	3.2 <sup>a</sup> (0.8)	67 <sup>a</sup> (33)	165 <sup>a</sup> (179)
Treated	9	S	39 <sup>a</sup> (9)	14.7 <sup>a</sup> (9.4)	73 <sup>b</sup> (42)	43.1 <sup>b</sup> (20.0)	2.6 <sup>b</sup> (0.5)	26 <sup>b</sup> (34)	334 <sup>a</sup> (197)
Tye									
Untreated	9	NW	38 <sup>a</sup> (17)	24.6 <sup>a</sup> (12.8)	1244 <sup>a</sup> (1417)	20.7 <sup>a</sup> (13.6)	4.4 <sup>a</sup> (0.5)	100 <sup>a</sup> (0)	63 <sup>a</sup> (71)
Treated	9	W	22 <sup>a</sup> (11)	15.8 <sup>a</sup> (5.6)	218 <sup>b</sup> (98)	30.7 <sup>b</sup> (0.7)	3.0 <sup>b</sup> (0.0)	74 <sup>b</sup> (17)	142 <sup>b</sup> (75)
Cottonwood									
Untreated	12	W	21 <sup>a</sup> (14)	30.0 <sup>a</sup> (19.7)	578 <sup>a</sup> (571)	31.3 <sup>a</sup> (11.7)	4.0 <sup>a</sup> (0.8)	78 <sup>a</sup> (32)	194 <sup>a</sup> (146)
Treated	12	S	11 <sup>b</sup> (5)	30.3 <sup>b</sup> (5.5)	262 <sup>b</sup> (184)	39.8 <sup>b</sup> (8.4)	2.7 <sup>b</sup> (0.6)	26 <sup>b</sup> (27)	225 <sup>a</sup> (210)
Hochderffer									
Untreated	12	N	11 <sup>a</sup> (6)	25.0 <sup>a</sup> (8.1)	765 <sup>a</sup> (441)	21.9 <sup>a</sup> (7.0)	4.4 <sup>a</sup> (0.6)	99 <sup>a</sup> (1)	—
Treated	12	N	13 <sup>b</sup> (6)	23.3 <sup>a</sup> (11.0)	556 <sup>a</sup> (410)	24.2 <sup>a</sup> (6.5)	2.1 <sup>b</sup> (1.0)	29 <sup>b</sup> (38)	—

**Table 4. *P*-values for univariate comparisons using MRPP (Good 1994) comparing basal area (m<sup>2</sup>/ha), density (#stems/ha) and diameter (cm) between treated and untreated plots for the four sites**

\* indicates that the treated and untreated plots are significantly different,  $\alpha=0.05$

	<i>P</i> -value for:		
	Basal area	Density	Diameter
Webb	0.37	0.01*	0.01*
Tye	0.14	0.01*	0.02*
Cottonwood	0.04*	0.05*	0.03*
Hochderffer	0.49	0.32	0.45

**Table 5. Multivariate MRPP (Good 1994) comparisons for basal area (m<sup>2</sup>/ha), density (#stems/ha), and diameter (cm) on the four sites**

These data were standardized [( $x$ -median)/range] to eliminate differences in units. \* Indicates that the treated and untreated plots are significantly different,  $\alpha=0.05$

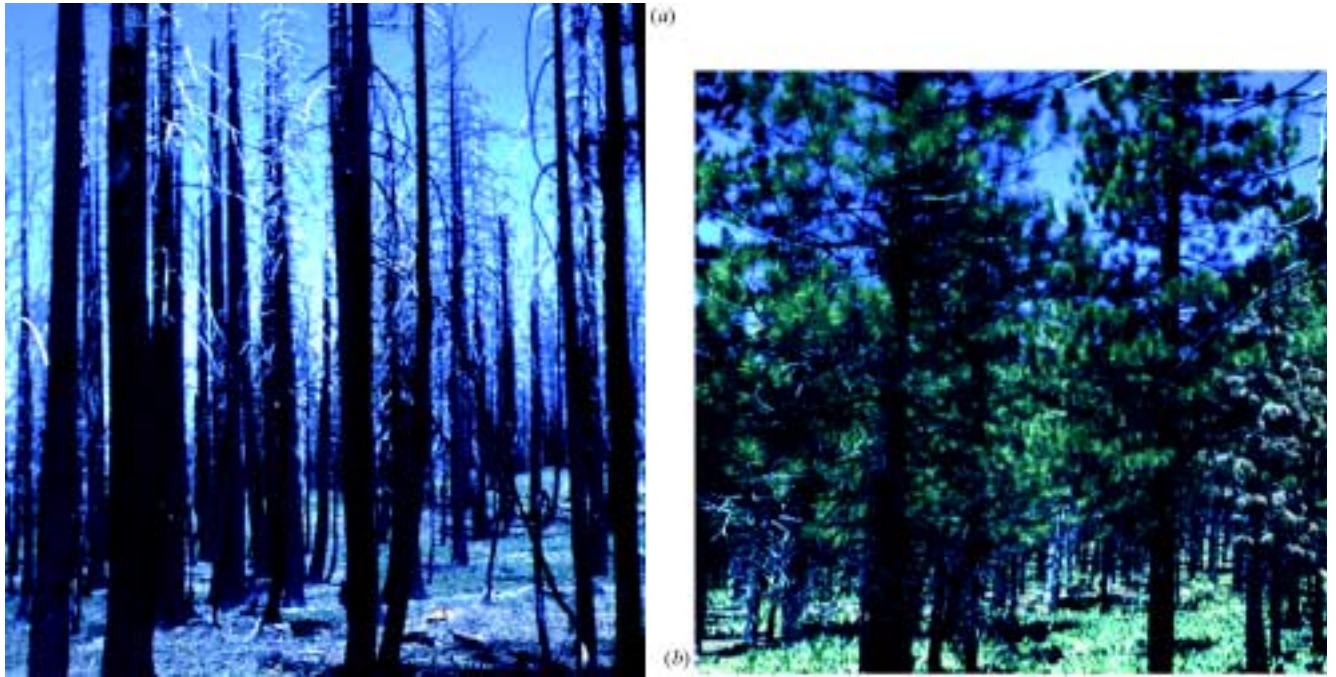
	<i>P</i> -value
Webb	0.01*
Tye	0.02*
Cottonwood	0.02*
Hochderffer	0.96

**Table 6. *P*-values for univariate comparisons using MRPP (Good 1994) comparing fire severity rating and percentage crown scorch between untreated and treated plots for the four sites**

All comparisons are significantly different,  $\alpha=0.05$

	<i>P</i> -value for:	
	Fire severity rating	Percentage crown scorch
Webb	0.01	0.03
Tye	0.01	0.0
Cottonwood	0.01	0.01
Hochderffer	0.01	0.01

From these results we infer that the types of fuel treatments studied reduce fire severity rating and crown scorch. Based on the statistical results and field reconnaissance, sites with mechanical fuel treatment appear to have more dramatically reduced fire severity compared to the site with prescribed fire only. Although fire severity ratings and percentage crown scorch are significantly different for untreated versus treated plots at all sites (Tables 3 and 6), the Webb site's differences were the least extreme. Apparently, mechanical fuel treatments at the Tye, Cottonwood and Hochderffer sites allow for more precise and controlled results compared to prescribed fire. For example, mechanical fuel treatment programs may specify



**Fig. 3.** Untreated (a) and treated (b) stands at the Cottonwood Fire site at adjacent locations.



**Fig. 4.** Untreated (a) and treated (b) stands at the Hochderffer Fire site at adjacent locations. Multiple stems with full crowns in the foreground of the treated photo mask the larger diameter trees in this plot.



**Table 7. Summary of correlation coefficients ( $r$ ) for Webb, Tyee, Cottonwood and Hochderffer sites for fire damage/severity variables (fire severity rating and percentage crown scorch), stand structure variables (density, basal area, average diameter of trees on the plot and crown weight) and slope**

Crown weight was computed for Webb, Tyee and Cottonwood sites only.  $P$ -values are in parentheses

	Dependent variables			Independent variables			
	Fire severity rating	Percentage crown scorch	Density	Basal area	Diameter	Crown weight	Slope
Fire severity rating	<b>1.00</b>	0.79 ( $<0.01$ )	0.57 ( $<0.01$ )	0.40 ( $<0.01$ )	-0.48 ( $<0.01$ )	-0.40 ( $<0.01$ )	0.09 (0.43)
Percentage crown scorch		<b>1.00</b>	0.45 ( $<0.01$ )	0.26 (0.03)	-0.45 ( $<0.01$ )	-0.43 ( $<0.01$ )	0.12 (0.28)
Density			<b>1.00</b>	0.56 ( $<0.01$ )	-0.63 ( $<0.01$ )	-0.46 ( $<0.01$ )	0.02 (0.88)
Basal area				<b>1.00</b>	-0.11 (0.34)	-0.16 (0.22)	-0.05 (0.67)
Diameter					<b>1.00</b>	0.86 ( $<0.01$ )	0.05 (0.67)
Crown weight						<b>1.00</b>	-0.03 (0.82)

the exact number of post-treatment residual trees per hectare and the treatment can be applied uniformly across the stand. By contrast, prescribed fire fuel treatment often varies across a stand and results in less precise stand structure changes.

For the Webb, Tyee and Cottonwood sites, the stand characteristics contributed to the differences in fire severity. The fuel treatments at these three sites resulted in forests with much lower density and larger trees. Stands with fewer trees have less continuous crown and ladder fuels. Larger trees generally have crowns higher off the ground and have thicker bark which makes them more fire resistant. Benefits of treated stands are lower potential for crown fire initiation and propagation, and less severe fire effects.

Stand structure for the Hochderffer site is not significantly different among the treated and untreated stands; other factors must have contributed to less severe fire effects in the treated stands since fire severity and percentage crown scorch differences cannot be explained by stand structure manipulations. Two unstudied factors may have accounted for severity differences between treated and untreated stands: surface dead downed fuel loading and fuel moistures. Due to the *post-facto* nature of this study, we could not adequately quantify pre-fire fuel loadings or fuel moistures. Although fuel loading was not quantified in this study, we assume that the studied fuel treatments reduce surface fuel loading. For example, a recent prescribed burn will reduce surface fuel loading in the short-run. The Hochderffer site had a recent prescribed burn after the mechanical thinning treatment. Therefore, it is likely that lower surface fuel loading contributed to less severe fire effects in the treated stands at the Hochderffer site.

Fuel moistures may be affected by microclimate and probably vary between the untreated and treated stands. A more open stand allows more wind and solar radiation,

resulting in a drier microclimate compared to a closed stand. A drier microclimate generally contributes to more severe fire behavior. However, our study does not support the assertion that more open stands experience higher fire severity. More open stands had significantly lower fire severities compared to the more densely stocked untreated stands in this study. The degree of openness in the studied treated stands may not have been sufficient to increase fire activity.

Density and average tree diameter are closely related to fire severity (Table 7). Based on our results, removing small diameter trees from a ponderosa pine stand reduces subsequent wildfire severity. At the four sites, the fuel reduction overcomes any microclimatic effects on fire behavior resulting from a more open stand. These findings agree with years of forest managers' field observations (Agee 1996).

Wildfire, prescribed fire, and mechanical thinning all reduce tree densities and accomplish fuel treatments. Wildfire, or natural fire, is often impracticable. Letting natural fires play their historical role may have unwanted effects in forests that have undergone major stand structural changes. Prescribed fire may be effective in stands that have moderate to steep slopes that preclude mechanical treatment, and in locations where experts can plan and implement large scale prescribed burns. Mechanical tree removal may work best on forests that are too densely packed to burn, and areas that have nearby markets for small diameter trees. Fiedler *et al.* (1997) assert that mechanized tree harvest of large amounts of small diameter trees on moderately steep terrain can generate considerable revenue. Periodic underburns and programs for restoring natural fire are critical to maintain these post-harvest stands.

## Conclusions

Our findings indicate that fuel treatments do mitigate fire severity. Treatments provide a window of opportunity for effective fire suppression and protecting high-value areas. Although topography and weather may play a more important role than fuels in governing fire behavior (Bessie and Johnson 1995), topography and weather cannot be realistically manipulated to reduce fire severity. Fuels are the leg of the fire environment triangle (Countryman 1972) that land managers can change to achieve desired post-fire condition. However, in extreme weather conditions, such as drought and high winds, fuel treatments may do little to mitigate fire spread or severity.

Since fuel treatment programs may be costly and time-consuming we suggest focusing programs, funding and management attention where the risk resulting from severe wildfire is greatest: urban-interface, tree plantations, critical watersheds and habitat for threatened and endangered species. Treating high-volume areas in locations with viable markets for small diameter trees may be more advantageous than fuel removal on steep slopes with little merchantable timber. Costs associated with wildfire suppression far outweigh the costs of fuel treatment on similar landscapes.

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