Influences of Stand Structure and Fuel Treatments on Wildfire Severity at Blacks Mountain Experimental Forest, Northeastern California

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Abstract

This study utilizes forest stand structures and fuel profiles to evaluate the influence of different types of silvicultural treatments on fire severity in the Blacks Mountain Experimental Forest (BMEF), located within Lassen National Forest of northeastern California. We compare the severity of fire, assessed based on tree crown and bole scorch on 100 ha experimental treatment plots, following a wildfire started on adjacent national forest lands. Non-parametric statistical testing showed that selective thinning combined with prescribed surface fuel burning is the most effective method for preventing crown fire and minimizing fire severity in an interior *Pinus ponderosa* forest. These results also suggest that various combinations of the silvicultural treatments assessed can be effective at reducing the potential for severe fire spreading into wildland-urban interface (WUI) areas (supporting defensible space CA law PRC 4291), while suggesting approaches for U.S. Forest Service lands that can result in more resilient ecosystems in similar western U.S. forests treated with similar silvicultural methods.

Key words: Fire ecology, fuels management, California forests, wildland-urban interface (WUI)

Introduction

In most summer-dry forests of California, frequent fires have long been an important ecosystem process (Whitlock 2001). Historically, the fire return intervals, or number of years between successive fires, have been short in the interior ponderosa pine (*Pinus* *ponderosa* Laws.) forests (1- to 25-year return intervals) (Agee 1993; Taylor 2000; Norman and Taylor 2003). The majority of these fires were mostly of low intensity; however, intense fires, especially in patches, could occur after fuel buildup resulting from longer-than usual-return intervals or other factors such as (drought and) insect outbreaks (Agee 1993).

Recent studies indicate that northeastern Californian mixed-conifer forests have undergone major structural and compositional changes since the exclusion of fire (Taylor 2000; Norman and Taylor 2005). Needle litter and native grasses have been replaced by needle and branch fuels with more vertical continuity, in the form of both live saplings and dead fuel. This contributes to a greater possibility of increased fire intensity and severe crown fire (Mutch 1994). A low-intensity fire regime has been replaced by a moderate- to high-intensity fire regime that is essentially the result of change in fuel load and stand structure (Agee 1994; Agee and Skinner 2005).

A result of the structural change in these forests is the development of ladder fuels that contribute to high-intensity crown fires. Van Wagner (1977) described ladder fuels as "bridge fuels," combustible matter in the understory serving as an intermediary between the surface fuels and the main canopy, which allows fires to move into the canopy. Crown fire potential is dependent on the quantity and arrangement of these fuels (Kilgore and Sando 1975). Kilgore and Sando (1975) state that the probability of a surface fire moving into the crowns is greatly increased by an understory of saplings that provide continuous fuels from the ground to the dominant tree crowns. This continuous fuel supply was absent during a mostly low- to moderate-intensity fire regime (Kilgore and Sando 1975). This increase in ladder fuels has led to increased levels of crown scorch and bark char, indicators of fire severity (Davis and Cooper 1963) and tree mortality (Stephens and Finney 2002). The suppression of fire has also allowed a shift in species composition from dominance of fire-tolerant ponderosa pine to a greater proportion of less fire-tolerant species in the understory—primarily white fir (*Abies concolor* [Gordon & Glend] Lindley) and incense cedar (*Calocedrus decurrens* [Torrey] Florin). The seedlings of these less-tolerant species are no longer eliminated by low- to moderate-intensity surface fires as they were under a pre-suppression fire regime. The result is a less resilient forest condition than one under a pre-suppression fire regime (Agee et al. 1978).

California is a region noted for its high-intensity fires assisted by annual summer drought and long-term drought cycles. The uniqueness of this study allowed for us to assess California law PRC 4291 (California law, 2005), which requires property owners in wildland areas and along wildand-urban interfaces (WUI) to create 100 feet of defensible space for fire protection around their homes and buildings in the following manner: (1) by removing all flammable vegetation within 30 feet immediately surrounding a structure (i.e., lean, clean and green zone), and (2) by creating a fuel-reduction zone in the remaining 70 feet by focusing on removing lower-level vegetation components (i.e., shrub layer) and removing lower tree branches at least six feet from the ground. These are important considerations to test, as the WUI area covers 20.7% of the state of California, and 5.1 million homes in California are in the WUI area (highest nationally) (Radeloff et al. 2005).

Purpose of Forest Fuel Management

Forest fuel management may help to reverse human induced changes that have "produced successional changes in wildland vegetation and fuels" (Arno and Brown 1991). There are many different strategies and techniques available for fuels treatment, depending on management goals and the characteristics of the forest ecosystem. Selective thinning, mechanical fuel removal (Arno and Brown 1991), and/or prescribed fire (Arno and Brown 1991) are potential ways of altering a forest structure from its original state to a state that might decrease the probability of a severe wildfire. In essence, fuel reduction strategies are viable options for managing areas that have been subjected to fire exclusion or suppression (Agee and Skinner 2005).

Selective harvesting of smaller trees, for example, may help to create old growth-like vegetation structures while lowering the potential severity of a fire in a forest, or preventing a fire from moving into the managed area at all by reducing the amount of consumable fuels in the understory (Arno and Brown 1991). Crown fires depend on the vertical profile of fuels, starting from the ground surface and continuing into the canopy (Agee and Skinner 2005; Cruz et al. 2003; Cruz et al. 2004). Studies have shown that the probability of a crown fire can be reduced by manipulating ladder fuels (Graham et al. 2004).

Thinning alone may not achieve as significant a reduction in fire intensity as when the thinning is followed by surface fuels treatment. Thinning may add fuel to the surface by contributing parts of cut trees and small trees damaged by the thinning operation (Weatherspoon 1996). At the least, the existing surface fuels are not reduced. This slash, if not treated appropriately, can contribute to greater fire intensity. Thinning also influences the regeneration of small trees, changes the overall levels of competition, and affects the microclimate by increasing solar radiation and winds (Weatherspoon 1996). Thinning can be a viable alternative in areas with dense understory, however (Arno and Brown 1991). Additionally, the effects on fire behavior from increases in solar drying and wind movement in the stand are usually more than offset by the overall reduction in potential for crown fire and resulting fire intensity (Weatherspoon 1996; Agee and Skinner 2005).

Prescribed fire can enhance the effects of thinning by further reducing fire intensity. Prescribed fire can help to achieve a desired composition and structure, such as reducing stand density (Mutch 1994), controlling undesirable species (Arno and Brown 1989), or reducing dead-fuel accumulation (Mutch 1994). By focusing on reducing surface fuels and horizontal and vertical fuel continuity, especially removing smaller trees, intense crown fires may be reduced (Agee and Skinner 2005).

In forests that have excluded fire for long periods, thinning and burning can be combined for maximum results (Graham et al. 2004). Many studies have examined post-fire results of fire exclusion (Martinson and Omi 2004; Omi and Martinson 2004; Finney et al. 2005; Strom and Fulé 2007; Schmidt et al. 2008). In a study conducted by Omi and Martinson (2002), wildfire severity indicators (scorch height, crown volume scorch, stand damage) were greater in untreated areas than treated areas. Pollet and Omi (2002) found that in ponderosa pine forests having either treatment by prescribed fire only, thinning, or a combination of thinning and prescribed fire, crown fire severity was less in areas that had been treated compared with areas that had not been treated.

This study utilizes stand structural and fuel profiles to evaluate the influence of different silvicultural treatments on wildfire severity in interior ponderosa pine forests of the Blacks Mountain Experimental Forest (BMEF) in northeastern California. The fortuitous movement of the Cone Fire (an accidental fire started during a logging operation on adjacent National Forest land in September 2002) into the Blacks Mountain Experimental Forest has allowed the effect of different silvicultural treatments to be evaluated in an experimental manner. We compare the levels of fire severity following the Cone Fire, which impacted several existing 100 ha experimental treatment plots, utilizing crown and bole scorch damage present after the fire (sensu Omi and Martinson 2002). Treatments implemented before the fire included creation of two stand structures through mechanical thinning with and without follow-up prescribed fire. All treatments were accomplished between two and five years prior to the wildfire occurrence.

Methods

Study Area

The study area was in the Blacks Mountain Experimental Forest (BMEF), located within Lassen National Forest in the southern Cascade Range of northeastern California (Figure 1). The U.S. Forest Service's Pacific Southwest Research Station has established a research project in which they have created experimental treatment plots of contrasting stand structures and silvicultural management (Oliver 2000). BMEF lies on a volcanic plateau with predominant plant communities of the Jeffrey pine (*Pinus jefferyi* Grev. & Balf.) ponderosa pine series, with white fir and incense cedar as associates (Oliver 2000). Temperatures range from a minimum of –6°C to a maximum of 30°C, with mean annual precipitation ranging from 51 to 115 centimeters (Miles and Goudey 1997). Half of BMEF lies in a basin surrounded by moderate slopes (predominantly 0–10°, with few 10–20° slopes), with an elevation range from 1,600 to 2,300 meters (Hallin 1959). BMEF consists of ±4,172 ha, of which ±1,200 ha were set aside as 12 100-ha study plots and subjected to four specific structural silvicultural treatments. A high-diversity (HiD) treatment included retaining large old trees, big snags, multiple canopy layers with clusters of small trees, gaps, and canopy openings. This was contrasted with a low-diversity (LoD) treatment that created a single layer of intermediate-size trees with a continuous but open canopy, few snags, few canopy gaps, and few forest openings by removing the large, old trees and thinning the smaller poles and saplings (Oliver 2000). Some areas of BMEF outside the treatment plots had been previously treated at least 20 years prior to the Cone Fire as either partially cut under sanitation/salvage prescriptions or commercially thinned (Skinner et al. 2004; Ritchie et al. 2007) and were not part of any ongoing study (Oliver 2000). Each BMEF plot was then split to allow prescribed fire in one half,

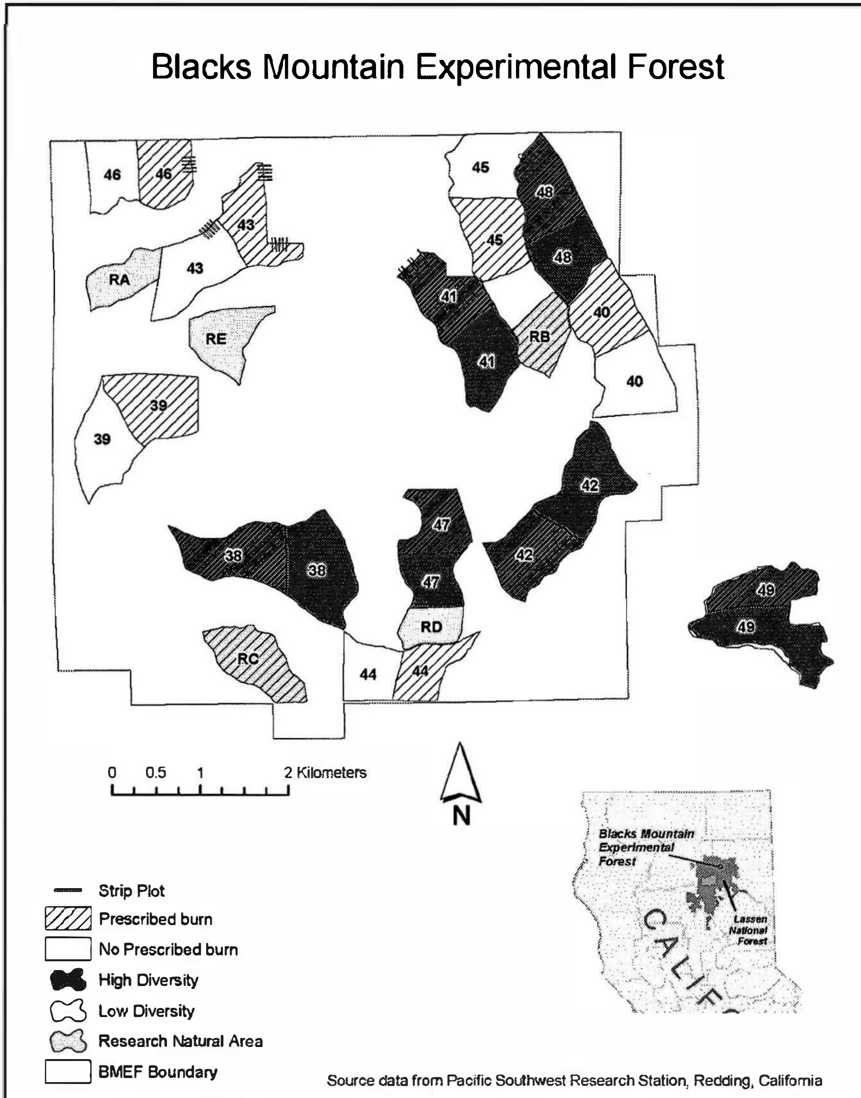

Figure 1.

and no fire in the other. Each of the two structural treatments was replicated six times in 100-ha treatment plots. Due to changes in elevation, species composition varied among units, with lower areas (1,600–1,850 meters) dominated by almost pure ponderosa pine or Jeffrey pine, while higher areas (1,850–2,300 meters) had a substantial amount of white fir and incense cedar. The historic fire regime of this ecosystem was of the frequent/low-moderate intensity type, typical of interior ponderosa pine in the southern Cascade Range of northeastern California (Skinner and Taylor 2006).

Field Methods

Data were collected on each of three silvicultural treatment types, as well as in the adjacent areas that had not recently had silvicultural treatments, to describe wildfire severity and compare the effects of the Cone fire in the different silvicultural treatment plots. In this paper, we refer to the areas not recently treated (> 20 years since treatments) as being untreated, since they were not treated as part of the ongoing BMEF study. Three treatment units and treatment types were affected by the fire. Fire behavior and resulting severity varied throughout the BMEF (Figure 2), with much of the area outside the treatment units being burned by a high-intensity, mostly passive crown fire. Within the treatment units, the fire burned as a surface fire with varying intensity and effects depending on type of treatment. The nature of the terrain at the BMEF is quite gentle; weather conditions during the Cone Fire overwhelmed any

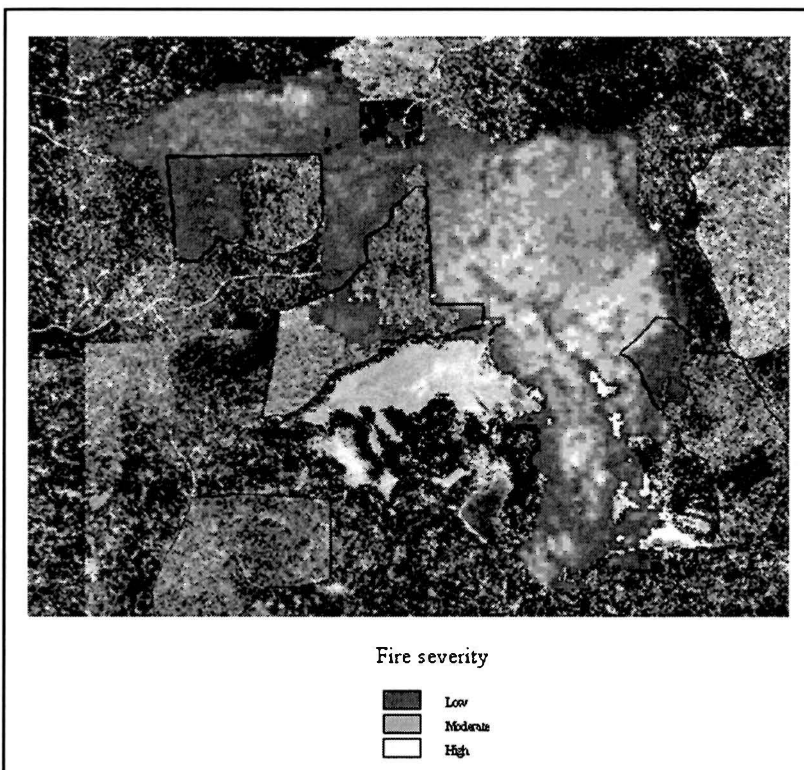

Figure 2.

potential effects of topography. Details on fire behavior in the different stand conditions and tree mortality patterns can be found in Ritchie et al. (2007). For this study, data were collected to describe how fire severity indicators changed as the fire burned from outside to inside the treated plots using sets of treatment-type replicates (sample) that could be laid out based on the Cone Fire's path. Each tree (sub-sample) found within the spatially defined replicates was specifically measured for crown scorch and bole scorch. Twenty-five 10 m x 150 m strip plots were placed in three groupings in order to represent the effects of the fire approaching and entering the treated areas (Figure 1). Five strips were located in Unit 46, a LoD unit, on the eastern edge of the half that had been prescribe-burned (LoDF). Fifteen strips were located in Unit 43; also a LoD unit, five on the northern edge of the half without prescribed fire (LoDNF), five on the northeastern edge of the half with prescribed fire (LoDF), and five on the southeastern edge of the half with prescribed fire (LoDF). Five strips were located in Unit 41, a HiD unit, on the northern edge of the half that had been prescribe burned (HiDF).

The strip plots were systematically established using a fiberglass measuring tape oriented perpendicular to treatment plot boundaries affected by the Cone Fire. The strip transects extended 100 meters into treated areas and 50 meters into untreated areas. All trees greater than 10 cm DBH had the following data recorded: species, distance from treatment boundary (m), diameter at breast height (cm), mortality, indicator of scorched or torched, total height (m), height of bole scorch for all cardinal directions (m), height of crown scorch for all cardinal directions (m), and height to base of live crown before wildfire (m). We were unable to sample thinning without prescribed fire in Unit 41, as the adjacent area was salvaged before we were able to establish measurement plots.

Data Analysis

We used paired statistical tests to make comparisons among the variables for the silvicultural treatments and by spatial distance increments (Table 1). The specific variables examined were the percentage of bole scorch and the percentage of crown scorch for each tree, based on total tree height. The percentages were calculated by taking an average of the scorch measurements in each of the four cardinal directions. We use the non-parametric Mann-Whitney U-test for analysis involving two factors; treatment, or lack thereof, and silvicultural structure. We used the Kruskal-Wallis One Way Analysis of Variance tests for analysis involving three or more factors; treatment, distance increment, and treatment and distance increment (Table 1). Each grouping included several distance increment and/or silvicultural treatment parameters, as shown in Table 1.

Table 1. Data structure for statistical analysis of Cone Fire behavior.

Data Type	Parameters	Test used
Treatment Presence/Absence	Treated Untreated	Mann-Whitney U-test
Silvicultural Treatment Stand Structure	High diversity (HiD) Low diversity (LoD)	Mann-Whitney U-test
Silvicultural Treatment	High Diversity w/fire (HiDF) Low Diversity w/fire (LoDF) Low Diversity w/o fire (LoDNF) Untreated (UT)	Kruskal-Wallis One Way Analysis of Variance
Distance Increments (aggregated data)	0–50 meters 50–100 meters 100–150 meters	Kruskal-Wallis One Way Analysis of Variance
Silvicultural Treatment and Distance Increment	High Diversity w/fire (HiDF) • 0–50 meters • 50–100 meters • 100–150 meters Low Diversity w/fire (LoDF) • 0–50 meters • 50–100 meters • 100–150 meters Low Diversity w/o fire (LoDNF) • 0–50 meters • 50–100 meters • 100–150 meters	Kruskal-Wallis One Way Analysis of Variance

Non-parametric tests were used to preserve the integrity of the data while recognizing its non-normal skewness. While individual tree data were recorded (i.e., hundreds of trees), this data has been summarized to averages per strip-plot, from which the number of statistical cases varied from 5 to 15 depending on the structural and treatment type. This was done to avoid the error of pseudo-replication (Hurlbert 1984) in the statistical analysis. The probability being tested against was $p < 0.05$, or an alpha of 95% confidence. *Post-hoc* testing with the Bonferroni method was done after preliminary test-

Table 3. Kruskal-Wallis One-Way Analysis of Variance for percentage bole scorch and percentage crown scorch comparing parameters by data type (Table 1).

Data Type Silvicultural Treatment			
Variable	Parameter	Mean (%)	Standard Deviation (%)
Bole Scorch			
	HiDF n= 5 $p < 0.00001$	18.54	9.82
	LoDF n= 15 $p < 0.00001$	2.29	3.86
	LoDNF n= 5 $p < 0.116$	13.38	5.76
Crown Scorch			
	HiDF n= 5 $p < 0.001$	66.50	8.54
	LoDF n= 15 $p < 0.001$	25.93	8.52
	LoDNF n= 5 $p < 0.064$	47.23	15.63

Distance Increments (aggregated data)			
Variable	Distance (m)	Mean (%)	Standard Deviation (%)
Bole Scorch n= 25 $p < 0.0001$			
	0–50	62.62	24.94
	50–100	12.07	16.13
	100–150	2.99	6.10
Crown Scorch n= 25 $p < 0.0001$			
	0–50	88.54	18.36
	50–100	34.22	34.00
	100–150	9.04	17.41

Fire Effects Transition with Distance into Silviculturally Treated Plots

To further analyze the transition of the fire effects as the fire moved into silviculturally treated areas, Kruskal-Wallis One-Way Analysis of Variance testing was performed for both percentage bole scorch and percentage crown scorch (Table 3) in 50-meter increments. This determined whether or not there was an area of transition between the adjacent, not treated, areas (0–50 meters) and the silviculturally treated plots (50–150 meters). There was a significant difference ($p < 0.0001$) between each 50-meter increment with regard to percentage bole scorch and percentage crown scorch. For most strip plots, the 50–100 meter area acted as a transition zone in which the Cone Fire transitioned from a crown fire to a surface fire. In 13 out of 25 plots, the fire went out before reaching 100 meters into a treatment area.

The 50-meter increments were further analyzed with a Bonferroni *Post-hoc* adjustment to isolate the increment contributing to the significant difference between increments. There was a significant difference ($p < 0.0001$) between all three 50-meter increments, with regard to percentage bole scorch and percentage crown scorch.

Fire Transition into Treatment Plots, Grouped by Treatment Type and Distance

High diversity with prescribed fire treatment. There was a significant difference between all distance increments with regard to percentage bole scorch ($p < 0.006$) and percentage crown scorch ($p < 0.03$) (Table 4). The high variation within the 50–100 meter increment can be attributed to this being a transition zone for the Cone Fire, with some trees experiencing much more scorch than others.

A Bonferroni *Post-hoc* adjustment to isolate the increment contributing to the significant difference between increments indicated that there was a significant difference ($p < 0.0001$) between all three 50-meter increments for both percentage bole scorch and percentage crown scorch. The fire severity indicators were reduced as the fire moved farther into the treatment areas.

Low diversity with prescribed fire treatment. There was a significant difference ($p < 0.0001$) between all distance increments with regard to percent of both bole scorch and crown scorch (Table 4).

A Bonferroni *Post-hoc* adjustment indicated there was no significant difference between the 50–100 meter and 100–150 meter increment in percent of bole scorch. The change in severity of bole scorch occurred at the treatment plot boundary. There was a significant difference ($p < 0.0001$) between all three distance increments with regard to percentage crown scorch. The change in severity of crown scorch occurred over a longer transition area than bole scorch.

Table 4. Kruskal-Wallis One-Way Analysis of Variance by silvicultural treatment for percentage bole scorch and percentage crown scorch grouped by distance increment.

Silvicultural-Treatment	Variable	Distance (m)	Mean (%)	Standard Deviation (%)
HiDF n= 5				
	Bole Scorch $p < 0.006$			
		0–50	86.87	8.09
		50–100	34.41	22.46
		100–150	2.52	2.23
	Crown Scorch $p < 0.03$			
		0–50	99.96	0.08
		50–100	98.27	2.98
		100–150	20.20	19.72
LoDF n= 15				
	Bole Scorch $p < 0.0001$			
		0–50	52.13	26.07
		50–100	8.07	8.15
		100–150	4.14	7.59
	Crown Scorch $p < 0.0001$			
		0–50	81.87	21.35
		50–100	26.81	24.46
		100–150	8.33	18.28
LoDNF n= 5				
	Bole Scorch $p < 0.006$			
		0–50	69.87	8.68
		50–100	1.76	2.88
		100–150	0.00	0.00
	Crown Scorch $p < 0.0001$			
		0–50	97.11	2.53
		50–100	4.35	6.54
		100–150	0.00	0.00

Low diversity without prescribed fire treatment. While there was a significant difference between all distance increments with regard to percentage bole scorch ($p < 0.006$) and percentage crown scorch ($p < 0.0001$) (Table 4), there was less variation than for the high diversity with prescribed-fire silvicultural treatment and the low diversity with prescribed-fire silvicultural treatment.

The Bonferroni *Post-hoc* adjustment indicated that there was a significant difference with regard to percent of bole scorch between the silviculturally treated plot and the adjacent untreated area. Within the silviculturally treated plot, there was no significant difference with regard to bole scorch between the 50–100 meter and 100–150 meter increments, most likely due to an abundance of understory fuels that carried the Cone Fire throughout the strip plots. With regard to percentage crown scorch, there was no significant difference between the 0–50 meter increment and the 50–100 meter increment. There was a significant difference with regard to crown scorch between the 50–100 meter increment and the 100–150 meter increment. Thus, the low diversity without prescribed fire silvicultural treatment had a longer transition area than in the low-diversity with prescribed fire silvicultural treatment.

Semivariogram analysis of fire severity. The scale is defined by the range size, which represents the distance to where samples greater than the range are not spatially autocorrelated with samples less than the range values. The points less than the range distance are spatially autocorrelated and represent the scale of the fire severity variables. The following range averages were calculated by treatment type and effect measured: Bole scorch – LoDNF 175m, LoDF 35.8m, HiDF 69.1m; Crown scorch – LoDNF 32.8m, LoDF 43.5m, HiDF 106.1m

Discussion

Fire Transition Zone Comparing Silvicultural Treatment to Adjacent Untreated Areas

Though the Cone Fire ceased to burn as a crown fire immediately upon entering any of the silviculturally treated plots, there was variation in the subsequent proportion of bole and crown scorch in the different types of treatment plots. The large variations in both the percentage bole scorch and percentage crown scorch (Table 2) for the silviculturally treated plots can be explained by the differences in surface fuel beds encountered as the Cone Fire crossed from the adjacent untreated areas into the treated plots. This difference may be attributed to several reasons. For instance, ladder fuels in an understory can lead to crown fire (Van Wagner 1977). After the silvicultural treatments, the BMEF plots had insufficient seedlings and saplings to act as ladder fuels compared to the adjacent untreated areas. Additionally, silviculturally treated plots had fewer trees in general (Oliver 2000; Symons 2006), of which most were of a size class large enough (> 13 cm dbh) to not have low-hanging branches contributing to the ladder fuels structure and were spaced sufficiently far apart to not support active crown fire.

Fire Effects in Low-diversity Treatment Plots Versus High-diversity Treatment Plots

Both percentage bole scorch and percentage crown scorch were much lower for the LoD plots than the HiD plots, even though the fire ceased to burn as a crown fire immediately upon entering both plot types. This is most likely due to the more uniform removal of small trees in the low diversity silviculturally treated plots, leaving only widely-spaced trees in the 13–28 centimeter and 29–53 centimeter size classes. The larger numbers of small trees left in the HiD plots were susceptible to scorch from even low-intensity surface fire. The large variation in both the percentage bole scorch and percentage crown scorch (Table 2) in the high-diversity, silviculturally treated plots appears to be due to both (1) convective heat driven by wind into the plot from the intensely burning adjacent stands, and (2) scorching of smaller trees by the low-intensity surface fire that continued in the HiD stands. It appears that the denser stands with larger trees left in the HiD plots (Vaughn and Ritchie 2005) had produced sufficient needle cast in the five years since prescribed fire to carry a low-intensity surface fire. This was in contrast with the LoD stands, where even a low-intensity surface fire would not carry in the plots, even where it had been five years since prescribed fire. Generally, tree crowns in the high diversity strip plots closer to the treatment boundary experienced much higher levels of crown scorch than similar-sized trees located farther into the plot. In addition, the 50–100 m increment of the high-diversity silvicultural treatment plots (Plot 41) was influenced by wind speed and direction and the intensity of the fire in the adjacent untreated area (Ritchie et al. 2007). Therefore, the percentage bole scorch and percentage crown scorch near the silviculturally treated/not recently silviculturally treated boundary was likely influenced by convective heat from adjacent areas.

Fire Effects Comparing Silvicultural Treatment

In all cases, with the exception of bole scorch in the LoDNF treatment, there was a significant difference ($p < 0.05$) between silvicultural treatments for both percentage bole scorch and percentage crown scorch (Table 3). There was a very large difference between the low diversity with prescribed fire treatment and all other treatments. In the low diversity with prescribed fire treatment, removing the small trees (i.e., trees < 12 cm dbh) eliminated the low-hanging branches that act as ladder fuels into the canopy. This is in contrast to the high-diversity structural treatment, which left trees of many size classes and occasional thickets, some of which could act locally as ladder fuels. The reduction of surface fuels in the LoD structural treatment with prescribed burning contributed to the significant reduction in bole and crown scorch compared to the low diversity without prescribed fire treatment, as the Cone Fire was unable to burn even as a low-intensity surface fire in the former.

The Cone Fire dropped from a passive crown fire to a surface fire almost immediately upon hitting a thinned treatment plot, regardless of the specific type of treatment (Skinner et al. 2004; Ritchie et al. 2007). As predicted by fire behavior simulations, there was a gradient of change in fire severity that followed the intensity of the treatments (Ritchie et al. 2007). The absence of understory fuels to act as ladders to the canopy, combined with reduced surface fuels in the low diversity with prescribed fire treatment, caused the Cone Fire to immediately drop from the crowns and become a low-intensity surface fire, usually extinguishing itself without outside influence. There was no significant difference between the high diversity with prescribed fire and the low diversity without prescribed fire treatments for bole and crown scorch. There are likely different reasons, however, for the higher levels of scorch in the two treatments. Ritchie et al. (2007) determined the likelihood for considerable differences in tree mortality between the two treatments. They found a significantly higher level of tree mortality in the low diversity without fire than in the high diversity with prescribed fire. The high diversity with fire treatment included a higher degree of structural stratification, with more small clustered trees, and low-hanging branches that were susceptible to scorch from the surface fire. Thus, the more small trees there were in a stand, the higher the percent scorch was, even if the fire behavior was the same—whereas the low diversity without prescribed fire silvicultural treatment had a greater abundance of surface fuels (i.e., duff and woody fuels) to generate greater heat for higher scorch levels.

Fire Transition Comparing Distance into Treated Plots

Data was grouped by distance increments in order to determine if there was an area of transition as the fire moved into the silviculturally treated plots. There was a significant difference between all three increments (Table 4). The Cone Fire transitioned from a crown fire to a surface fire almost immediately upon entering any of the treatment areas. Crown scorch and bole scorch were reduced, compared to outside the treatment areas in the first 50–100 meter increment upon entering the stand. Only in the areas that did not receive prescribed fire following thinning did the fire continue to burn through the units beyond the 100–150 m increment distance from the edge of the treatment area. Some units experienced a greater range of the fire than others, based on the silvicultural treatment, as was discussed in a previous section.

California law PRC 4291 specifies at least 100 feet of fuels reduction around a structure to provide for defensible space. In this regard, defensible space is area where fuels have been modified to reduce fire behavior sufficiently to not rapidly spread fire and to allow fire suppression forces the opportunity to safely defend the property. Thus, defensible space is not necessarily expected to stop a fire, but to slow its spread and reduce its intensity, similar to the concept of a fuelbreak (Agee et al. 2000). Notably, all of the treatments assessed in this study were effective at bringing the fire out of the crowns and to the surface almost immediately as the fire encountered the treatment. The differences between treatments were primarily in a gradient of how the fire was subsequently able to burn through each of the treatment areas. As noted by the semi-variance analysis, the scale of the fire effects into a treated area tended to range between 35.8 and 175 m for bole scorch and 32.8 to 106.1 m for crown scorch. The longer penetrations of the Cone Fire into the HiDF as crown scorch tended to be due to more low-hanging fuels and small trees that were more susceptible to crown scorch. The large range of percentage crown scorch for HiDF and LoDF can also be attributed to convective heat and intensity of the Cone Fire being pushed strongly by wind as it reached the planned treatment boundaries. Overall, all treatments were effective in halting the crown fire almost immediately, with the low diversity with fire structural treatment the more effective, as it essentially stopped the fire from burning into the treatment area. Since California law PRC 4291 represents an average of various flammable vegetation types found in the state, i.e., chaparral, oak woodland, conifer forest, etc., a homeowner should consider from these results that 100 feet is the minimum defensible space for ponderosa pine-dominated forest areas with similar silvicultural treatments.

Conclusion

The analysis of fire effects in ponderosa pine-dominated forests based on different combinations of silvicultural treatments provides an insight into more-effective wildland-urban interface (WUI) area fire hazard-management techniques in the 21st century for California's drought-prone conifer forest regions. Since the turn of the 20th century, wildfires have often become severe events, largely as a result of built-up fuels due to active fire exclusion (Arno and Brown 1991). Recent studies reinforce that northeastern Californian mixed-conifer forests have undergone a major structural and compositional change since beginning the exclusion of fire (Taylor 2000; Norman 2002; Norman and Taylor 2005). This can contribute to higher probability of increased fire intensity, fewer fire-tolerant forest stands, and more-severe crown fire (Mutch 1994). A low-severity fire regime has been replaced by a moderate- to high-severity fire regime that is largely the result of the changes in fuel loading and stand structure (Agee 1994).

The results of this study show that a combination of selective thinning with prescribed fire can significantly reduce the severity of wildfire effects in an interior ponderosa pine forest. Percentages of bole scorch and crown scorch were lower in areas that had been selectively thinned followed by prescribed fire than in areas that had not had similar silvicultural treatments (Table 4). A low-diversity structural treatment combined with prescribed fire resulted in less bole scorch and crown scorch than a low-diversity structural treatment without prescribed fire, or a high-diversity structural treatment with prescribed fire.

Forest managers are now faced with up to a century of built-up fuels and dense understories. A complete return to historical regimes is not likely, as forest composition, structure, and function have been drastically affected by a century of fire exclusion. These results suggest that a combination of silvicultural treatments can spatially reduce the potential for severe fire damage in WUI areas (supporting CAL FIRE's defensible space policy/CA law PRC 4291), while suggesting active vegetation management approaches for the broader forested landscape. Active management approaches will likely result in more-resilient forest ecosystems in western U.S. ponderosa pine forests.

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