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Probability of tree survival after wildfire in an interior pine forest of northern California: Effects of thinning and prescribed fire

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Abstract

A wildfire at Blacks Mountain Experimental Forest provided the opportunity to observe fire severity at the point of transition between treated and untreated stands. At several locations in the forest, the wildfire burned from a dense stand of largely pole-size trees, into an area that had been recently treated with combinations of thinning and prescribed fire. These treatment areas are part of a large-scale experiment designed to evaluate stand structure, grazing and prescribed fire in an interior ponderosa pine (*Pinus ponderosa* P.&C. Lawson) forest.

Tree survival and damage were sampled on strip plots arranged perpendicular to the treatment plot boundary. Logistic regression was used to develop a model relating the probability of initial mortality (within 9 months after the fire) to distance from treatment plot boundary, and treatment history (thinning and prescribed fire). Fire behavior simulation was used to evaluate the effectiveness of the pre-fire stand treatments.

The model shows that probability of survival was greatest in those areas that had both thinning and prescribed fire prior to the wildfire event. Survival was near zero for the untreated areas. Survival in thinned-only areas was greater than untreated areas but substantially less than the areas with both treatments.
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1. Introduction

In recent years, large fires with high rates of tree mortality have raised interest in land management policies and the effect such policies may have on wildfire severity in the western United States. These concerns are likely to remain as human populations continue to expand in the wildland–urban interface.

The management of forested lands in many areas of the western United States is increasingly focused on efforts to mitigate damage from wildfires (Fitzgerald, 2005; Youngblood, 2005), especially in forests that originally had fire regimes that were characterized by frequent, low–moderate intensity surface fires (Agee and Skinner, 2005).

The primary management tools are the application of mechanical treatments (e.g., thinning or masticating) and prescribed fire. Both thinning and prescribed fire treatments serve to reduce fuel levels and fire intensity, but in very different ways. Prescribed fire primarily reduces surface fuels and deprives subsequent fires of fuel. Thinning, by itself, reduces ladder and canopy fuels and reduces the likelihood of crown fires while not necessarily altering surface fuels and the expected intensity of surface fires (Agee and Skinner, 2005). If fire intensity can be reduced substantially, tree survival should increase.

Observing wildfire behavior in the context of a designed experiment is fraught with difficulty. Wildfire is, by definition, an unplanned event; and hence ill suited for a designed experiment. Observational studies involving stands with a known treatment history may provide one means to evaluate treatment effectiveness.

The primary objective of this study is to evaluate the effectiveness of thinning and prescribed fire treatments in reducing wildfire severity at Blacks Mountain Experimental Forest. This is quantified by modeling tree survival along treatment boundaries in an interior pine forest burned in 2002. In addition we compare modeled behavior of the fire with observations made after the fire.

Blacks Mountain Experimental Forest (BMEF) was established in 1934 as a research facility for the study of forest management in interior ponderosa pine (*Pinus ponderosa*

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P.&C. Lawson) forests (SAF Type 237, Eyre, 1980). The forest is located in the rain shadow of the volcanic Cascade Range of northeastern California at 40°40′N latitude and 121°10′W longitude. Elevation on the forest ranges from 1700 to 2100 m. Summers are typically dry; annual precipitation ranges from 231 to 743 mm with most (90%) falling as snow between October and May (Hallin, 1959).

Fire history studies in the vicinity of BMEF show that before 1900 AD fires were mostly frequent, low-intensity surface fires (Taylor, 2000; Norman and Taylor, 2003). Fire occurrence at BMEF declined in the late 1800s with the introduction of sheep grazing and virtually ceased in the early 1900s with the onset of fire suppression (Skinner and Taylor, 2006). This change in the fire regime has led to increased stand density, especially of small and intermediate sized trees (Norman, 2002), and surface fuels.

Numerous studies have been conducted at BMEF, with focus on methods-of-cutting (Dunning and Hasel, 1938; Dolph et al., 1995), Unit Area Control (Hallin, 1959), and risk rating systems (Salman and Bongberg, 1942). Currently, a large-scale interdisciplinary study is underway designed to evaluate the effects of stand structure, grazing, and prescribed fire on a number of different response variables (Oliver, 2000). Treatments were imposed to create two contrasting stand structures: high-structural diversity and low-structural diversity. These structural contrasts were established by thinning stands with different prescriptions. Each ~100 ha treatment plot was subsequently split, with prescribed fire applied to one of these two splits.

Fuels transects were established to quantify coarse woody debris post treatment (Brown, 1974). Summaries were developed (Table 1) using California coefficients from van Wagtendonk et al. (1996).

On September 26, 2002, the Cone Fire ignited mid-day on the Hat Creek Ranger District of the Lassen National Forest, near the northwest corner of BMEF (Fig. 1). Later in the afternoon, the fire was reported to be approximately 4 ha with winds out of the west at 14 km h^{-1} and relative humidity at 6%. In the evening, a wind shift with gusts to 51 km h^{-1} from the north pushed the fire south into the Experimental Forest. By 2:30 a.m. of the 27th, the fire had reached 653 ha. At the time of fire ignition, fuel moisture was extremely low; nearby Ladder Butte weather station recorded 1000-h fuels at 5%, 10- and 100-h fuels both at 2%.

This fire burned portions of three of the twelve treatment plots at Blacks Mountain (Oliver, 2000). This event provided an opportunity to evaluate the effects of the fire, specifically the survival of trees, in relation to the stand conditions prior to the burn and distance from treatment boundaries. We evaluated the effectiveness of the different stand conditions on influencing fire behavior through simulating expected fire behavior.

2. Field methods

In early summer of 2003, following the Cone Fire, 25 strip plots (in five groups) were installed across the treatment plot boundaries of the three units impacted by the Cone Fire (Fig. 1). These 10-m wide plots extended 100 m into the recently treated areas and 50 m across the other side of the treatment plot boundary (Fig. 2). The low variability in mortality outside the plots allowed for a shorter (50 m) extension into the untreated areas. Five strips were installed in a high-structural diversity treatment with prescribed fire, fifteen in a low-structural diversity treatment with prescribed fire, and five in a low-structural diversity treatment study unit without prescribed fire. Each group of five strips was established with uniform spacing from an arbitrary starting point, with the exception of those in the high diversity unit. In that unit, strips had to be staggered to avoid untreated clumps within the unit. Note, there are no strip plots located in the high diversity treatments without prescribed fire; the wildfire did not burn into any of those treatments found within the Blacks Mountain Ecological Research Project.

On each of the strip plots, the following data were recorded for all trees and snags ≥10 cm DBH:

- species;
- distance from treatment boundary (m);
- diameter at breast height (cm);
- mortality class (live or dead);
- indicator of scorched or torched;
- total height (m);
- height of bole char for all cardinal directions (m);
- height of crown scorch for all cardinal directions (m);
- height to base of live crown before wildfire (m).

Height to base of the live crown before wildfire was estimated by assuming that dead branches were consumed by the crown fire. Trees <10 cm DBH were separated into two 5 cm classes, then tallied by species and mortality class. Tallies were referenced by 1 m increments along the primary axis of the strip plot. Trees were classed as dead if no green foliage was retained 9 months after the fire.

3. Analysis

3.1. Probability of tree survival

We observed a trend in the relationship between rates of survival and distance from treatment unit boundary. It appeared that much of the mortality was adjacent to the boundary. In order to quantify this, we fit a probability of survival function

Table 1
Woody debris (metric tonnes ha^{-1}) for 100 h fuels (2.54–7.62 cm diameter) and 1000 h (>7.62 cm diameter), sampled in the treated areas at Blacks Mountain Experimental Forest prior to the Cone Fire

Piece size (cm)	High diversity with fire	Low diversity with fire	Low diversity without fire
2.54–7.62	4.59 ± 0.52	3.55 ± 0.51	7.38 ± 0.69
>7.62	14.58 ± 2.04	10.89 ± 1.43	34.36 ± 5.63

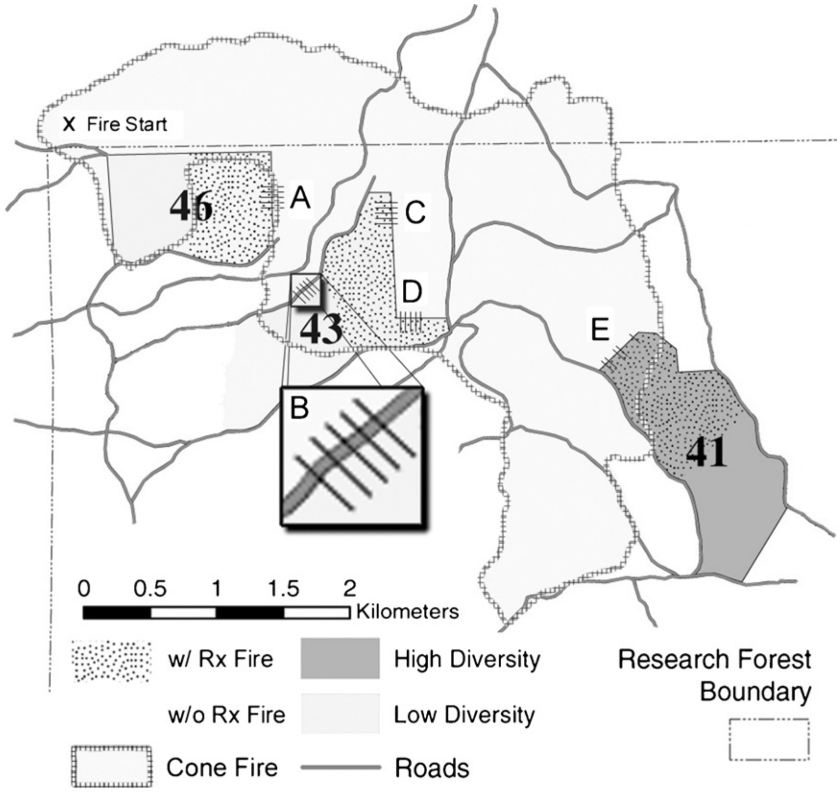

Fig. 1. Location of strip plots at Blacks Mountain Experimental Forest: high-structural diversity with prescribed fire (E), low-structural diversity with prescribed fire (A, C and D), and low-structural diversity without prescribed fire (B) are all present.

for all trees >10 cm DBH to express the relationship between a binary response variable (survival; 1 = dead, 0 = live) and both discrete and continuous covariates. We fit a nonlinear mixed-effects model for the tree survival in the strip plots. The probability of survival model applied is:

$$P\,(\text{Survival}) = \left[\frac{1}{(1+\exp(f))}\right]$$

where,

$$f = \beta_0 + \beta_1 T + \beta_2(T \times F) + \beta_3(T \times \sqrt{D}) + \beta_4(T \times S \times \sqrt{D}) + \beta_5(T \times \sqrt{\text{DBH}}) + \beta_6(T \times S\sqrt{\text{DBH}}) + e$$

$\beta_0, \beta_1, \ldots, \beta_6$, are parameters to be estimated where, S = structural diversity; 1 = high diversity, 0 = low diversity; T = treatment; 1 = treated, 0 = untreated; F = prescribed fire; 0 = burned, 1 = not burned; D = distance from treatment boundary (positive values are interior to treatment, negative values are exterior to treatment).

The error term is partitioned into group and strip-within-group terms, assumed to have expectation 0, and respective variances σ_1^2 and σ_2^2.

Because observations were made in the spring following the burn, this analysis reflects immediate (first year) mortality rates; any secondary mortality is not reflected in the analysis.

This model parameterization produces the following expressions for areas within the treated side of the plots:

$f\ (T = 1,\ F = 0,\ S = 1) = \beta' + (\beta_3 + \beta_4)\sqrt{D} + (\beta_5 + \beta_6)\sqrt{\text{DBH}}$
$f\ (T = 1,\ F = 0,\ S = 0) = \beta' + (\beta_3)\sqrt{D} + (\beta_5)\sqrt{\text{DBH}}$,
$f\ (T = 1,\ F = 1,\ S = 0) = \beta' + \beta_2 + (\beta_3)\sqrt{D} + (\beta_5)\sqrt{\text{DBH}}$,
and $\beta' = \beta_0 + \beta_1$, for $D > 0$, as D is positive for all trees in the treatment.

To aid in interpretation of results, we also evaluated, graphically, the amount of bole char and crown scorch observed in the strip plots.

3.2. Fire behavior simulation

Surface fuels were estimated by comparing pre-fire photos taken in the vicinity of the strips, before and after treatments (Oliver, 2000), to available photo series (Maxwell and Ward, 1980; Blonski and Schramel, 1981) and then subjectively selecting an appropriate standard fire behavior fuel model (Anderson, 1982; Rothermel, 1983). Fuel models used were model 10 for areas adjacent to and model 8 for areas within the low diversity with prescribed fire units and the high diversity with prescribed fire unit. Model 11 was used for both the areas adjacent to and within low diversity without prescribed fire because the adjacent area had been previously thinned with no follow-up surface fuel treatment. Model 8 was used for estimating fire behavior in the areas that had been treated with

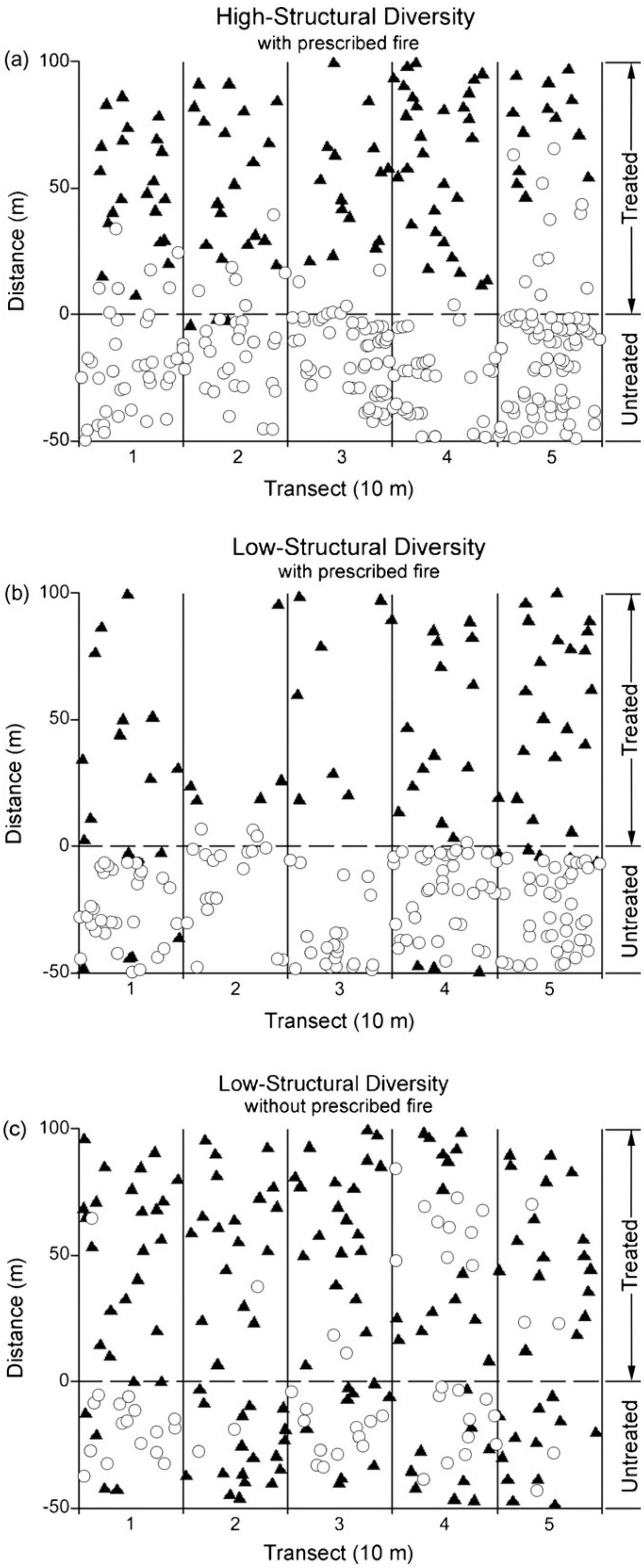

Fig. 2. (a–c) Spatial distribution of tree mortality for each block treatment. Dead (○) and live (▲) trees are shown for all strips in the high-structural diversity treatment, low-structural diversity treatment without prescribed fire and a sample of five strips in the low-structural diversity treatment with prescribed fire.

prescribed fire because it generates the lowest intensity fire of the fuel models. However, it should be noted that the Cone Fire flaming front died at entering and did not carry through both low diversity units with prescribed fire.

Canopy fuel conditions were estimated following the procedure used by Skinner (2005). Several variables necessary for estimating crown-fire potential and behavior were calculated with program FUELCALC (Reinhardt, 2004) using the tree data from the strips. Variables were determined for each treatment plot from an average of conditions from both inside and outside of treated areas separately. Output from FUELCALC included the following variables: canopy bulk density (CBD, kg/m^3), averaged canopy base height (CBH, m), averaged stand height (SH, m), total canopy fuel weight (TFW, tonnes/acre), plot canopy cover (COV, %), plot basal area of trees (BA, m^2/ha), and trees per unit area (TPA, trees/ha). The 25th percentile of canopy base height was used for predicting passive crown-fire behavior (e.g., Fulé et al., 2001; Skinner, 2005). Stand height is the average height of the five tallest trees on each plot (Scott and Reinhardt, 2001).

Fire weather and fuel moisture conditions that existed during the Cone Fire were used in the fire behavior simulation. Fire weather conditions during this fire were as follows, 1-h fuel moisture (%) = 1, 10-h fuel moisture (%) = 2, 100-h fuel moisture (%) = 2, wind speed = 24 km h^{-1} (range 14–32) (Skinner et al., 2004). A wind reduction factor of 0.3 was used to reduce the 6.1 m measured wind speed to mid-flame wind speed to account for the influence of stand structure and canopy on wind. Canopy foliage moisture content was estimated to be 75% since the Cone Fire burned under dry, north wind conditions following the long, dry summer of the area.

Fire behavior was simulated using the spreadsheet program NEXUS (Scott, 1999). Fuel models and stand conditions used to parameterize NEXUS are shown in Table 2. NEXUS quantifies fire hazard by coupling existing models of surface and crown-fire behavior to simulate overall fire spread and intensity as described by Scott and Reinhardt (2001). For this study, the NEXUS estimates of Fire Type (surface fire, passive crown fire, active crown fire), crown fraction burned, scorch height (m), torching index (wind speed when crowning begins), and crowning index (wind speed when active crown fire can be sustained) were used for comparing expected fire behavior outside and inside of treatment areas.

Table 2
Fuel model and stand parameters used to estimate fire behavior for inside and outside of treatment plots

Index	Plot 41; T + B		Plot 43; T		Plot 43; T + B		Plot 46; T + B	
	Out	In	Out	In	Out	In	Out	In
FM[a]	10	8	11	11	10	8	10	8
HtLC[b]	1	3	1	1	1	4	1	3
CBD[c]	.073	.032	.071	.066	.103	.027	.144	.067

T + B: Thin followed by prescribed fire; T: thin only.
[a] FM: Standard fuel model used.
[b] HtLC: Height to live crown (m).
[c] CBD: Canopy bulk density (kg/m^3).

Table 3
Mean (and standard error) of density, N (stems ha^{-1}), and basal area, BA (m^2 ha^{-1}), in strip plots perpendicular to treatment plot boundary sampled after the Cone Fire

	High diversity with prescribed fire		Low diversity with prescribed fire		Low diversity without fire	
	N	BA	N	BA	N	BA
Within unit (treated)	246 (17)	25.9 (5.0)	137 (18)	8.4 (1.4)	218 (11)	10.4 (0.8)
Outside unit (untreated)	824 (158)	13.4 (11.9)	767 (103)	29.8 (3.4)	388 (28)	21.4 (2.2)

These values reflect both living and dead trees.

4. Results

4.1. Observed survival

Initial density, at the time of the Cone Fire, within the strip plots is summarized in Table 3. Untreated areas of strips had much greater densities than the treated areas. Note that basal area is greater in the treated high diversity units due to the presence of many larger trees. Thus, even though there are fewer trees ha^{-1}, stand basal area is higher. Tree density (stems ha^{-1}) was low in the ‘‘untreated area’’ adjacent to the unburned low diversity unit due to thinning some 20 years ago.

Fig. 2a–c illustrates the spatial distribution of live trees and dead trees greater than 10 cm DBH found in both treated and untreated portions of the strip plots. Since high diversity with prescribed fire and low diversity without prescribed fire have five strip plots each, only one block of five of the three blocks in the low diversity with prescribed fire were selected for display (Fig. 3b). Survival averaged 1% adjacent to the high diversity treatment, 11% adjacent to the low diversity treatment with prescribed fire, and 53% adjacent the low diversity treatment without prescribed fire.

4.2. Within-treatment survival function

The parameter estimates (Table 4) for the probability of survival function were all highly significant ($p < 0.01$), with the exception of the intercept term ($p = 0.25$). Thus, both tree diameter and distance from treatment unit boundary were significantly related to probability of survival. There is no evidence of over-dispersion in the fit, χ^2/d.f. = 0.77. Estimated variance for groups is 6.7 and groups-within-blocks is 2.3. The fitted probability of survival function within treatment plots is displayed in Fig. 3. Tree survival outside of the treatment boundaries was not included to reduce complexity of interpretation; the model is based on an assumption that distance from boundary is irrelevant outside the treatment plots. Since the fire burned from untreated areas into the treated areas, there is no reason to expect the distance term is relevant in untreated areas. Low diversity with prescribed fire had the greatest survival at nearly 100% within 10 m of the boundary. Low diversity had moderate survival overall, with a gradual increase in survival within the unit. High diversity without prescribed fire had poor survival within the first 10 m but increased dramatically to nearly 100% at approximately 25 m from the boundary.

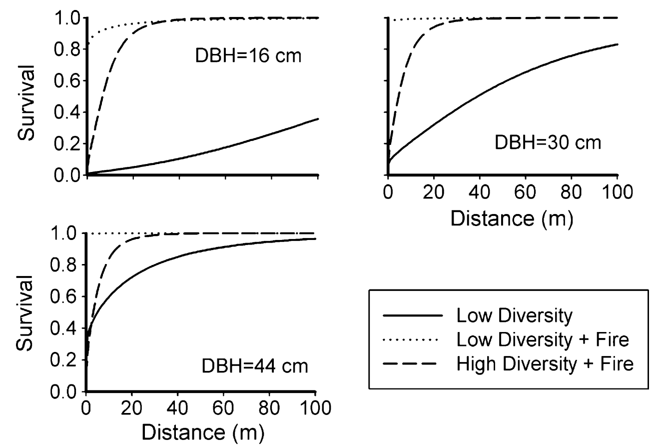

Fig. 3. Fitted logistic regression showing the probability of survival over distance from treatment boundary for low-structural diversity with prescribed fire, low-structural diversity without prescribed fire, and high-structural diversity with prescribed fire.

Bole char and crown scorch for all trees greater than 10 cm DBH may be indicative of fire intensity (Fig. 4a and b). Mean percent bole char (a) and percent crown scorch (b) are depicted along quarterly increments, 100 m within the treated strip, and in the untreated portions. This figure illustrates the strong relationship between proximity to treatment edge and variables that may be considered as surrogates for fire intensity. Bole char

Table 4
Parameter estimates (β_0–β_6), estimated standard error (S.E.) and parameter correlation matrix (ρ) for the logistic survival function

Parameter			ρ					
β	Estimate	S.E.	0	1	2	3	4	5
0	2.5081	1.54						
1	2.0305	1.12	0.0198					
2	6.1796	0.716	0.0019	−0.1819				
3	−0.4239	0.105	0.0059	−0.5087	−0.4273			
4	−0.7595	0.187	−0.0398	−0.2312	0.3350	−0.2999		
5	−1.4736	0.203	0.0087	−0.7780	−0.0762	0.1812	0.301	
6	1.1065	0.208	−0.0245	0.2361	0.1701	0.0899	−0.583	−0.569

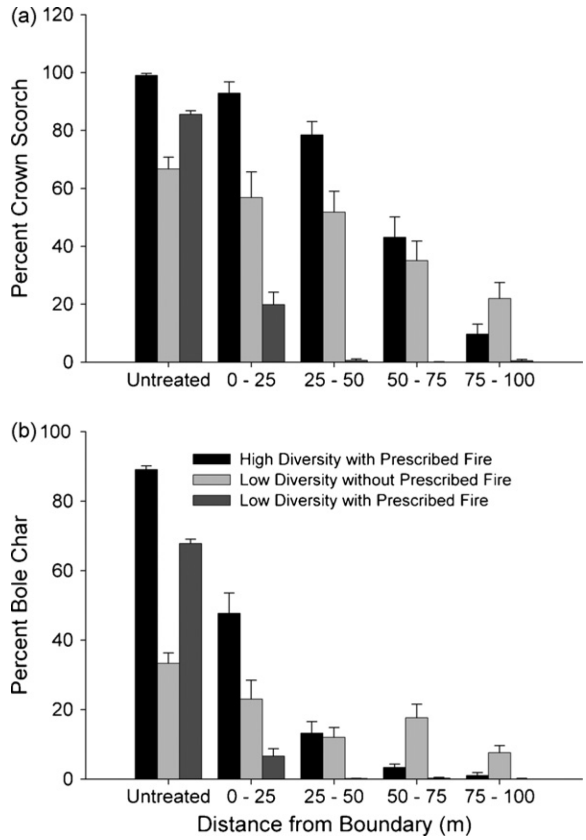

Fig. 4. Percent crown scorch (a) and percent bole char (b) within the untreated section and along quarterly increments of the 100-m strip (±1 S.E.).

was almost non-existent 50 m within the units with prescribed fire. Crown scorch, although generally reduced within the treated areas, was very high within the first 25 m for the high diversity treatment. The amount of crown scorch in border trees of the low diversity treatments was much less than that observed in the high diversity treatment.

Statistical significance of parameter estimates does not necessarily imply a good fit for all combinations represented in the data. In order to evaluate the strength of the relationships, we calculated the width of a 90% confidence interval for predicted survival for combinations of distance (*D*) and breast height diameter (Table 5). Narrow confidence limits are indicative of a modeled survival rate that is more likely close to the true probability of survival. We found that for low diversity without fire, the relationships were weak, as indicated by the very wide confidence limits. However, for the units with prescribed fire, the relationships were much tighter. In general the larger trees had tighter confidence limits. Confidence limits near the edge of the treatment units were much wider than those within the units where confidence limit width approached zero. It should be noted that there were very few tree less than 16 cm in diameter in the low diversity treatments. These understory trees were removed during thinning and this absence contributes to the wide confidence limits for small trees in these units.

Table 5
Confidence limit width ($\alpha = 0.90$) for estimates from probability of survival model for combinations of tree DBH and distance (*D*) from the treatment boundary

D (m)	Low diversity with fire			Low diversity without fire			High diversity with fire		
	Diameter (cm)			Diameter (cm)			Diameter (cm)		
	12	24	36	12	24	36	12	24	36
0	0.87	0.48	0.18	0.06	0.34	0.73	0.41	0.55	0.65
20	0.55	0.13	0.02	0.25	0.72	0.91	0.65	0.52	0.44
40	0.37	0.06	0.01	0.41	0.82	0.84	0.17	0.11	0.08
60	0.25	0.03	0.01	0.56	0.86	0.77	0.04	0.02	0.02
80	0.17	0.03	0.01	0.67	0.86	0.69	0.01	0.01	0.02
100	0.12	0.02	0.01	0.77	0.84	0.59	0.01	0.01	0.01

4.3. Fire behavior

The fire behavior simulated by NEXUS (Table 6) indicated that each of the low diversity with prescribed fire and high diversity with prescribed fire units would experience a passive crown fire outside of the plot dropping to a surface fire within. In fact, in both of the low diversity with prescribed fire units, the fire would not burn into the treated area and went out at the edge of the unit. The fire did continue into the high diversity with prescribed fire, but dropped immediately to a very low-intensity surface fire within the treated area as the model predicted.

The model predictions of 23–45% of the crowns burned in the area adjacent to these treatment units were generally less than half of what actually occurred. Most of the crowns in the adjacent untreated areas torched and the NEXUS predictions of 0% crowns burned within these treated areas were correct. However, there was considerable scorch on the edges of the treated areas where they were affected by radiant and convective heat from the high-intensity fire outside the units.

NEXUS predicted a passive crown fire outside of the low diversity treatment without prescribed fire that would continue through the treated area. Though there was considerable scorch within this treatment, only a small portion of crowns was torched. This indicates this treatment experienced mostly a high-intensity surface fire rather than the passive crown fire the model predicted.

4.4. Torching index

Consistent with observed patterns of crown scorch and consumption in the fire, the torching index predicted the fire would begin torching in untreated stands with very little wind (Table 6). Within the stands treated by thinning and prescribed fire, the index indicates that there would be no torching under the conditions of the Cone Fire. However, in the stands thinned without prescribed fire, the index over predicted the likelihood of torching, as we observed little torching in that stand.

4.5. Crowning index

Wind speeds during the Cone Fire appear to have been on the verge of supporting an active crown fire in the untreated areas. However, the crowning index indicates that only the untreated

Table 6
Comparison of estimated fire behavior within and adjacent to treatment plots

Index	Plot 41; T + B		Plot 43; T		Plot 43; T + B		Plot 46; T + B	
	Out Type[a] P	In Type[a] S	Out Type[a] P	In Type[a] P	Out Type[a] P	In Type[a] S	Out Type[a] P	In Type[a] S
SH[b]	20.1	0.7	2.7	2.3	29.5	0.7	31.3	0.7
TI[c]	0	39.7	2.4	2.4	0	53.2	0.4	32.9
CI[d]	11.4	20.9	11.7	12.2	8.9	23.5	6.9	12.1
CFB[e]	0.23	0	0.29	0.27	0.33	0	0.45	0

T + B: Thin followed by prescribed fire; T: thin only.
[a] Type: P, passive crown fire; S, surface fire.
[b] SH: Scorch height (m).
[c] TI: Windspeed (m/s) to initiate crown torching.
[d] CI: Windspeed (m/s) needed to maintain an active crown fire once it has crowned.
[e] CFB: Crown fraction burned.

area adjacent to the high diversity with prescribed fire was likely to have an active crown fire. This high diversity treatment area had been treated with prescribed fire and had the highest crown scorch in each distance category from the edge of all areas treated with prescribed fire (Fig. 4). Since the treated stand could support only a low-intensity surface fire, the relatively high amounts of crown scorch was most likely due to radiant and convective heat from the intense fire in the adjacent untreated stand.

5. Discussion

The differences in tree survival between the treated and untreated areas at Blacks Mountain were striking. The survival rate in the untreated area adjacent to the high-structural diversity with prescribed fire treatment was about 1%, yet within this unit survival rates exceeded 80% beyond 25 m from the boundary. The lower survival along the boundary of the high diversity unit is likely influenced by wind patterns and fuel load in the adjacent stand (Weatherspoon and Skinner, 1995). The adjacent stand was very dense and the wind drove the fire directly into the treated unit.

The low diversity units with prescribed fire gave evidence of an abrupt change in behavior as evidenced by the change in survival, bole char and crown scorch observed. The logistic function predicts nearly 100% survival even at the treatment plot edge, while on the untreated side of the boundary, survival rates of only 11% were found. The fire did not carry through surface fuels in these units despite the severe weather conditions and efforts on the part of suppression crews to burn out these areas. Crown scorch in these units was limited to the very edge of the treatment plot and the degree of bole and crown scorch on the interior of these units was near zero.

The contrast between survival rates associated with the low diversity without prescribed fire treatment are complicated by confounding factors. First, survival outside this area (53%) was generally higher than observed in other untreated areas of the forest. This is probably due to modifications to stand density resulting from a thinning operation some 20 years prior to the Cone Fire. On the other hand, within this treatment, survival rates were generally lower than the other treated units. This higher rate of mortality may be attributable to the much higher observed levels of surface fuels in this unit. The low diversity treatment had tops and limbs from the largest trees cut off and scattered. It appears that the prescribed fire at BMEF reduced surface fuel biomass by two-thirds (Table 1). This reduction in surface fuels may be related to less bole char (Fig. 4b) and higher rates of survival.

The model expressing probability of survival as a function of tree size and distance from treatment plot boundary suggests a strong positive effect of treatment on tree survival and the significant influence of tree location. Trees in close proximity to the treatment unit boundary were less likely to survive than those within the unit. Survival rates just within the treatment boundary range from below 20% to nearly 100%, depending on tree size and treatment. However, survival rates of trees more than 25 m from the boundary increased dramatically for all but the smallest trees in the unit without prescribed fire. This phenomenon is consistent with an expectation that small trees are less likely to survive a surface fire than larger trees with thicker bark. The lower survival rates in the immediate proximity of the boundary of the high diversity with prescribed fire treatment is likely due to the extreme fire intensity in this particular area of the fire immediately adjacent to the treatment plot. The model also predicts higher rates of survival for larger trees.

Survival in trees scorched by heat from the adjacent stand was low but rapidly increased within the stand. While the specific rates at which this phenomenon is exhibited will vary, the survival model suggests that benefits to tree survival may not be realized in narrow fuelbreaks or very small treatment areas. Treated areas as small as 0.5 ha in size may have a large portion of the trees succumb to the heat though not consumed by the flames because of this observed "edge effect." Thus, the size of an area to be treated should be considered in the design and implementation of fuels treatments.

As with all observational studies, there are some weaknesses in the analysis due to lack of experimental control. We could not choose which treatment plots would be burned, nor were we able to alter efforts of fire suppression crews who, in some instances attempted to burn out some of our treatment plots. These efforts were largely unsuccessful in the areas that had been previously treated with prescribed fire. However, there is evidence from bark charring patterns that some of the observed mortality in the treatment without prescribed fire resulted from the efforts of suppression crews to burn these areas on the second day of the fire when initial attack was essentially completed.

Each of our treatment plots had been treated within 6 years of the Cone Fire event. Units 41 and 43 were harvested in 1996 and had prescribed fire applied in October of 1997. Unit 46 was harvested in 1998 and burned in 2000. So any conclusions about the impact on the severity is limited to such stands that have had similar recent treatments. However, treatments in these dry environments are likely to last for more than a decade. The area adjacent to treatment plot 43 (low diversity thin without prescribed fire), for example, was commercially thinned nearly 20 years before the Cone Fire and had fire severity patterns similar to that of the more recently treated area. Over the long term, treatment effectiveness will diminish as fuels accumulate and crown spacing decreases.

Generally, the NEXUS predictions appear to give reasonable estimates of relative differences resulting from the fire encountering different fuel and stand structural conditions. The only area that did not meet the predicted fire behavior was the low diversity without prescribed fire. This area did not appear to torch as easily as the model predicted.

The relative differences in effects of the Cone Fire in the untreated and different levels of treatments, acted as would be expected according to basic principles of fuels treatments (Agee and Skinner, 2005; Husari et al., 2006) and are consistent with results found in other recent post-fire studies assessing the effectiveness of stand treatments in ponderosa pine dominated forests (Pollet and Omi, 2002; Martinson and Omi, 2003; Finney et al., 2005; Strom and Fulé, 2007). The Cone Fire created a gradient of effects depending upon the intensity of the treatment. Fire severity (as expressed by tree mortality) was high in the untreated areas adjacent to treated stands. Stands with ladder fuels reduced by thinning and a follow-up surface fuel treatment by prescribed fire had the best survival and lowest occurrence of damage to boles and crowns. Stands in which ladder fuels were thinned, without follow-up treatment of surface fuels by prescribed fires, were intermediate between the other two. However, even the later brought the fire mostly to the surface with only occasional torching.

Fuel treatments need to be periodically reapplied in order to maintain their effectiveness (Husari et al., 2006). The area adjacent to the low diversity without prescribed fire treatment that was thinned approximately 20 years before the Cone Fire appears to have maintained a reduced fire hazard similar to results found by Strom and Fulé (2007) in Arizona ponderosa pine forests. Fuels treatments are likely to last longer in these dryer interior ponderosa pine dominated forests than in more mesic mixed conifer forests west of the Cascade Range-Sierra Nevada crest (cf. Weatherspoon et al., 1992).

6. Conclusions

Observed changes in severity were remarkable and provide strong evidence that the reduction in fuels from thinning or thinning with prescribed fire can reduce wildfire intensity and severity in interior ponderosa pine stands. Both bole char and crown scorch were reduced substantially within all our treatment units. The combination of thinning followed by prescribed fire created a very effective treatment that, in two of the three units, would not even carry fire; fire in these two units was spotty and left most of the area unburned, despite the efforts of fire crews to burn out these areas.

Although the fire behavior appeared to transition very quickly from a crown fire to a surface fire at our treatment boundaries, we observed ‘‘edge effect’’ mortality in these treatments. Radiant heat from the adjacent untreated areas appeared to generate substantial mortality along some treatment boundaries. Although the effect appears to have dissipated within about 25 m, this could be substantial for narrow fuelbreaks or small treatment areas as may be common in fragmented ownerships such as the rural–urban interface.

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