Fuel treatments alter the effects of wildfire in a mixed-evergreen forest, Oregon, USA

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Abstract: We had the rare opportunity to quantify the relationship between fuels and fire severity using prefire surface and canopy fuel data and fire severity data after a wildfire. The study area is a mixed-evergreen forest of southwestern Oregon with a mixed-severity fire regime. Modeled fire behavior showed that thinning reduced canopy fuels, thereby decreasing the potential for crown fire spread. The potential for crown fire initiation remained fairly constant despite reductions in ladder fuels, because thinning increased surface fuels, which contributed to greater surface fire intensity. Thinning followed by underburning reduced canopy, ladder, and surface fuels, thereby decreasing surface fire intensity and crown fire potential. However, crown fire is not a prerequisite for high fire severity; damage to and mortality of overstory trees in the wildfire were extensive despite the absence of crown fire. Mortality was most severe in thinned treatments (80%–100%), moderate in untreated stands (53%–54%), and least severe in the thinned and underburned treatment (5%). Thinned treatments had higher fine-fuel loading and more extensive crown scorch, suggesting that greater consumption of fine fuels contributed to higher tree mortality. Fuel treatments intended to minimize tree mortality will be most effective if both ladder and surface fuels are treated.

Résumé : Les auteurs ont eu une occasion exceptionnelle de quantifier la relation entre les combustibles et la sévérité du feu en utilisant des données récoltées avant un incendie sur les combustibles de surface et dans la canopée ainsi que des données sur l'intensité du feu après un incendie de forêt. L'aire d'étude est une forêt mélangée de conifères du sud-ouest de l'Oregon avec un régime de feux d'intensité mixte. La modélisation du comportement du feu a montré que l'éclaircie a réduit les combustibles dans la canopée, ce qui a diminué le potentiel de propagation d'un feu de cime. Les risques d'initiation d'un feu de cime n'ont pas changé malgré la réduction des combustibles étagés parce que l'éclaircie a augmenté les combustibles de surface, ce qui a contribué à accentuer l'intensité du feu de surface. L'éclaircie suivie d'un brûlage au sol a réduit les combustibles dans la canopée, le long du tronc et en surface, diminuant par conséquent l'intensité du feu de surface et les possibilités d'un feu de cime. Cependant, un feu de cime n'est pas nécessaire pour avoir un feu de forte intensité; les dommages et la mortalité chez les arbres de l'étage dominant causés par un incendie de forêt ont été importants malgré l'absence d'un feu de cime. La mortalité était la plus élevée dans les peuplements éclaircis (80–100 %), modérée dans les peuplements non traités (53–54 %) et la moins élevée dans les peuplements éclaircis et soumis à un brûlage dirigé (5 %). Les peuplements éclaircis avaient une quantité plus importante de combustibles fins et plus de roussissement des cimes, ce qui indique qu'une plus grande consommation de combustibles fins a contribué à une plus forte mortalité des arbres. Le traitement des combustibles visant à minimiser la mortalité des arbres aura le maximum d'efficacité si les combustibles étagés et de surface sont traités.

[Traduit par la Rédaction]

Introduction

United States federal policies, including the Healthy Forest Restoration Act of 2003 (Bill H.R.1904), National Fire Plan (Public Law 106-291), and the Ten-year Comprehensive Strategy Implementation Plan, direct federal land managers to reduce fire hazard (defined as the potential magnitude of fire behavior and effects related to fuel conditions) in forests of the western United States. Recent large wildfires such as the 2002 Biscuit fire in southwestern Oregon have had detrimental impacts on forest resources, have threatened lives, and have cost millions of dollars to suppress. Fuel reduction treatments are one strategy advocated, and mandated by law, to reduce fire hazard caused by forest fuel accumulations in the absence of more frequent low-severity fires (Peterson et al. 2005). A central question of this effort is where and how should forest fuels be treated to effectively reduce fire hazard.

The theoretical basis for changing fuel structure to reduce fire hazard is well established (Scott and Reinhardt 2001; Graham et al. 2004; Peterson et al. 2005). According to Rothermel's (1972) surface fire model, surface fire intensity is a function of surface fuel abundance, fuel moisture, and rate of spread. Based on this model, decreasing surface fuels can reduce surface fire intensity, all else being equal. According to Van Wagner's (1977) crown fire initiation model, the transition from surface fire to crown fire is a function of surface fire intensity, canopy base height, and canopy foliar moisture. According to Van Wagner's (1977) crown fire spread model, active crown fire spread is a function of the relationship be-

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tween canopy bulk density and rate of spread. Based on these models, decreasing surface fuels and vertical fuel continuity (ladder fuels) can inhibit crown fire initiation, and reducing the abundance and horizontal continuity of canopy fuels can prevent crown fire spread, all else being equal.

Previous studies on fuel treatment efficacy use Rothermel's surface fire model and Van Wagner's crown fire model to determine fuel treatments effects on potential fire behavior (Stephens 1998; Scott 1998; Fulé et al. 2001; Brose and Wade 2002). These studies have shown that thinning treatments can reduce crown fire hazard by reducing ladder and canopy fuels, and treatments are most effective if the residual stand includes larger, more fire resistant trees (thinning from below) (Graham et al. 1999; Brown et al. 2004; Stephens and Moghaddas 2005) and if activity fuels are subsequently removed (Alexander and Yancik 1977; Stephens 1998). These simulation studies provide essential information on fuel treatment efficacy, but they rely on simplified fire behavior models that are based on limited empirical data from specific geographical regions, and they do not address treatment effects on fire severity that cannot be predicted by the models.

Current scientific research on underburning (prescribed fires beneath the canopy layer) supports the ability of these treatments to reduce surface fire hazard. Underburning alone has been shown to effectively reduce surface fuel loading (Kauffman and Martin 1989) and fire severity (Fulé et al. 2004) and alter fire behavior (Helms 1979; Buckley 1992) in some forests. Underburning treatments generally reduce only surface fuels, but can also reduce ladder and canopy fuels if sufficient subcanopy vegetation is removed (Kilgore and Sando 1975; Fulé et al. 2004). A combination of thinning and underburning has also been shown to change fire behavior (Stephens 1998; Fulé et al. 2001) and reduce fire severity (Brose and Wade 2002; Pollet and Omi 2002). However, underburning may not be a management option in some places because it may pose problems for air quality (Conard et al. 2001).

More empirical data are needed on the effectiveness of fuel treatments to alter fire behavior and reduce fire severity in wildfires, even though the limitations associated with opportunistically studying wildfires may preclude a rigorous experimental design. Empirical studies of wildfires often require reconstruction of prefire fuel structures, which can typically be done for canopy fuels, but not surface fuels (Omi and Kalabokidis 1991; Pollet and Omi 2002). Any research on wildfires is inherently retrospective, but it can provide essential information on fuel treatment effectiveness under wildfire conditions (Fulé et al. 2004).

There is little information on the effectiveness of fuel treatments in forests with mixed-severity fire regimes, for which the roles of fire exclusion and fuel accumulations are not well understood. Most studies on fuel treatments have been conducted in arid and semiarid forests, e.g., ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.) forests in the southwestern United Stated and mixed-conifer forests in California, where fuels are the primary control of fire behavior (Schoennagel et al. 2004). Prior to fire exclusion, these forests experienced low-severity (high-frequency) fire regimes in which surface fires consumed low-growing vegetation and woody fuels, leaving larger, fire-resistant trees (Fulé et al. 1997; Allen et al. 2002). Now fuel accumulations caused by fire exclusion have increased fire hazard and caused more high-severity fires, so fuel treatments may be an effective means for reducing these fuel accumulations and restoring low-severity fire regimes (Brown et al. 2004). Forests with mixed-severity fire regimes have the greatest range of natural variability for both fire frequency and severity (Agee 1993), so it may be more difficult to determine whether a century of fire exclusion has increased fuels sufficiently to affect fire hazard.

In this study, we quantify the effects of fuel treatments in a mixed-evergreen forest of southwestern Oregon with a mixed-severity fire regime, which burned in the Biscuit fire of 2002. Abundant prefire fuel data for surface and canopy fuels provide a rare opportunity to directly quantify the relationship between fuel structure and fire severity. Treated and untreated stands were sampled before and after treatment implementation and again after the wildfire, enabling us to avoid most complications associated with reconstructing prefire fuel conditions. We use a three-step process to evaluate the effectiveness of fuel treatments for reducing potential fire behavior and fire severity of a wildfire. First, we determine whether two fuel treatments (thinning and thinning followed by underburning) reduced fire hazard based on simulated potential fire behavior. Second, we compare damage to and mortality of overstory trees in treated and untreated forests that burned in a wildfire. Lastly, we explore the mechanisms for differences in fire severity by quantifying changes in fuel structure (canopy bulk density, canopy base height, tree density, and woody surface fuels) and comparing foliar moisture of subcanopy tree species.

Methods

Site description

Lightning ignited several small fires in southwestern Oregon on 12 July 2002, which eventually merged and became the Biscuit fire. The fire burned 202 000 ha until it was finally extinguished by rain on 8 November 2002. It was the largest wildfire in Oregon in recorded history and one of the largest ever on US national forest land. It burned primarily on the Siskiyou National Forest and coverd nearly all the Kalmiopsis Wilderness Area (Fig. 1). The study area is located on the western perimeter of the Biscuit fire and burned on 16 August 2002. Observations of fire behavior and immediate postfire effects indicate that the area burned as a surface fire, since tree crowns still contained red and green needles. On the day the sites burned, the closest Remote Automated Weather Station (42.1°N, 124.2°W) recorded a daily maximum temperature of 26 °C, a relative humidity of 8%, a 10 h fuel moisture of 4%, and an average wind speed of 4 km·h^{-1} out of the northwest (archived data at www.fs.fed.us/land/wfas.html), although exact fire weather conditions at the sites most likely differed because of differences in aspect, elevation, and stand structure. The local Keetch Byram Drought Index, a measure of soil moisture deficiency on a scale of 0 to 800, was 663 (archived data at www.fs.fed.us/land/wfas.html). The energy release component, a measure of seasonal fuel moisture conditions, was 69 (archived data at www.fs.fed.us/land/wfas.html. An energy release component greater than 60 indicates the potential for severe fire behavior.

Fig. 1. Location of study area and the Biscuit fire in southwestern Oregon, USA. The study area burned in the Biscuit fire on 16 August 2002.

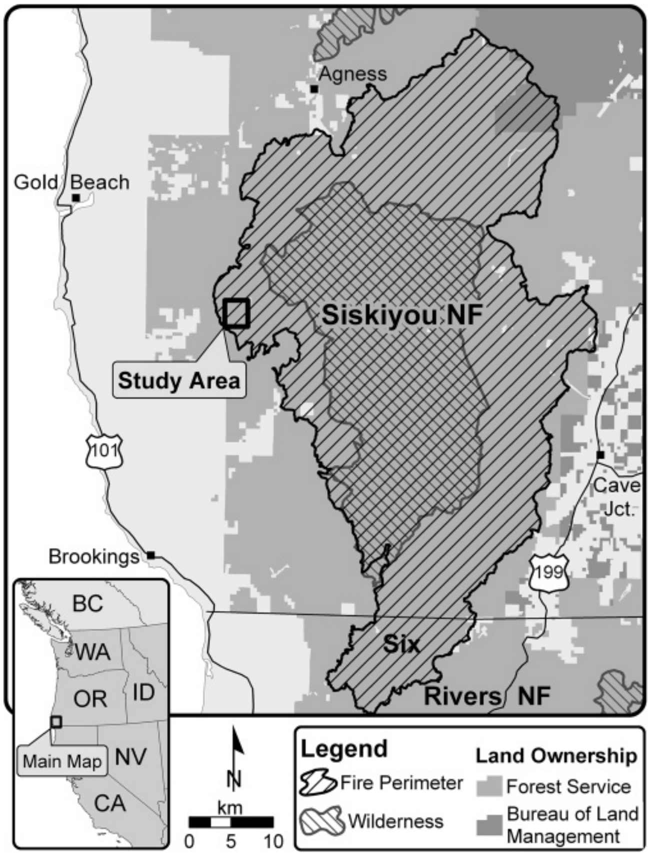
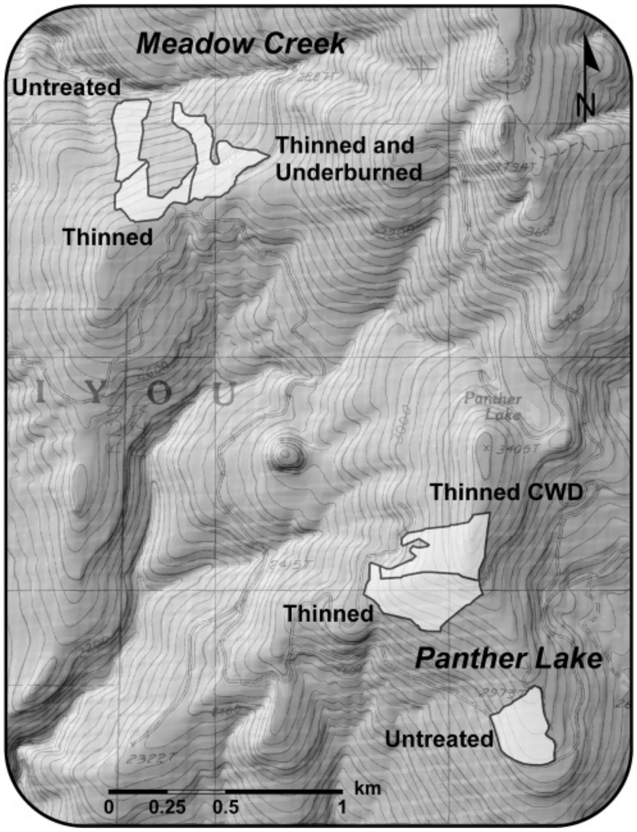


Fig. 2. Location of treatments in the Meadow Creek and Panther Lake sites.



The study area is located in the Coast Range of southwestern Oregon, 20 km from the Pacific Coast, and is managed by the Siskiyou National Forest. Climate of the study area is characterized by cool, wet winters and warm, dry summers. Mean January temperature is 6 °C, and mean July temperature is 16 °C. Mean annual precipitation is 206 cm, with most precipitation falling between October and May and only 15 cm falling between June and September (Little et al. 1995). The geologic substrate is sandstone and schist–phyllite, with Typic Hapludults and Typic Dystrochrepts as the dominant soil subgroups. The overstory canopy is dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), with some knobcone pine (*Pinus attentuata* Lemm) and sugar pine (*Pinus lambertiana* Dougl.), and the subcanopy tree layer is composed of three evergreen broad-leaved species: tanoak (*Lithocarpus densiflorus* (Hook. & Arn.) Rehd), Pacific madrone (*Arbutus menziesii* Pursh), and chinquapin (*Chrysolepis chrysophylla* (Dougl. ex Hook.) Hjelmqvist), with some smaller Douglas-fir.

The study area includes two sites, Meadow Creek established in 1995 and Panther Lake established in 1992, which are part of the Long-Term Ecosystem Productivity (LTEP) study, a controlled experiment designed to assess the effects of plant community composition and coarse woody debris on the processes that affect forest productivity. At Meadow Creek, slopes range from 20% to 35%, elevation ranges from 670 to 850 m, and aspect is northeast. At Panther Lake, slopes range from 10% to 25%, elevation ranges from 820 to 1030 m, and aspect is southwest.

The stand established after a stand-replacing fire in 1881, and tree age ranges from 90 to 120 years (Little et al. 1995). The only management conducted in the stand prior to the establishment of these experimental treatments was fire suppression. In the Coast Range of southwestern Oregon fire frequency varies along a gradient from the coast to drier inland forests, with fire frequencies of 90 to 150 years on the western side and 50 years for the inland portion (Agee 1991). Located 20 km inland from the coast, the study area is more typical of fire frequencies on the western side. Lightning ignitions are frequent throughout the fire season (Agee 1991), so this system is not ignition limited.

Treatments

Meadow Creek contains three treatment plots (6–8 ha each): one untreated, one thinned, and one thinned and underburned (Fig. 2). Panther Lake also contains three treatment plots (6–8 ha each): one untreated, one thinned, and one thinned with additional coarse woody debris (CWD) left after the thinning treatment (Fig. 2). All treatments were randomly assigned, and thinning operations were completed in the winter of 1996. Logs were yarded by helicopter, and tree crowns were removed except in the treatment that was subsequently underburned, where crowns were left on site. For the treatment with high CWD, 15% of the harvested logs were left scattered on site. The thinning in both sites was a combination of thinning from below and crown thinning (Graham et al.

1999), meaning that suppressed, intermediate, and a portion of codominant crown classes were removed. Douglas-fir was thinned to a relative density (proportion of standard volume for a given stand age and site quality) of 0.25. Evergreen broad-leaved species were thinned to 8 m spacing, not taking into account the remaining conifers. Snags, conifers other than Douglas-fir, and remnant trees that survived the last known fire were not harvested.

The thinned and underburned treatment was burned in fall 2001 (1 year before the Biscuit fire) with a light surface fire and no crown fire activity. This treatment is within the Biscuit fire perimeter, and the Biscuit fire burned all around it, but stopped at the edge of the treatment. We assumed this was due to fuel conditions within the treatment and not to a lack of ignition source, changes in weather, or physical barriers.

Field sampling

A grid-point system (either 4 × 4 or 3 × 5) with 25 m spacing was permanently established within each treatment, and all fine-wood samples, overstory tree plots, and woody line transects were located at randomly selected distances and azimuths from the grid points. Surface fuels and overstory were sampled three times: prior to thinning, after thinning, and after the Biscuit fire. The thinned and underburned treatment at Meadow Creek was sampled between the thinning and underburning, but no additional sampling was done between the underburning and the Biscuit fire.

Surface fuels

Fine woody debris (defined by time-lag class where 1 h fuels are 0.0–0.6 cm, 10 h fuels are 0.6–2.5 cm, and 100 h fuels are 2.5–7.6 cm in diameter) was sampled before treatment, 1 to 3 years after treatment, and 1 year after the Biscuit fire. Fine fuels were sampled before the thinning using the planar transect method (Brown et al. 1982), with 8 or 10 transects per treatment; 1 h and 10 h fuels were measured along 2 m transects, and 100 h fuels were measured along 3 m transects. After the thinning treatment, all fine fuels between 1.0 and 10.0 cm were collected in sixteen 1 m^2 clip plots, oven-dried, and weighed. After the Biscuit fire, fine wood was again sampled in sixteen 1 m^2 clip plots, but all wood between 1.0 and 10.0 cm was collected and separated into size classes, so loading by time-lag size class could be computed.

Coarse woody debris (defined as the 1000+ h time-lag class, which is all downed wood >7.6 cm in diameter) was measured before treatment, 1 to 3 years after treatment, and 1 year after the Biscuit fire using the planar transect method (Brown et al. 1982). Before the treatment all 1000+ h fuels were sampled along eight or ten 8 m transects. After the treatment and after the Biscuit fire, transect length for 1000+ h fuels was extended to 25 m.

Forest structure

All trees greater than 3.5 cm DBH (diameter at 1.37 m above the ground) were sampled in five 18 m × 18 m plots before thinning, after thinning, and after the Biscuit fire. After thinning, trees were marked with aluminum tags and their location was mapped. DBH, species, and crown class (dominant, codominant, intermediate, and suppressed) were noted for all trees. Total tree height and height to crown base were measured for a representative subset of trees (two trees per species and crown class for each plot) before and after thinning. After the Biscuit fire, however, height and height to crown base of all trees were recorded.

Foliar moisture

Foliar moisture samples were collected from understory tanoak and Douglas-fir trees in August 2004 in nearby LTEP sites that did not burn in the Biscuit fire. Ten samples of 1-year-old foliage, >1-year-old foliage, and small twigs (0.0–0.6 cm) for each species were collected from the lower crown on the south side of the tree between 1400 and 1700 h to minimize variation (Agee et al. 2002). Samples were sealed in plastic bags, weighed wet, and then dried at 70 °C for 48 h. Douglas-fir samples were approximately 25 g, and tanoak samples were approximately 45 g.

Fire damage and mortality

Fire-caused damage was measured for all trees in the five 18 m × 18 m tree plots in August 2003. Crown scorch volume was measured as an ocular estimate of the percentage of prefire crown volume scorched (CS) (Peterson and Arbaugh 1986), and the height of crown scorch (CSHT) was measured to the top of the highest scorched branch (Peterson 1985). Sampling was conducted 1 year postfire at which time the scorched needles had fallen, so crown scorch was estimated to be the crown volume with fine branches remaining but no needles. All trees with DBH >10 cm were assessed for the condition of the cambium at 0.5 m above the ground (Peterson and Arbaugh 1989). A 1–2 cm core including cambial cells was extracted with an increment hammer from four points around the bole: uphill, downhill, and both side slopes. Each sample was treated with a 1% solution of urea peroxide and orthotolidine in methanol, which reacts with the enzyme peroxidase that is found in most living plant tissue (Hare 1965), and recorded as dead or alive. All overstory trees were revisited in August 2004 and classified as dead or alive based on the absence or presence of green foliage.

Data analysis

Forest structure

Summary statistics were calculated for all stand structure variables (tree density, basal area, DBH, canopy base height, and canopy bulk density) for each inventory year. Canopy bulk density (CBD) and canopy base height (CBH) were calculated using species-specific crown biomass equations for Pacific Northwest conifers and hardwoods as compiled in the Fuels Management Analyst™ (Carlton 2001) and following the methods of Scott and Reinhardt (2001). CBD is a measure of the arrangement and amount of fuels in the canopy used to predict crown fire spread and is calculated for an entire stand rather than an individual tree (Scott and Reinhardt 2001). CBH is a measure of ladder fuels; it is important for calculating crown fire initiation (Van Wagner 1977) and also is calculated for an entire stand. CBH is the lowest height in the stand at which there is sufficient CBD to sustain vertical fire spread, typically defined as 0.011 $kg \cdot m^{-3}$ (Reinhardt and Crookston 2003). Height and crown ratio are

Table 1. Fuel model parameters used for surface fire modeling in NEXUS.

	Pretreatment							Posttreatment						
	Fuel loading (Mg·ha^{-1})							Fuel loading (Mg·ha^{-1})						
	1 h	10 h	100 h	Live herb	Live wood	Fuel depth (m)	MOE (%)	1 h	10 h	100 h	Live herb	Live wood	Fuel depth (m)	MOE (%)
Meadow Creek														
Untreated	1.2	4.1	4.8	1.2	0.0	0.3	25	—	—	—	—	—	—	—
Thinned	1.2	2.2	7.5	1.2	0.0	0.3	25	3.6	10.9	13.1	0.0	4.8	0.5	20
Thinned and underburned	1.2	3.6	4.8	1.2	0.0	0.3	25	0.1	1.5	3.5	0.0	0.0	0.1	20
Panther Lake														
Untreated	4.4	6.8	8.7	1.2	0.0	0.3	25	—	—	—	—	—	—	—
Thinned	5.1	9.2	8.9	1.2	0.0	0.3	25	5.3	16.9	17.4	0.0	4.8	0.5	20
Thinned (high CWD)*	4.6	6.0	8.7	1.2	0.0	0.3	25	6.5	20.5	21.5	0.0	4.8	0.5	20

Note: MOE, dead fuel moisture of extinction.
*Additional coarse woody debris was left after thinning.

Table 2. Fuel moistures used for the fire behavior modeling.

Fuel class	Moisture (%)
1 h	3
10 h	4
100 h	6
Live herb	30
Live wood	78
Tree foliar	100

required input variables for these calculations, but height and crown base height were not measured for all trees in the prethinning and postthinning inventories, so we developed four regression equations based on a subset of height and crown base height measurements to generate a complete list of heights and crown base heights (Appendix A).

Surface fuels

Summary statistics were calculated for fine, sound coarse, and rotten coarse wood loading before thinning, after thinning, and after the Biscuit fire. Different sampling methods were accounted for by converting all samples to fuel loading in megagrams per hectare. Some assumptions and additional data collection were required to reconstruct prefire fine fuels by time-lag size class. First, only wet masses were available for some treatments postthinning, so historical fuel moisture levels were used to convert wet masses to dry masses (Appendix B). This is not ideal and may introduce additional error in the fuel loading calculations, but the error should be minimal because fine-wood moisture content in southwestern Oregon stabilizes in late summer when temperatures are high and precipitation is absent. Second, fine-wood samples, including all wood between 1 and 10 cm, were not conducive to analysis by time-lag size class, so additional fine-wood samples were collected in thinned and untreated LTEP sites that did not burn in the Biscuit fire and were divided into three size classes (1.0–2.5, 2.5–7.6, and 7.6–10.0 cm). The proportions of these size classes were applied to the postthinning fine-wood samples from sites that burned in the Biscuit fire (Appendix B). The portion of wood in the 7.6–10.0 cm size class was subtracted from the samples because all wood >7.6 cm was accounted for on the woody line transects. Additional fine-wood samples were collected to quantify the lower end of the size classes (0.0–0.6 and 0.6–1.0 cm), and proportions of these size classes were related to the amount of 1.0–2.5 cm fuels (Appendix B). Prethinning and postfire samples were subdivided in the field, so this procedure was necessary only for the postthinning samples.

Potential fire behavior

We modeled potential fire behavior before and after thinning using the NEXUS spreadsheet (Scott 1999), which links Rothermel's (1972) surface fire spread model as adjusted by Albini (1976) and Rothermel's (1991) crown fire spread model using the crown fire initiation model of Van Wagner (1977). We used customized fuel models for each treatment (Table 1) based on existing fuel models as described by Anderson (1982) and mean values of fuel loading, CBH, and CBD. Fuel moisture (Table 2) and wind speed (23 km·h^{-1}) input values were the historical 98th percentile weather data from the nearest Remote Automated Weather Station (archived data at www.fs.fed.us/land/wfas.html). Slope inputs were the higher end of the slope range at each site (35% for Meadow Creek and 25% for Panther Lake).

Foliar moisture

We sampled foliar moisture of subcanopy Douglas-fir and tanoak because foliar moisture content of the subcanopy affects crown fire initiation according to Van Wagner's (1977) crown fire initiation model and may also influence crown scorch (Van Wagner 1973). The greater foliar moisture content of subcanopy tanoak trees may provide one explanation for differences in patterns of tree damage and mortality between stands with a subcanopy tree layer and those without. A two-sample t test with a two-tailed hypothesis ($\alpha = 0.05$) was used to test for differences in foliar moisture as a percentage of dry mass for the two primary subcanopy tree species (Douglas-fir and tanoak). Foliar components (1-year-old foliage, >1-year-old foliage, and small branches (0.0–0.6 cm)) were compared separately.

Fire damage and mortality

Fire damage variables are reported for overstory trees (defined as trees with DBH >24 cm, based on DBH distributions of thinned and untreated plots). CSHT and CS were tested using one-way analysis of variance (ANOVA) (α = 0.05) with trees as replicates. The two sites were tested separately, and multiple comparisons were made using the Tukey honestly significant difference test (Zar 1999). A block design was not used because the sites had different treatments. Residuals were examined to ensure test assumptions were met, and percentage data were divided by 100 and then transformed with the arcsin square-root transformation.

To estimate CS as a function of fuel structure for each of the five 18 m × 18 m tree plots per treatment (n = 30), we used a logistic regression function of the form

$$[1] \qquad \mathrm{CS} = \frac{1}{1 + \exp(b_0 + b_1 x_1)}$$

where the b's are the regression coefficients, and the x's are the independent variable. The significance of each independent variable (fine-wood loading, sound and rotten coarse wood loading, tree density, CBH, and CBD) was tested by comparing the reduction in deviance to a χ^2 distribution with degrees of freedom equivalent to the reduction in degrees of freedom when the variable is added to the model (α = 0.05). A deviance test was used to test for satisfactory model fit (α = 0.05) (Neter et al. 1996). If the logistic model is a satisfactory fit and the sample size is large, then model deviance will approximately follow a χ^2 distribution with degrees of freedom equal to the residual degrees of freedom from the model. The null hypothesis for this one-tailed test is that the logistic model is a satisfactory fit. Therefore large p values mean that null hypothesis cannot be rejected and that the model is a satisfactory fit. Diagnostics of the residuals were performed to ensure all model assumptions were met.

Mortality results were analyzed to answer two questions. First, a χ^2 test (α = 0.05) for homogeneity on 3 × 3 contingency tables (Zar 1999) was used to test whether the proportions of dead and alive trees differed among treatments. Contingency tables were compared separately for the two sites and further subdivided and tested again when significant differences were found among treatments (Zar 1999). The Yates' correction for continuity was used whenever a subdivision created 2 × 2 contingency tables. Second, the fire damage variables (CS, CSHT, and number of dead cambium samples (NDEAD)) were used along with DBH to construct models that predict mortality for Douglas-fir trees (DBH ≥10 cm). We used a logistic multiple regression function of the form

$$[2] \qquad P_{\mathrm{m}} = \frac{1}{1 + \exp(-b_0 - b_1 x_1 - \ldots - b_i x_i)}$$

where P_{m} is the probability of mortality, the b's are regression coefficients, and the x's are the independent variables. The variance inflation factor (VIF) was calculated for all variables, and if a VIF >3 was present, then the predictor variable that reduced the deviance the least was eliminated (Neter et al. 1996) to minimize collinearity in the predictors.

Significance of the logistics models was tested with the same deviance test listed above, and percent deviance explained (PDE) (roughly equivalent to R^2) was calculated as 1 – (residual deviance / null deviance) for each model. Then models were tested for their ability to correctly predict the observed status of each tree (Ryan et al. 1988). The predictions of the logistic regression are probabilities, so a tree was classified as dead if the predicted P_{m} exceeded a threshold value in order to compare model predictions with observed mortality (1 or 0). The prediction errors depend highly on the selected threshold value for P_{m}, so the prediction errors were tallied and compared for three values: $P_{\mathrm{m}} = 0.4$, $P_{\mathrm{m}} = 0.5$, and $P_{\mathrm{m}} = 0.6$.

Results

Forest structure

DBH and tree density were similar for all treatments within sites prior to thinning, but Meadow Creek treatments had lower basal area, CBD, and CBH than Panther Lake treatments (Table 3). The thinning treatment decreased tree density, basal area, and CBD and increased CBH and mean DBH in all thinned treatments (Table 3). The increase in CBH in thinned treatments was greater at Meadow Creek (10.2–17.5 m increase) than at Panther Lake (4.3–5.5 m increase). The thinned-only treatment at Meadow Creek had a lower reduction in tree density and less of an increase in mean DBH because many subcanopy evergreen broad-leaved trees were not removed.

Surface fuels

Treatments within sites had similar fine-wood loading, but treatments at Meadow Creek had lower fine-wood loading than treatments at Panther Lake before the thinning (Table 4). Sound coarse wood loading was more variable, ranging from 17.4 to 34.7 $\mathrm{Mg \cdot ha^{-1}}$ at Meadow Creek and from 14.9 to 31.6 $\mathrm{Mg \cdot ha^{-1}}$ at Panther Lake. At Meadow Creek, rotten coarse wood was less abundant than sound coarse wood in all treatments, ranging from 0 to 2.4 $\mathrm{Mg \cdot ha^{-1}}$. Rotten coarse wood was not detected at Panther Lake (Table 4).

Fine wood and rotten coarse wood increased in all thinned treatments after the thinning (Fig. 3). Fine wood increased by 15.2 to 27.0 $\mathrm{Mg \cdot ha^{-1}}$ (70%–203%), and rotten coarse wood increased by 1.7 to 6.2 $\mathrm{Mg \cdot ha^{-1}}$. Sound coarse wood loading decreased by 0.9 to 5.8 $\mathrm{Mg \cdot ha^{-1}}$ (4%–53%) in all thinned treatments except the thinned treatment with high CWD, which had an increase in sound coarse wood of 10.7 $\mathrm{Mg \cdot ha^{-1}}$ (72%). In the thinned and underburned treatment, fine wood decreased after the prescribed burn by 16.6 $\mathrm{Mg \cdot ha^{-1}}$, so that there was a net decrease in fine wood after both the thinning and underburn treatments (Fig. 3).

Consumption of fine wood was high during the Biscuit fire, with more fine wood consumed in thinned treatments (95%–100%) than in untreated stands (87%–88%) at both sites (Fig. 4). Percent consumption of rotten coarse wood was also high regardless of treatment, ranging from 62% to 100%; however, in terms of overall biomass consumption, rotten coarse wood consumption was relatively minor compared with fine-wood consumption, because rotten coarse wood was not very abundant before the fire (Fig. 4). The portion of sound coarse wood (25%–34%) consumed was low compared with other fuel types, except in the thinned-only treatment at Meadow Creek, where 65% of sound coarse wood was consumed. Con-

Table 3. Means (standard deviations) of prethining and postthinning stand structure variables.

(A) Meadow Creek site.

	Preharvest			Postharvest	
	Untreated	Thinned	Thinned and underburned	Thinned	Thinned and underburned
DBH (cm)	17.4 (4.3)	16.2 (5.8)	22.7 (6.1)	26.6 (27.5)	42.4 (8.0)
Density (stems·ha^{-1})	1395 (296)	1074 (345)	1025 (233)	383 (341)	185 (31)
Basal area (m^2·ha^{-1})	45.1 (9.1)	40.6 (17.3)	55.6 (4.2)	15.2 (13.9)	29.6 (6.0)
CBD (kg·m^{-3})	0.090 (0.030)	0.047 (0.025)	0.104 (0.026)	0.020 (0.011)	0.058 (0.015)
CBH (m)	5.4 (1.9)	6.2 (5.7)	7.0 (3.2)	23.7 (22.3)*	17.2 (1.1)

(B) Panther Lake site.

	Preharvest			Postharvest	
	Untreated	Thinned	Thinned (high CWD)[†]	Thinned	Thinned (high CWD)[†]
DBH (cm)	24.5 (1.3)	23.5 (4.6)	24.5 (5.3)	35.3 (5.0)	38.4 (3.1)
Density (stems·ha^{-1})	1247 (236)	1180 (274)	1273 (271)	185 (44)	210 (40)
Basal area (m^2·ha^{-1})	74.6 (12.2)	62.7 (12.2)	69.8 (13.0)	18.8 (6.2)	25.3 (4.2)
CBD (kg·m^{-3})	0.174 (0.046)	0.185 (0.051)	0.215 (0.050)	0.050 (0.023)	0.094 (0.014)
CBH (m)	8.2 (0.9)	9.7 (4.7)	8.7 (3.5)	14.0 (1.2)	14.2 (1.4)

*The standard deviation is large for canopy base height (CBH) in the thinned-only treatment at Meadow Creek, because canopy bulk density (CBD) did not exceed the critical threshold in one tree plot, so the plot was assigned a CBH value of 200.

[†] Additional coarse woody debris was left after thinning.

Table 4. Means (standard deviations) of surface wood loading (Mg·ha^{-1}).

	Meadow Creek			Panther Lake		
	Untreated	Thinned	Thinned and underburned	Untreated	Thinned	Thinned (high CWD)*
Prethinning						
FWD	9.3 (3.6)	9.0 (4.8)	10.1 (10.8)	18.4 (5.9)	21.6 (7.7)	18.0 (5.4)
SCWD	17.4 (11.1)	24.1 (24.7)	34.7 (35.8)	18.6 (18.6)	31.6 (34.4)	14.9 (13.3)
RCWD	2.4 (4.0)	0.0 (0.0)	0.6 (1.3)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Total	28.0	31.9	44.2	33.0	48.5	28.7
Postthinning						
FWD	8.9 (6.7)	27.3 (29.4)	25.9 (23.0)	29.7 (18.0)	36.8 (16.5)	45.0 (26.4)
SCWD	14.5 (7.2)	23.1 (14.1)	28.9 (18.4)	8.8 (3.9)	15.4 (10.2)	25.6 (23.4)
RCWD	5.1 (7.2)	3.4 (6.1)	2.3 (2.1)	2.9 (2.7)	4.4 (3.5)	6.2 (5.0)
Total	25.4	47.7	51.3	31.2	48.2	66.8
Postfire						
FWD	1.2 (1.8)	0.6 (1.3)	4.7 (4.5)	3.6 (5.3)	1.7 (4.3)	0.1 (0.2)
SCWD	9.6 (4.7)	7.3 (5.3)	19.3 (11.1)	4.4 (3.0)	11.4 (7.7)	19.2 (5.9)
RCWD	0.4 (0.4)	0.6 (0.3)	0.8 (0.9)	1.1 (0.7)	0.0 (0.0)	0.6 (1.0)
Total	11.2	8.1	24.8	9.1	13.1	19.9

Note: Fire did not spread into the thinned and underburned treatment, so postwildfire fuel loading is the same as fuel loading after the underburn treatment. FWD, fine wood (1 h, 10 h, and 100 h fuels); SCWD, sound coarse wood (1000+ h fuels); RCWD, rotten coarse wood (1000+ h fuels).

*Additional coarse woody debris was left after thinning.

sumption of surface fuels is measured by the change in loading from prethinning to postfire, but because wood from fallen snags is excluded and partial consumption is not measured, consumption may be underestimated.

Foliar moisture

The August foliar moisture of 1-year-old foliage and fine twigs did not differ between the two dominant subcanopy tree species, but significant differences were found for moisture of old foliage ($p = 0.001$). Mean foliar moisture content of >1-year-old foliage was 91% (SE = 2%) for tanoak and 147% (SE = 6%) for Douglas-fir. Mean foliar moisture content of 1-year-old foliage was 144% (SE = 18%) for tanoak and 137% (SE = 12%) for Douglas-fir. Mean foliar moisture content of fine twigs (0.0–0.6 cm) was 90% (SE = 6%) for tanoak and 88% (SE = 6%) for Douglas-fir.

Potential fire behavior

The output of the NEXUS model consists of three related measures of potential fire behavior: (1) fire type (surface

Fig. 3. Posttreatment change in fuel loading by decay and size class for each of the three treatments at the two sites. The values for the thinned and underburned treatment are for after the underburn.

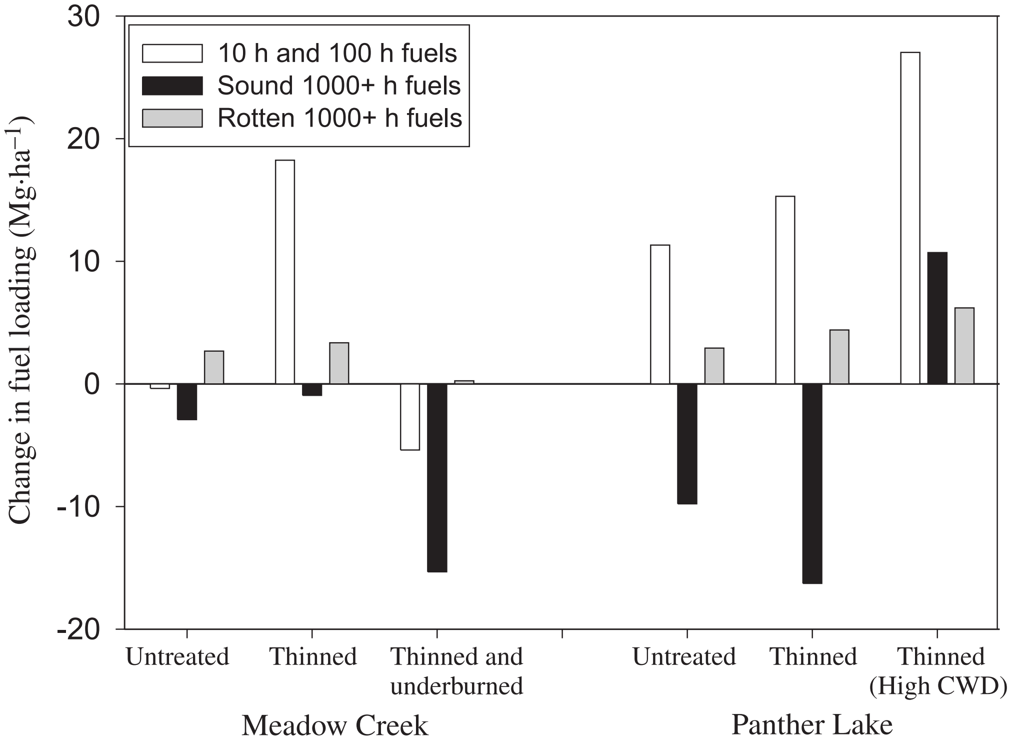
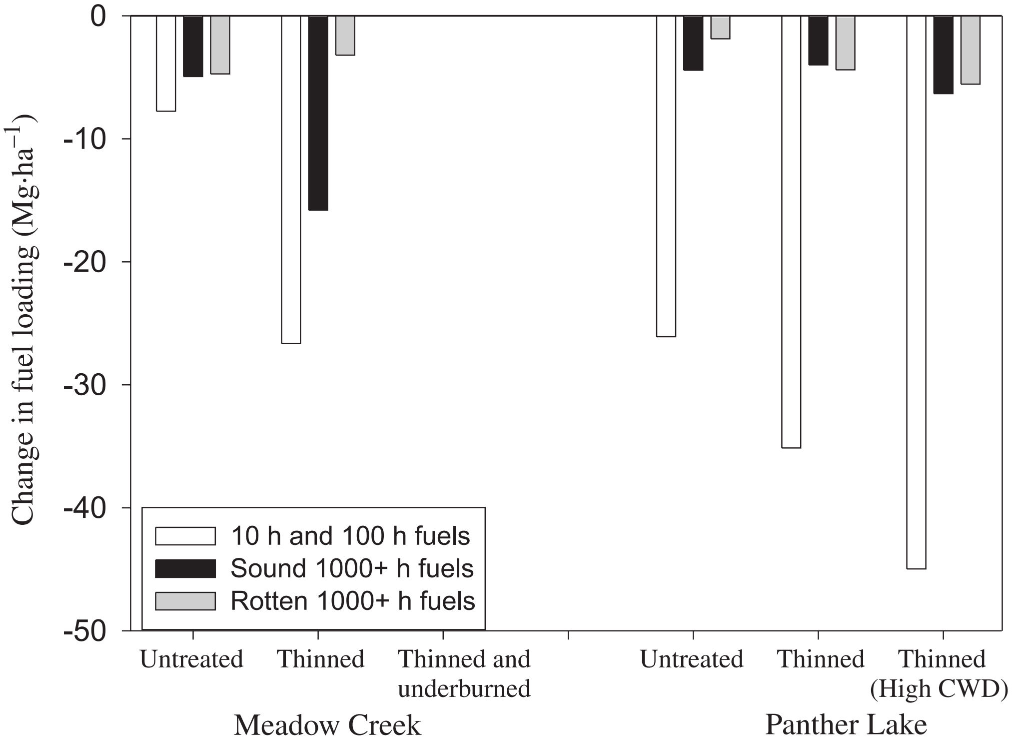


Fig. 4. Postwildfire change in fuel loading by decay and size class for each of the three treatments at the two sites.



fire, conditional crown fire, and active and passive crown fire), (2) torching index, and (3) crowning index (Scott and Reinhardt 2001). Fire type is the expected fire type under specified wind and fuel moisture conditions. Torching index (km·h^{-1}) is the wind speed required to initiate crown fire, and crowning index (km·h^{-1}) is the wind speed required to sustain horizontal crown fire spread under specified fuel structure and moisture conditions.

The Panther Lake site had greater potential for crown fire than the Meadow Creek site prior to treatment. The pre-

Table 5. Potential fire behavior as computed in NEXUS.

	Prethinning			Postthinning		
Treatment	Fire type	Torching index ($km \cdot h^{-1}$)	Crowning index ($km \cdot h^{-1}$)	Fire type	Torching index ($km \cdot h^{-1}$)	Crowning index ($km \cdot h^{-1}$)
Meadow Creek						
Untreated	Surface	177	38	—	—	—
Thinned	Surface	212	62	Surface	311	116
Thinned and underburned	Surface	260	38	Surface	5202	53
Panther Lake						
Untreated	Surface	163	23	—	—	—
Thinned	Conditional crown	187	22	Surface	141	60
Thinned (high CWD)*	Conditional crown	161	19	Surface	141	40

*Additional coarse woody debris was left after thinning.

Table 6. Means, standard deviations, and ranges of tree damage variables for overstory trees.

		DBH (cm)	Crown scorch height (m)			Crown scorch (%)		
Treatment	*n*	Mean	Mean	SD	Range	Mean	SD	Range
Meadow Creek								
Untreated	45	39.1	24.5a	4.3	16.7–34.7	83a	26	15–100
Thinned	6	57.9	30.8b	7.2	20.3–41.9	94a	11	75–100
Thinned and underburned	26	50.0	0.4c	1.9	0.0–9.5	0.1b	0.4	0–2
Panther Lake								
Untreated	77	36.8	17.4d	12.6	0.0–31.3	59d	47	0–100
Thinned	27	37.9	24.5e	3.5	17.9–31.3	98e	7	65–100
Thinned (high CWD)*	32	39.2	24.6e	3.2	13.9–30.8	100e	1	95–100

Note: The thinned and underburned treatment did not have added tree damage from the Biscuit fire. Different lowercase letters indicate that means are significantly different within sites ($\alpha = 0.05$).

*Additional coarse woody debris was left after thinning.

dicted fire type for Meadow Creek was surface fire, and the torching index was at least 177 $km \cdot h^{-1}$ (Table 5). The predicted fire type for the Panther Lake site was conditional crown fire prior to treatment. At Panther Lake the torching index was at least 161 $km \cdot h^{-1}$, making the transition from surface fire to crown fire unlikely, but the crowning index of 20 to 23 $km \cdot h^{-1}$ means that horizontal crown fire spread would be possible under 98th percentile weather conditions. Prior to thinning the Panther Lake site could be susceptible to crown fire if a crown fire moved into the stand, but not if a surface fire moved into the stand from adjacent stands.

Potential fire behavior was similar in all thinned treatments after the thinning. Surface fireline intensity increased but canopy base height increased as well, so the torching index remained similar (Table 5). The crowning index increased by at least 26 $km \cdot h^{-1}$ in all thinned treatments, so wind speeds would need to be double the 98th percentile wind speed for crown fire to spread (Table 5). The predicted fire type for thinned treatments at Panther Lake was reduced from conditional crown fire to surface fire. In the thinned and underburned treatment at Meadow Creek the crowning index increased and the torching index greatly increased.

Fire damage and mortality

At Meadow Creek fire damage was lowest in the thinned and underburned treatment and highest in the thinned-only treatment, but not all differences were significant (Table 6). All measures of fire damage had the highest variability in the untreated stand. CSHT was different for all treatments, the thinned treatment having the highest CSHT and the thinned and underburned treatment having the lowest CSHT. The untreated and thinned-only treatments did not have significantly different CS, although CS ranged from 15% to 100% in the untreated stand and from 75% to 100% in the thinned-only treatment.

Fire damage was lowest in the untreated stand and similar in the two thinned treatments at Panther Lake. CS and CSHT differed significantly between the untreated stand and the thinned treatments, but there were no significant differences between the two thinned treatments. As at Meadow Creek, the untreated stand at Panther Lake had the largest range of CS, from 0% to 100%, compared with 65% to 100% in the thinned treatment and 95% to 100% in the thinned treatment with additional CWD (Table 6).

The extent of cambial tissue damage was similar in all treatments at Panther Lake, but was more variable for treatments at Meadow Creek. Cambial tissue damage was greater in knobcone pine than in Douglas-fir. Approximately 25% of Douglas-fir trees in all treatments at Panther Lake had two or more dead cambium samples. At Meadow Creek, approximately 25% of Douglas-fir trees in the untreated stand also had two or more dead cambium samples, but this value was 5% in the thinned and underburned treatment and 100% in the thinned-only treatment. Cambial damage of knobcone

Table 7. Mortality status of overstory Douglas-fir trees 2 years postfire.

Treatment	*n*	Tree status		Mortality (%)
		Dead	Live	
Meadow Creek				
Untreated	38	20	18	53a
Thinned	5	4	1	80a
Thinned and underburned	21	1	20	5b
Panther Lake				
Untreated	78	42	36	54c
Thinned	25	24	1	96d
Thinned (high CWD)*	30	30	0	100d

Note: Different lowercase letters indicate significant differences within sites ($\alpha = 0.05$).

*Additional coarse woody debris was left after thinning.

pine was similar in all treatments and sites, with all trees having two or more dead samples except one tree in the untreated stand at Meadow Creek.

Mortality of overstory Douglas-fir trees was highest in thinned treatments, moderate in the untreated stands, and lowest in the thinned and underburned treatment. Mortality was 53%–54% in untreated stands, 80%–100% in thinned treatments, and 5% in the thinned and underburned treatment (Table 7). Mortality of knobcone pine trees was almost 100% regardless of treatment. Mortality of subcanopy (DBH <24 cm) broad-leaved and conifer trees was also almost 100%, but many of the broad-leaved trees sprouted shortly after fire. The proportion of dead and live trees (excluding the thinned and underburned treatment) differed between Meadow Creek and Panther Lake ($p = 0.06$), so treatments were compared within sites. At Meadow Creek the only treatment with significantly different proportions of dead and live trees was the thinned and underburned treatment ($p = 0.001$). At Panther Lake the proportion of dead and live trees differed significantly between the untreated stand and the two thinned treatments ($p = 0.001$).

Crown scorch and fuel structure

Sound and rotten coarse wood, tree density, CBD, and CBH were not significant predictors of CS at the plot level. The only significant predictor was fine-wood loading (FWD) ($p = 0.02$). The equation for CS as a function of FWD is

$$[3] \qquad \mathrm{CS} = \frac{1}{1 + \exp[0.800 - 0.0998(\mathrm{FWD})]}$$

The model had sufficient fit ($p = 0.85$), but the 23% deviance explained suggests much of the variability remains unexplained.

Predicting postfire mortality

All single variable and multiple-regression logistic models for predicting tree mortality had sufficient fit, but the large number of degrees of freedom ($n = 244$ trees) makes it difficult to use this criterion to compare the relative effectiveness of the different models, so PDE and the prediction errors of each model were used. CSHT was highly correlated with CS and DBH together (VIF >3), so models with these three variables were not considered further. The single-variable model with the greatest PDE was CS. The CS model can be improved by adding NDEAD, DBH, or both (Table 8). Treatment as a dummy variable (1 for thinned and 0 for untreated) was also significant in a model with CS, NDEAD, and DBH, suggesting that some other factor related to treatment and not captured by the measured damage variables is also important for predicting mortality at these sites. The total and net prediction errors — the model predicts a tree to be dead when it is observed live and live when it is observed dead — were compared among several models. For the single-regression models, CS had the least prediction errors regardless of the P_m cutoff (Table 8). The model with CS predicted mortality of any tree with >60% CS. The multiple-regression model with the fewest total prediction errors included DBH, CS, and NDEAD, but it was only slightly better than the model that contained DBH and CS (Table 8). All models had positive net prediction errors regardless of the P_m cutoff, suggesting that these models tended to over predict mortality.

Discussion

Forest structure and potential fire behavior

Thinning changed the overstory structure and composition to that of a more fire resistant stand by increasing CBH and mean DBH and selecting for fire-resistant species. Fire resistance of Douglas-fir trees increases with size as bark becomes thicker (Ryan et al. 1988) and tree crowns higher (Agee 1993). Mean DBH in all thinned treatments was higher after the thinning, so residual trees are likely to be more fire resistant, although the less fire resistant knobcone pine were also left. The thinning removed a large portion of the subcanopy Douglas-fir and evergreen broad-leaved trees that are not fire resistant. Removing these subcanopy trees also raised the CBH in all thinned treatments, eliminating the ladder fuels that can enable crown fire initiation.

The thinning and underburning treatment reduced crown fire potential more than thinning alone. Prior to treatment the predicted fire type was surface fire or conditional crown fire, so crown fire hazard was low initially at these sites. Thinning had little effect on the torching index because increases in surface fuel loading contributed to greater surface fireline intensity, offsetting the reductions in fire hazard associated with higher CBH. At Panther Lake where initial CBD was higher, thinning reduced crown fire potential by increasing the crowning index and changing the predicted fire type from conditional crown fire to surface fire. Scott and Reinhardt (2001) define conditional crown fire as a condition that occurs when CBH is too high to meet the conditions necessary for a surface fire to transition to crown fire, but CBD is sufficient to support the horizontal spread of crown fire, a phenomenon that anecdotal evidence suggests is real but rare. The combination of thinning and underburning increased the torching index and crowning index more than thinning alone because it reduced surface fuels and also decreased CBD and increased CBH.

Forest structure and fire damage

Crown damage to overstory trees in the Biscuit fire was extensive despite low crown fire potential and the absence of crown fire at this site during the Biscuit fire. Crown fire is

Table 8. Logistic models and prediction errors for the probability of mortality of Douglas-fir with DBH >10 cm (n = 244 trees).

								$P_m = 0.6$		$P_m = 0.5$		$P_m = 0.4$	
Model	b_o	DBH	CS	NDEAD	TRT	PDE	p (χ^2)	Total errors	Net errors	Total errors	Net errors	Total errors	Net errors
1	–2.576		0.050			44.3	0.99	31	15	31	15	32	16
2	0.227	–0.082	0.053			54.2	0.99	24	4	27	11	29	13
3	–3.977		0.055	1.323		56.9	0.99	21	9	22	12	25	19
4	–1.540	–0.079	0.062	1.348		64.1	0.99	16	6	18	12	18	12
5	–0.331	–0.115	0.055	1.336	3.539	70.3	0.99	—	—	—	—	—	—

Note: Probability of mortality: $P_m = 1 / [1 + \exp(-b_0 - b_1x_1 - \ldots - b_ix_i)]$. CS, crown scorch volume; NDEAD, number of dead cambium samples; TRT, teatment; PDE, percentage of deviance explained. Large p values indicate sufficient model fit.

not a prerequisite for high fire severity, because crown scorch from high-intensity surface fires can also cause tree damage and mortality (Ryan et al. 1988). Evaluating fuel treatments based only on potential fire behavior may not adequately reflect treatment effects on fire severity parameters such as crown scorch and related mortality.

Fire damage (CS and CSHT) was greater in thinned treatments than in untreated stands and lowest in the thinned and underburned treatment, with differences being most extreme at Panther Lake. Two years postfire, the mortality of overstory Douglas-fir showed the same treatment effect, with 80%–100% mortality in thinned treatments, 53%–54% mortality in untreated stands, and 5% mortality in the thinned and underburned treatment. At Meadow Creek, damage to and mortality of trees did not differ significantly between the thinned and untreated treatments, perhaps because relatively steep slopes contributed to more uniform fire severity across the site, or because the small number of overstory trees in the thinned-only treatment decreased the power of the ANOVA.

The untreated stands had the highest within-treatment variability in fire damage. The fire heavily scorched some patches of trees, but left others undamaged, creating small-scale spatial variability in canopy structure and species composition in the untreated stands. Crown scorch of overstory trees ranged from 0% to 100% (compared with 65%–100% in thinned treatments), and patterns of individual-tree damage and mortality were more specific to tree species and size. Mortality was higher for knobcone pine than for Douglas-fir, and mortality of Douglas-fir decreased with increasing DBH. Mortality was high for subcanopy broad-leaved and conifer trees, but the broad-leaved trees sprouted following the fire.

The additional fine wood left from the thinning operation (despite whole-tree yarding) most likely caused higher surface fireline intensity, which contributed to greater scorch and mortality of overstory trees in the thinned treatments. Fine-wood loading was the only fuel-structure variable significantly correlated with crown scorch. The considerable damage to tree crowns and minor damage to cambial tissue suggest that most tree mortality was caused by a faster moving fire with high flame heights, fire behavior that would be expected in stands with abundant dry fine fuels. The Biscuit fire consumed a greater portion of the fine wood in thinned treatments than in untreated stands. The untreated and thinned treatments burned at roughly the same time (similar wind and fuel moisture conditions), so the increase in consumption of fine wood most likely contributed to greater fireline intensity, which caused more crown scorch (Van Wagner 1973). High temperatures for long durations could also contribute to greater crown scorch, but the low abundance and consumption of coarse fuels relative to fine fuels in these sites suggests that crown scorch was more a function of high fireline intensity from the relatively fast consumption of fine fuels.

The importance of fine-wood loading as a control over surface fire spread is shown by the fire behavior in the thinned and underburned treatment during the Biscuit fire. The Biscuit fire spread to the edge of this treatment but not into the treatment. The underburn reduced fine-wood loading to below the prethinning levels, thereby eliminating much of the fine fuels on which surface fire spread depends. After the underburn most of the remaining surface fuels were in the 1000+ h size class, and these larger fuels generally do not contribute to the spread of surface fires (Rothermel 1991). The effects of underburns have been shown to decrease with time since treatment (Kilgore and Sando 1975), so the effectiveness of this treatment may be due to the short time interval between the underburn and the Biscuit fire (only 1 year).

Microclimatic changes that are a consequence of thinning may have also contributed to higher fireline intensity in the thinned treatments; however, the lack of fire in the thinned and underburned treatment suggests that fine-wood loading was a more important control over spread and intensity. Previous studies have shown that stands with low tree density may have higher wind speeds and temperatures and lower relative humidity (Scott 1998). In some cases this could increase fireline intensity indirectly by reducing fuel moisture and directly if higher wind speeds and temperatures accelerate fire spread (Weatherspoon 1996). In our study a greater percentage of fine wood was consumed in the thinned treatments than in the unthinned stands, suggesting that fine-fuel moisture may have been lower in the thinned treatments. Although given the stabilization of fine-fuel moisture during the fire season, higher wind speeds and temperatures under the opened canopy likely affect fire behavior more, but this was not measured directly.

The low-growing vegetation, litter, and ground fuels were not quantified for this study, and these fuels also contribute to biomass consumption and affect fireline intensity. The subcanopy broad-leaved trees sprouted after the thinning treatment and grew to a dense layer of woody vegetation during the 5 years between the thinning and the Biscuit fire. This woody vegetation was consumed during the Biscuit fire, but this consumption could not be quantified because the new growth was not measured after the thinning and before the fire. An estimate of the woody biomass based on a shrub fuel model was included in the custom surface fuel models used for fire behavior predictions to account for these fuels.

Foliar moisture

The comparison of foliar moisture content in subcanopy Douglas-fir and tanoak trees does not indicate that tanoak has higher foliar moisture content than Douglas-fir. Foliar moisture content may affect crown fire initiation (Van Wagner 1977) and crown scorch (Van Wagner 1973), but our results suggest that fine-wood loading was a more important control over fire damage and mortality than foliar moisture content. Foliar moisture of 1-year-old foliage and small branches in late August was not different between tanoak and Douglas-fir, and old foliage of tanoak was drier than that of Douglas-fir. Van Wagner's models for crown fire initiation and height of crown scorch are based on conifer species, and therefore more information is needed on how subcanopy evergreen broad-leaved species may affect vertical fire propagation to and crown scorch of the upper canopy.

Predicting postfire mortality

Crown scorch volume was the most important variable for predicting mortality of Douglas-fir trees following the Biscuit fire in these sites. The predictive ability of a model with crown scorch volume can be slightly improved by adding DBH or the number of dead cambium samples. Crown scorch height and crown scorch volume are correlated, so if mortality is a primary interest in postfire sampling, effort can be saved by measuring only crown scorch volume. These models are applicable to Douglas-fir with DBH from 10 to 60 cm and crown scorch from 0% to 100%.

Our results corroborate previous studies that indicate crown scorch volume is a better predictor of mortality than crown scorch height (Peterson 1985; Peterson and Arbaugh 1986; Ryan et al. 1988). Our results differ from those of Ryan et al. (1988), who found the number of dead cambium samples to be the most important predictor of Douglas-fir mortality. This discrepancy may be explained by the fact that our study included more trees with extensive crown scorch and fewer trees with extensive cambial damage, and that most trees with any cambial damage also had extensive crown scorch. Also our models were developed following a wildfire rather than a prescribed fire. Crown damage may be a better indicator of tree mortality than cambial damage under wildfire conditions, but the opposite may be true for prescribed fires, which have high residence time.

Management implications

Applying fuel reduction treatments simultaneously to multiple fuels strata is the most effective approach to reducing fire severity. Fire hazard treatments intended to decrease tree mortality should reduce surface fire intensity, as well as crown fire potential, in order to minimize mortality from crown scorch.

This is a retrospective and opportunistic study, as is often the case for wildfire research, so we had limited control over experimental design. Nonetheless, studying wildfires provides critical information that can be difficult to obtain from experimental burns because wildfires typically occur under more extreme conditions (van Mantgem et al. 2001). Treatments were not replicated elsewhere in the Biscuit fire or other wildfires, so inferences are limited and the biogeographical scope is restricted to the mixed-evergreen forest of southwestern Oregon with moderate slopes. This study has several advantages compared with most opportunistic wildfire studies because we use sites that were established for a planned ecological experiment before the wildfire. Thinned and untreated areas were selected to be similar prior to treatment, treatments were randomly assigned, and we use data that were collected before the fire for prefire and postfire comparisons. However, the prefire data were not collected for the purpose of studying fuel structure and fire effects, so we supplemented the prefire data with additional data from sites that did not burn in the Biscuit fire and made some assumptions in calculating CBD, CBH, and surface fuel loading to evaluate changes in fuel structure and predict fire behavior for prefire stand conditions. These assumptions, especially those regarding fuel moistures from off site, may introduce additional error in the prefire data and fire behavior modeling.

Comparing fire severity at the scale of a few hectares is informative for evaluating the relative effects of three management options (no action, thinning, and thinning followed by burning) on fuels and fire severity at small scales. However, further inference is limited by the small spatial scale of this study relative to the spatial scale of the disturbance being studied (Lertzman and Fall 1998). The Biscuit fire burned a large area, creating a mosaic of low, moderate, and high fire severity patches (Parsons and Orlemann 2002; Harma and Morrison 2003), and when the study area is evaluated in the context of the larger fire, then each treatment is simply one patch within this mosaic. At this scale, factors in addition to forest structure, such as topography, weather, and climate, may control the size and relative abundance of patches within the burn mosaic.

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Appendix A. Linear regression equations for total height and crown base height.

The equation for predicting total height (m) as a function of ln(DBH) for trees with DBH >7 cm (n = 972) is

$$\text{[A1]} \quad \text{total height} = -25.07 + 14.40 \ln(\text{DBH})$$

DBH is significant ($p < 0.001$) and $R^2 = 0.83$.

The equation for total height (m) as a function of ln(DBH) for trees with DBH ≤7 cm (n = 93) is

$$\text{[A2]} \quad \text{total height} = -1.74 + 3.77 \ln(\text{DBH})$$

DBH is significant ($p < 0.001$) and $R^2 = 0.30$. The natural log transformation was used for both equations to linearize the data.

The equation for predicting crown base height (m) as a function of total height (m) for trees sampled prior to thinning (n = 1047) is

$$\text{[A3]} \quad \sqrt{\text{crown base height} + 1} = 1.15 + 0.16\,(\text{total height}) - 0.002\,(\text{total height}^2)$$

Total height and total height squared are significant ($p < 0.001$) and $R^2 = 0.78$.

The equation for predicting crown base height (m) as a function of total height (m) for trees sampled after thinning (n = 74) is

$$\text{[A4]} \quad \sqrt{\text{crown base height} + 1} = 1.00 + 0.17\,(\text{total height}) - 0.002\,(\text{total height}^2)$$

Total height and total height squared are significant ($p < 0.001$) and $R^2 = 0.89$. Use of the quadratic function requires that predictions be limited to the maximum height used to generate the model, total height = 43 m. Only measured values of total height were used to generate the equations that predict crown base height as a function of total height, but fitted values of total height were then used in the equations to obtained fitted values for crown base height. Although this introduces additional error, the error is minimal because the confidence bands ($\alpha = 0.05$) for the predicted values of the total height equations (eqs. A1 and A2 above) were narrow.

Appendix B. Woody debris fuel moisture assumptions and size-class proportions.

The postthinning fine-wood sampling in the three Panther Lake treatments was measured between 27 July and 7 August 1999. The moisture content of fine fuels (<7.6 cm) likely stabilizes during midsummer in southwestern Oregon given the lack of summer precipitation and variability in daily temperature and relative humidity. Archived 100 h fuel moisture data for the area show that moisture levels ranged from 6% to 15% based on dry mass between 27 July and 7 August of 2000 through 2003 (National Fire Danger Rating System, available online www.fs.fed.us/land/wfas/wfas10.html). Data for 1999 are unavailable, but given the consistency of fuel moistures for the subsequent 4 years, we assumed the range of 6% to 15% to be appropriate for 1999. The changes in fuel loading associated with this range of moistures only minimally affect the magnitude of results, so the middle value of 10% was used to calculate the dry masses of fine wood for postthinning samples at Panther Lake (Table B1).

Proportions of fine wood by size class were calculated so that fine-wood samples that combined all wood between 1.0 and 10.0 cm could be divided into time-lag size classes for fire behavior simulations and surface fuel analysis (Table B2). Size-class proportions were calculated separately for thinned and untreated plots and used to subdivide the postthinning fine-wood samples collected in thinned and untreated plots that burned during the Biscuit fire.

Additional samples of fine wood <2.5 cm were taken in unburned LTEP plots and divided into three size classes: 0.0–0.6, 0.6–1.0, and 1.0–2.5 cm. Loading in each of the two smaller size classes was calculated as a proportion of loading in the 1.0–2.5 cm size class for thinned and untreated plots, and these relationships were then used to account for loading in the smaller two size classes for samples taken in the postthinning inventory. For thinned plots loading of the 0.0–0.6 cm size class was 40% of that of the 1.0–2.5 cm size class, and loading of the 0.6–1.0 cm size class was 26% of that of the 1.0–2.5 cm size class, and for untreated plots, loading of the 0.0–0.6 cm size class was 44% of that of the 1.0–2.5 cm size class, and loading of the 0.6–1.0 cm size class was 45% of that of the 1.0–2.5 cm size class.

Appendix continues on the following page.

Table B1. Means and standard deviations of fine-wood loading for a range of fuel moisture.

	Fine-wood loading ($Mg\cdot ha^{-1}$)				
Treatment	Prethinning	Postthinning (6% FM)	Postthinning (10% FM)	Postthinning (15% FM)	Post-Biscuit fire
Untreated	18.4 (6.1)	30.8 (18.6)	29.7 (18.0)	28.4 (17.2)	3.6 (5.3)
Thinned	21.6 (7.7)	38.2 (17.1)	36.8 (16.5)	35.3 (15.8)	1.7 (4.3)
Thinned (high CWD)*	18.0 (5.4)	46.7 (27.4)	45.0 (26.4)	43.1 (25.3)	0.1 (0.2)

Note: FM, fuel moisture.
*Additional coarse woody debris was left after thinning.

Table B2. Proportions of fine-wood samples by size class from unburned sites used to subdivide samples from the postthinning inventory.

Treatment	Partial 10 h (0.6–2.5 cm)	100 h (2.5–7.6 cm)	1000 h (7.6–10 cm)
Untreated	0.58	0.39	0.03
Thinned	0.38	0.5	0.12