The Effects of Fuel Treatments on Fire Severity in a Mixed-Evergreen Forest of Southwestern Oregon

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

University of Washington
2004

Program Authorized to Offer Degree:
College of Forest Resources

University of Washington
Graduate School

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Abstract

The Effects of Fuel Treatments on Fire Severity in a Mixed-Evergreen Forest of Southwestern Oregon

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Fuel treatments are now mandated by federal policy to reduce hazardous fuels on federal forest lands. More information is needed on the effectiveness of fuel treatments, especially in mixed-severity fire regimes. In this study I had the rare opportunity to quantify the relationship between fuel structure and fire severity using pre-fire surface and canopy fuels data and fire severity data after an intense wildfire. The study area is in a mixed-severity fire regime, the mixed-evergreen forest of southwestern Oregon. Thinning reduced canopy fuels, decreasing the potential for crown fire spread, but the presence of activity fuels increased potential surface fire intensity, so increases in canopy base height did not decrease the potential for crown fire initiation. Thinning followed by under-burning reduced canopy fuels and surface fuels, thereby decreasing both crown fire spread potential and the potential for crown fire initiation. However, crown fire is not a prerequisite for high fire severity; damage and mortality of overstory trees in the wildfire was extensive despite the absence of crown fire, and the low predicted crown fire potential before and after the fuel treatment. Damage to and mortality of overstory trees were most severe in thinned treatments (80 – 100% mortality), least severe in the thinned and under-burned treatment (5% mortality), and moderate in untreated stands (53-54% mortality) following a wildfire in 2002. Fine fuel loading was the only fuel structure variable significantly correlated with crown scorch of overstory trees. Percentage crown scorch was the best predictor of mortality 2 years post-fire. Efforts to reduce canopy fuels through thinning treatments may be rendered ineffective if not accompanied by adequate reduction in surface fuels.

Table of Contents

List of Figures

List of Tables

Acknowledgements

First, I thank my advisor, David Peterson, for his patience and advice throughout the process and especially for teaching me to be a better writer. I appreciate the efforts of my committee members, Jim Agee and Don McKenzie, whose careful and insightful reviews of this thesis were essential in improving the final product.

This project could not have been completed, or even started, without the funding and support of Roger Ottmar of the Fire and Environmental Applications Team at the USFS PNW Research Station in Seattle who was instrumental in getting me to graduate school. I owe special thanks to Bernard Bormann and Robyn Darbyshire of the Long-term Ecosystem Productivity project for being generous with their research sites, data and time.

Many graduate students in Winkenwerder Hall and employees of the Pacific Wildland Fire Sciences Lab helped me along the way; I greatly appreciate their support and friendship. To all those who accompanied me in the field, this research was possible because you were willing to work in the blazing southern Oregon sun with ash on your faces.

Lastly, I thank my parents for giving me a great appreciation for education that has enabled me to get where I am, and will, no doubt, inspire my future career decisions.

Introduction

United States federal policies, including the Healthy Forest Restoration Act of 2003 (HR 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 wildland fires such as the 2002 Biscuit Fire in southwestern Oregon have had detrimental impacts on forest resources, as well as threatened lives and 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. 2004). A central question of this effort is where and how should forest fuels be treated in order to effectively reduce fire hazard?

Fire hazard reduction treatments (fuel treatments) alter the fuel structures involved in fire dynamics. Fuel treatments include prescribed fire, manual and mechanical thinning of trees, or a combination of the two. The goals of these treatments are typically to reduce fire hazard, decrease the severity of fire effects, and increase opportunities for successful fire suppression.

The theoretical basis for changing fuel structure to reduce fire hazard is well established (Agee 1996; Scott and Reinhardt 2001; Graham et al. 2004; Peterson et al. 2004). Forest fuels occupy six strata (canopy, shrub, low vegetation, woody fuel, litter and ground) (Sandberg et al. 2001) and each stratum is involved in different types of wildland fire (surface fire, passive or active crown fire) (VanWagner 1993). Surface fire intensity is a function of surface fuel abundance, fuel moisture and rate of spread (Rothermel 1972). Decreasing surface fuels can reduce surface fireline intensity. Passive crown fire, or the transition from surface fire to crown fire, is a function of surface fire intensity, canopy base height and canopy foliar moisture. Decreasing surface fuels and vertical continuity between fuel strata can inhibit crown fire initiation. Active crown fire is a function of canopy foliar moisture, bulk density of canopy fuels and rate of spread

(Van Wagner 1977). Reducing the abundance and altering the horizontal arrangement of canopy fuels can modify crown fire spread.

Current scientific research on prescribed fires supports the ability of these treatments to effectively reduce surface fire hazard. Prescribed fire alone has been shown to effectively reduce surface fuel loading (Kauffman and Martin 1988), fire behavior (Helms 1979; Buckley 1992), and fire severity (Fulé et al. 2004) in some forests. Prescribed fire treatments generally reduce only surface fuels, but can also reduce canopy fuels if sufficient sub-canopy vegetation is removed (Kilgore and Sando 1975; Fulé et al. 2004). A combination of thinning and prescribed burning 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, prescribed burning can have unintended effects on future fire behavior and severity if overstory trees are killed, thereby increasing woody surface fuels (Peterson et al. 2004). Prescribed burning may not be a management option in some places because it may pose problems for air quality (Conard et al. 2001).

Thinning treatments alone can reduce crown fire hazard by decreasing fuels in the canopy stratum and reducing the vertical and horizontal continuity of canopy fuels. The thinning treatments will be most effective if the residual stand includes larger more fire resistant trees (Agee 1996; Graham et al. 1999) and activity fuels are subsequently removed (Alexander and Yancik 1977; Stephens 1998). However, forest stands with lower tree density may have higher surface wind-speeds and temperatures and lower relative humidity (Scott 1998). In some cases this could increase fire intensity indirectly by reducing fuel moisture and directly if higher wind-speeds and temperatures accelerate fire spread (Weatherspoon 1996).

Fuel treatments have been evaluated by using simulation models to predict potential fire behavior and severity in treated forest stands (Stephens 1998; Scott 1998; Fulé et al. 2001; Brose and Wade 2002). These modeling studies are an important tool for evaluating the relative effectiveness of different types of treatments and degrees of thinning. However, most fire behavior models are based on little empirical data from specific geographical regions, require many assumptions, and use standard fuel descriptions (Anderson 1982) that may not have adequate resolution to quantify the changes in fuel structure following fuel treatments. These models also have a limited ability to predict differences in fire severity between treatments under actual wildfire conditions (Fulé et al. 2001).

More empirical data are needed on the effectiveness of fuel treatments to reduce fire behavior and severity in wildfires, even though the limitations associated with opportunistically studying wildfires often preclude a rigorous experimental design. Empirical studies of wildfires often require researchers to reconstruct pre-fire fuel structures, and this can be done only for canopy fuels, not surface fuels (Omi and Kalabokidis 1991; Pollet and Omi 2002). Surface and canopy fuels are highly variable, and without knowledge of the pre-fire fuel conditions and treatment modifications, it is more difficult to relate fire severity to treatment effects. Long time lapses between the fire and post-fire field sampling can make it more difficult to assess fire severity. Any research on wildfires is inherently retrospective, but it can provide essential information on fuel treatment effectiveness under wildfire conditions (Fulé et al. 2004).

The effectiveness of fuel treatments varies for forest types, depending on whether fuels are the primary control of fire behavior (Schoennagel et al. 2004). Most studies on fuel treatments have been conducted in arid and semi-arid forests, e.g. ponderosa pine (*Pinus ponderosa* P.C. Lawson) forests in the American Southwest and mixed conifer forests in California. Prior to fire exclusion, these forests experienced low-severity (high-frequency) fire regimes in which surface fires consumed low vegetation and woody fuels, preventing the development of a sub-canopy layer, and leaving larger fire resistant trees (Fulé et al. 1997; Allen et al. 2002). Fuel accumulations caused by fire exclusion in these forests have increased fire hazard and caused more high-severity fires (Agee 1993). Fuel treatments can be effective in these forests because fuel structures strongly influence fire behavior. Fuel treatments are less effective in high-severity (low-frequency) fire regimes, e.g. subalpine forests, where weather rather than fuels is the primary control over fire behavior (Fryer and Johnson 1988, Bessie and Johnson 1995, Schoennagel et al. 2004).

There is little information on the effectiveness of fuel treatments in mixed-severity fire regimes, for which the relative importance of factors that control fire behavior (fuels, weather, topography) are less understood (Raymond and Peterson 2004).

Forests with mixed-severity fire regimes have the greatest range of natural variability for both fire frequency and severity (Agee 1993). With the exception of Weatherspoon and Skinner's (1995) analysis of remotely sensed fire severity data following 1987 fires in northern California, few studies have evaluated the role of forest structure in controlling fire severity and frequency in mixed-severity fire regimes. It is difficult to determine if a century of fire exclusion has increased fuels sufficiently enough to affect fire hazard given the variability typical of these fire regimes.

In this study, I quantify the effects of fuel treatments on fire severity in a mixed-severity fire regime, the mixed-evergreen forests of southwestern Oregon, following a large wildfire in 2002 (the Biscuit Fire). Abundant pre-fire fuels data for surface wood and canopy fuels provided a rare opportunity to directly quantify the relationship between fuel structure and fire severity. Study sites were established and sampled before the fuel treatments and before the wildfire in both treated and untreated stands. Post-fire sampling of fire severity was completed one year after the fire and is supplemented with immediate post-fire observations. I have the unusual combination of data on pre-fire fuel structure and actual, rather than potential, fire severity, so I am able to avoid some complications associated with reconstructing pre-fire fuel conditions or simulating potential fire effects.

I used a three-step process to quantify the effectiveness of fuel treatments in reducing fire severity in a forest stand that burned during the Biscuit Fire. First, I determined if two fuel treatments (thinning and thinning followed by under-burning) reduced fire hazard based on simulated potential fire behavior under extreme weather conditions. Second, I compared damage to and mortality of overstory trees in treated and untreated forests following a wildfire. Lastly, I explored the mechanisms that may explain treatment differences in fire severity by comparing foliar moisture of sub-canopy tree species and quantifying the changes in fuel structure components (canopy bulk density, canopy base height, woody surface fuels, and tree density).

Methods

Site Description

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 soils of Typic Hapludults and Typic Dystrochrepts.

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.). Beneath the overstory is a sub-canopy tree layer 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.). The sub-canopy layer also includes some smaller Douglas-fir. The stand established after a stand-replacing fire in 1881; tree age ranges from 80 to 110 years (Little et al. 1995), and the only management conducted in the stand prior to the establishment of these experimental treatments was fire suppression.

Fire regimes vary throughout the range where Douglas-fir is dominant. The mixed-evergreen forests at the southern end of the Oregon Coast Range are classified as a mixed-severity fire regime (Agee 1993). Fire frequency varies along a gradient from the coast to drier inland forests. Fire frequencies are 90 to 150 years on the western side of the Coast Range and as low as 50 years for the inland portion (Agee 1991). Located 20 km from the Pacific Coast, this study area is likely more typical of fire frequencies on the western side. Lightning ignitions are frequent throughout the fire season, so this system is not ignition limited (Agee 1991).

Lightning ignited several small fires in southwestern Oregon on July 12, 2002; these fires eventually burned together to become the Biscuit Fire. The fire burned 202,000 hectares until it was finally extinguished by rain on November 8, 2002. It is the largest wildfire in Oregon recorded history and one of the largest ever on national forest land. It burned primarily on the Siskiyou National Forest including nearly all the Kalmiopsis Wilderness Area (Figure 1). The Siskiyou National Forest has experienced three other extreme fire seasons since its establishment (72,500 ha burned in 1917, 61,500 ha burned in 1918, and 74,000 ha burned in 1987) (Atzet et al. 1988) but the extent of the Biscuit Fire is more than double the total area burned in any previous recorded year. Observations of fire behavior indicate that at times fire spread was driven by dry east winds and burned as an intense crown fire with rates of spread up to 2.4 km hr^{-1} (www.biscuitfire.com). Landsat Thematic Mapper 7 satellite imagery of vegetation in the Biscuit Fire area shows that 45% of the area was unburned or had low vegetation mortality, 25% moderate and 31% severe immediately after the fire (Harma and Morrison 2003).

The study area includes two sites located in the Siskiyou National Forest at the western perimeter of the Biscuit Fire (Figure 1). Meadow Creek was established in 1995 as a research study to assess the effects of thinning and under-burning on forest structure. Panther Lake was established as part of the Long-Term Ecosystem Productivity (LTEP) study. Scientists from the USDA Forest Service Pacific Northwest Research Station started the LTEP study in 1992 to assess the effects of plant community composition and coarse woody debris on the processes that affect forest ecosystem productivity. Meadow Creek has a slope range from 20% to 35%, elevation range from 670 m to 850 m and a northwest aspect (Table 1). Panther Lake has slopes ranging from 10% to 25%, with higher elevation ranging from 820 m to 1030 m, and has a southwest aspect (Table 1).

The two sites burned in the Biscuit Fire on August 16, 2002, over one month after the fire began. Fire suppression activities that could have impeded fire spread or behavior did not occur in the vicinity of the sites. Observations of fire behavior and immediate post-fire effects indicate that both sites burned with a surface fire; tree crowns still contained red and green needles and showed no evidence of crown fire. Wind-speeds and relative humidity at the time the sites burned were less extreme than the days when the Biscuit Fire burned large areas; however, seasonal soil and fuel moisture in the study area were extremely low. On August 16, 2002 the closest Remote Automated Weather Station (RAWS) (42.1° N, 124.2° W) recorded a daily high temperature of 26°C, relative humidity low of 8%, 10 hr fuel moisture of 4% and average wind-speed of 4 km hr^{-1} out of the northwest (archived data at www.fs.fed.us/land/wfas.html). The local Keetch Byram Drought Index (KBDI) was 663 (archived data at www.fs.fed.us/land/wfas.html). KBDI is a measure of soil moisture deficiency on a scale of 0 to 800; the range from 600 to 800 indicates severe drought. The energy release component (ERC), a measure of seasonal fuel moisture conditions, was 69 (archived data at www.fs.fed.us/land/wfas.html). An ERC value above 60 indicates the potential for severe fire behavior.

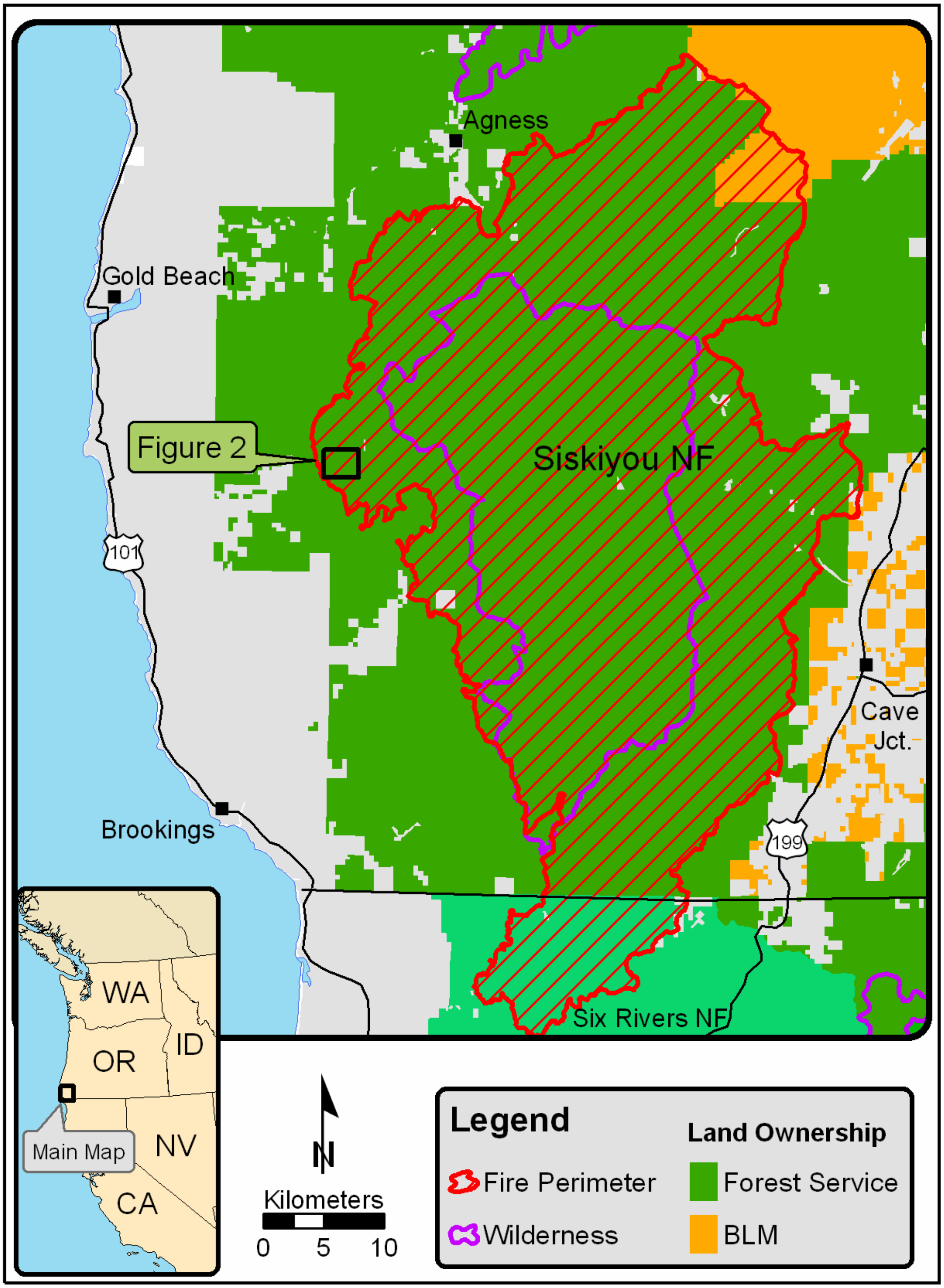

Fig 1. Location of study area and the Biscuit Fire in southwestern Oregon, USA.

Table 1. Summary of site characteristics

	Site	
	Meadow Creek	Panther Lake
Elevation (m)	670 – 850	820 – 1030
Slope (%)	20 – 35	10 – 25
Aspect	Northwest	Southwest
Treatment Plots	1 Untreated 1 Thinned 1 Thinned and under-burned	1 Untreated 1 Thinned 1 Thinned with high coarse woody debris

Treatments

Meadow Creek contains 3 treatment plots (6-8 hectares each): 1 untreated, 1 thinned, and 1 thinned and under-burned (Figure 2). Panther Lake contains 3 treatment plots (6-8 hectares each): 1 untreated, 1 thinned, and 1 thinned with additional coarse woody debris (CWD) left after the thinning operation (Figure 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 with the last log except in the treatment that was subsequently under-burned; in this treatment all crown material was left on site. For the treatment with CWD, 15% of the harvested logs were left on site.

The thinning in both sites was a combination of a thinning from below and a crown thinning (Graham et al. 1999); suppressed, intermediate and a portion of codominant crown classes were removed, and leave trees were marked to control the composition and structure of the remaining stand. Douglas-fir was thinned to a relative density (proportion of standard volume for a given stand age and site quality) (Husch et al. 1982) of 0.25. Only dominant and codominant Douglas-fir trees with the best form were selected for retention. Evergreen broad-leaved species were thinned to 8 m spacing independent of remaining conifers, and the largest diameter and healthiest trees were selected for retention. Snags, conifers other than Douglas-fir, and remnant trees that survived the last known fire in 1881 fire were not harvested.

The thinned and under-burned treatment was burned in fall 2001**,** one year before the Biscuit Fire with a light surface fire and no torching or crown fire. This treatment is within the Biscuit Fire perimeter, and the Biscuit Fire burned all around it, but did not spread into the treatment (Figure 3). This is assumed to be due to conditions within the treatment, not due to a lack of ignition source, changes in weather, or physical barriers.

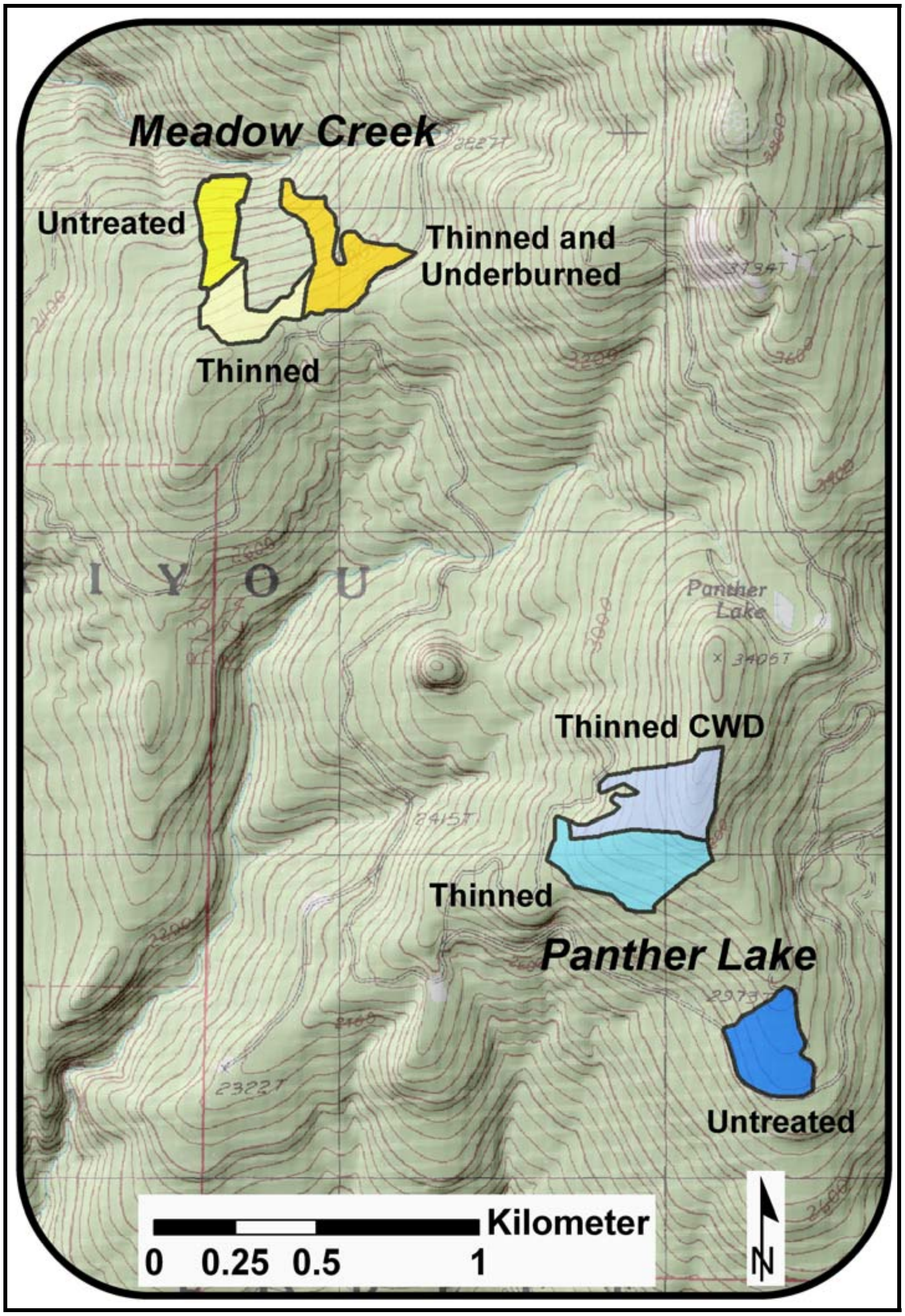

FIG. 2. Location of treatments in the Meadow Creek and Panther Lake sites.

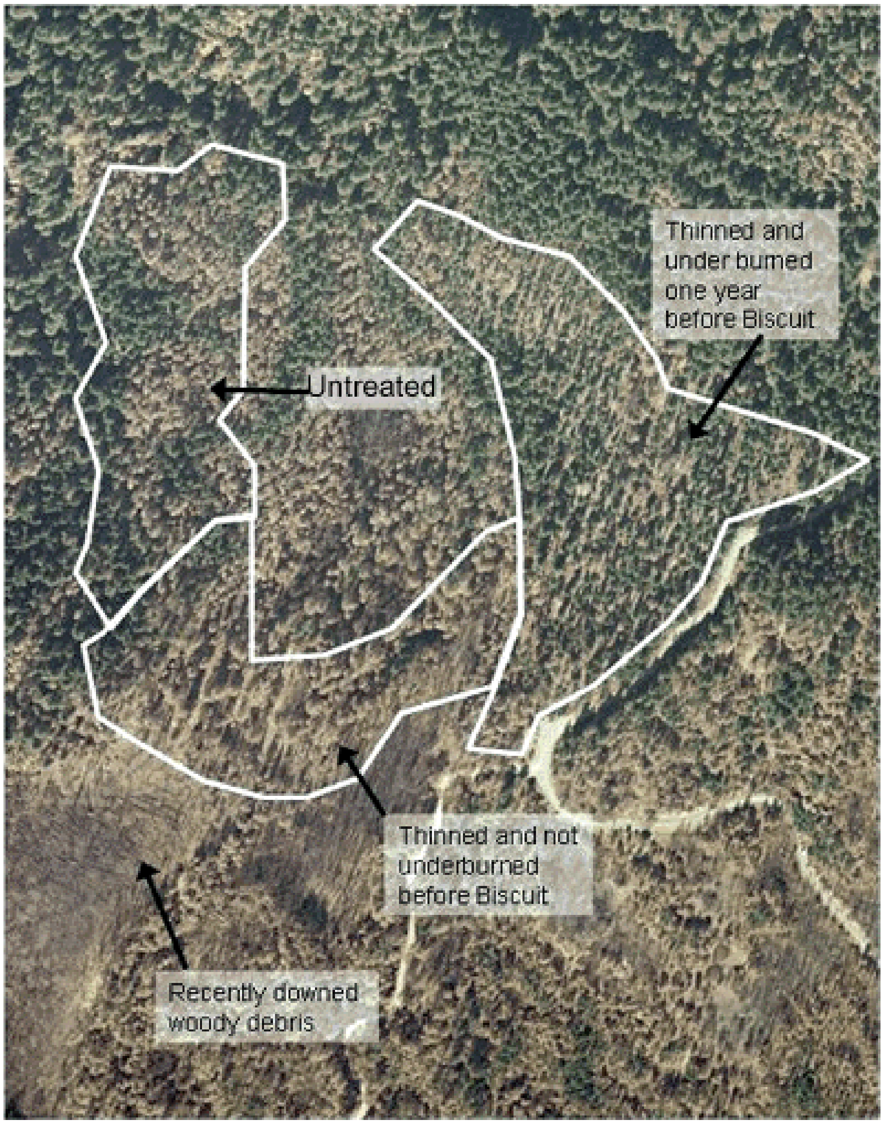

Fig. 3. High resolution (1:12000) aerial photo of treatment plots in Meadow Creek (Taken several months after the fire).

Field Sampling

A grid-point system (either 4 x 4 or 3 x 5) with 25 m spacing was permanently established within each treatment, and all fine wood plots, overstory tree plots and woody line transects were located at randomly selected distances and azimuths from the grid points (Appendix A). Surface fuels and overstory structure and composition were sampled three times: prior to thinning, after thinning and after the Biscuit Fire. The thinned and under-burned treatment at Meadow Creek was sampled between the thinning and under-burning treatment, but no additional sampling was done between the under-burn and the Biscuit Fire. The Biscuit Fire spread only to the edge of the treatment, so the field sampling conducted after the Biscuit Fire is considered representative of conditions after the under-burn.

Surface Fuels

Fine woody debris (defined by time-lag class where 1-hr fuels are 0.0 cm – 0.6 cm, 10-hr fuels are 0.6 cm – 2.5 cm and 100-hr fuels are 2.5 cm – 7.6 cm in diameter) was sampled before treatment, 1 to 3 years after treatment and 1 year after the Biscuit Fire. Before the thinning 1-hr, 10-hr and 100-hr fuels were sampled using the planar transect method (Brown et al 1982), with 8 or 10 transects per treatment; 1-hr and 10-hr fuels were measured along 2-m transects and 100-hr fuels were measured along 3-m transects. After the thinning treatment, all fine fuels between 1.0 cm and 10.0 cm were collected in 16 1-m^2 clip-plots, oven dried and weighed. A wet weight was measured in the field and a representative sub-sample was collected if the entire field sample was too large to be collected. The sub-sample was dried and weighed, and its moisture content was subtracted from the full field weight in order to get a dry weight. After the Biscuit fire, fine wood was again sampled in 16 1-m^2 clip-plots, but all wood was collected and separated into three size classes (1.0 – 2.5 cm, 2.5 – 7.6 cm and 7.6 – 10.0 cm) so loading by time-lag size class could be computed.

Coarse woody debris (defined as the 1000+ hr 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

1982). Before the treatment all 1000+ hr fuels were sampled along 8 or 10, 8-m transects. The diameter of each log was measured, and logs were categorized as sound or rotten. After the treatment and after the Biscuit Fire, the transect length for 1000+ hr fuels was extended to 25 m.

Forest Structure and Composition

All trees greater than 3.5 cm dbh (diameter at 1.37 m above the ground) were measured in five 18 x 18 m square plots before the thinning, after the thinning and after the Biscuit Fire. For each inventory year dbh, species and crown class (dominant, codominant, intermediate and suppressed) were measured for all trees in the tree plots. Total tree height and height to crown base were measured for a representative subset of trees (2 trees per crown class per plot) before and after the thinning, but after the Biscuit Fire the total height and crown base height of all trees were recorded. Following the thinning treatment, trees were marked with aluminum tags and the location of each tree was mapped, which enabled relocation of the trees after the Biscuit Fire.

Foliar Moisture

Foliar moisture samples were collected from understory tanoak and Douglas-fir trees in nearby LTEP sites that did not burn in the Biscuit Fire. Ten samples of new foliage, 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 14.00 h and 17.00 h. Samples were sealed in plastic bags, weighed wet, and then dried at 70º C for 48 hours (Agee et al. 2002). Douglas-fir samples were approximately 25 g, and tanoak samples were approximately 45 g.

Fire Severity

Fire severity is defined as the effect of fire on vegetation and for trees is usually reported in terms of mortality (Agee 1993). For this study I used two measures of fire severity: tree damage measured one year post-fire and mortality recorded two years post-fire. Fire damage was measured for all trees in the five 18 x 18 m square tree plots in

August 2003. The same trees were revisited in August 2004 and classified as dead or alive based on the absence or presence of green foliage.

Percentage crown scorch was measured as an ocular estimate of the percentage of pre-fire crown volume scorched (Peterson and Arbaugh 1986). Sampling was conducted one year post-fire 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. The height of crown scorch (m) was measured to the top of the highest branch scorched, and the height of bole char (m) was measured to the highest point of charred bark (Peterson 1985). Weekly calibration among crew members was conducted to ensure consistency among volume estimates and identification of scorched branches and bole char.

All trees were classified into a burn severity class on a scale of 1 to 5. The classes were an adaptation from the National Park Service Fire Monitoring Handbook (USDI NPS 2003). The NPS burn severity classes are broad and intended for a wide range of fire severities, so they were adjusted to accommodate the smaller range of variability in these sites (Table 2).

Table 2. Burn severity classes as adapted from USDI-NPS (2003).

Class	Description	Definition
1	Unburned	No bole char or crown scorch
2	Bole char only	Bole char present but no crown scorch
3	Mild crown scorch	Bole char and crown scorch of needles but some green needles still present
4	Severe crown scorch	All needles and fine branches completely scorched but no crown consumption
5	Crown consumption	Needles and fine branches consumed leaving only large branches.

Trees in the tree plots with dbh > 10 cm were assessed for the condition of the cambium at 0.5 m above the ground (Peterson and Arbaugh 1989). A sample of the cambium was extracted with an increment hammer from four points around the bole:

uphill, downhill, and both side slopes. The sample was a 1-2 cm core that included the bark and wood just inside the bark containing the cambial cells. Each sample was treated with a 1% solution of urea hydrogen peroxide and orthotolidine in methanol, which reacts with the enzyme peroxidase that is found in most living plant tissue (Hare 1965). The cambium was recorded as alive if it turned blue in reaction to the solution.

Data Analysis

Forest Structure and Composition

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 regression equations for Pacific Northwest conifers (Brown 1978; Snell and Anholt 1981) and hardwoods (Snell and Little 1983) as compiled in the Fuels Management Analyst™ program (Carlton 2001). Height and crown ratio are required input variables for the calculations, but total height and crown base height were not measured for all trees in the pre-thinning and post-thinning inventories, so I developed 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 B).

CBD is used in the prediction of crown fire spread and is a measure of the arrangement and amount of fuels in the canopy layer reported in metric units of kg m^{-3}. It is calculated for an entire stand rather than an individual tree. CBD is calculated using crown length, crown biomass, and stand density (Scott and Reinhardt 2001). Crown length is total tree height minus crown base height, stand density is the number of trees per hectare, and crown biomass is calculated from empirically derived species specific regression equations that predict crown biomass based on dbh. Crown biomass is then divided into foliage and time-lag size classes, but only the portion of biomass considered available for consumption is used in the CBD calculation (Scott and Reinhardt 2001). In a uniform stand CBD would be calculated as the available canopy biomass of an area divided by the mean crown length. However canopy fuels are not distributed uniformly throughout the depth of the canopy, especially in stands with multiple canopy layers, so in the Fire and Fuels Extension (FFE) to the Forest Vegetation Simulator (FVS), Reinhardt and Crookston (2003) calculated CBD by first dividing the canopy into 0.3 m horizontal sections, and for each section a running mean of canopy mass is taken using the seven sections above and the seven sections below. Then CBD is defined as the maximum of this 4.5 m running mean over the vertical length of the canopy.

CBH is a stand structure variable important for calculating crown fire initiation (Van Wagner 1977), and like CBD, it is calculated for an entire stand rather than an individual tree. CBH is defined as the height above ground at which a critical threshold of CBD is reached (Sando and Wick 1972). Crown base height for an individual tree is the height above ground at which the crown contains sufficient biomass to sustain vertical fire spread. However, the mean crown base height for all trees in a stand poorly represents the CBH of the stand as a whole, so the convention of using a critical level of CBD was adopted (Scott and Reinhardt 2001). Critical CBD thresholds used to calculate CBH are 0.011 kg m^{-3} (Reinhardt and Crookston 2003) or 0.037 kg m^{-3} (Sando and Wick 1972).

For this study, I calculated CBD and CBH using the methods employed by Reinhardt and Crookston 2003 in FFE-FVS. I defined available canopy biomass as foliage and 50% of the 0.0 cm to 0.6 cm branches (Scott and Reinhardt 2001) and further adjusted this available canopy biomass with a multiplier based on the crown class of each tree: 1.0 for dominant , 0.8 for co-dominant, 0.6 for intermediate and 0.4 for suppressed. I also calculated CBD for this study using the running mean to account for multiple canopy layers and the CBD threshold of 0.011 kg m^{-3} for calculating CBH.

Surface Fuels

Summary statistics were calculated for fine, sound coarse and rotten coarse wood loading for all treatment plots pre-thinning, post-thinning, and post-fire. Sampling methods varied between years, but results were adjusted to make transect and clip-plot data comparable by converting all data to fuel loading in Mg ha^{-1}.

The post-thinning fine wood samples presented difficulties for analysis, and some assumptions and additional data collection were required to reconstruct the pre-fire fine wood data by time-lag size class. First, only wet weights were available for some treatments in the post-thin sampling, so historical fuel moisture levels were used to convert wet weights to dry weights (Appendix C). Although this is not ideal it is probably of little consequence, because fine wood moisture content in southwestern Oregon stabilizes in late summer when temperatures are high and precipitation is absent.

Second, fine wood samples that had all wood between 1 cm and 10 cm combined in one sample were not conducive to analysis by time-lag size class, so additional data were collected to further sub-divide the samples. Additional fine wood samples were taken in thinned and untreated LTEP sites that did not burn in the Biscuit Fire. These samples were divided into three size classes (1.0 – 2.5 cm, 2.5 – 7.6 cm, and 7.6 – 10.0 cm), and the proportions of these size classes were applied to the post-thin fine wood samples from sites that burned in the Biscuit Fire (Appendix D). The portion of wood in the 7.6 – 10 cm size class was simply subtracted from the samples because all wood > 7.6 cm was accounted for on the woody line transects. Additional fine wood samples were also collected to quantify the lower end of the fuel size classes (0.0 – 0.6 cm, and 0.6 – 1.0 cm). Proportions of these size classes were calculated and related to the amount of 1.0 – 2.5 cm fuels in each sample (Appendix D). Pre-thin and post-fire samples were subdivided in the field, so this procedure was necessary only for the post-thin samples.

Potential Fire Behavior

I modeled potential fire behavior for all treatments prior to thinning and again for thinned treatments after the thinning. The output of this model is three related measures of potential fire behavior: (1) fire type (surface fire, conditional surface 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. The torching index (km hr^{-1}) is the wind-speed required to initiate crown fire, and the crowning index (km hr^{-1}) is the wind-speed required to sustain horizontal crown fire spread under specified fuel moisture conditions. I also calculated two related silvicultural parameters as indicators of fire hazard: target CBH and target CBD (Keyes and O’Hara 2002). Target CBH is the lowest canopy base height for which crown fire initiation is unlikely under specified wind and fuel moisture conditions. It is calculated as:

$$CBH_t = [FLI^{(1/1.5)}]/[(0.010)(460 + 26 * FMC)]$$

where *FLI* is the surface fireline intensity (KW m^{-1}) and *FMC* is the percent foliar moisture content based on dry weight. Target CBD is the highest CBD for which crown fire spread is resisted under specified wind and fuel moisture conditions. It is calculated as:

$$CBD_t = (3.0)/((3.34)(ROS_r))$$

where ROS_r (m min^{-1}) is the spread rate of a surface fire with fuel model 10 (Timber with litter and understory), a midflame wind-speed reduction factor of 0.4 and given wind-speed and fuel moisture conditions. Crown fire resistant stands will have a CBH that is above the target CBH and a CBD that is below the target CBD.

I modeled potential fire behavior 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). I customized fuel models for each treatment based on existing fuel models: 9 (Hardwood litter) and 10 (Timber with litter and understory) for the treatments prior to thinning and 11(Light logging slash) and 12 (Medium logging slash) for treatments after thinning (Anderson 1982) and empirically measured values for woody fuel loading (Appendix E). Mean values of fuel loading, CBH and CBD were used for all fire behavior calculations. Weather inputs for fire behavior predictions were the historical 98th percentile weather data for wind-speed and fuel moisture from the nearest RAWS station (archived data at www.fs.fed.us/land/wfas.html) (Appendix F), and slope inputs were the higher end of the slope range at each site (Meadow Creek = 35% and Panther Lake = 25%).

Foliar moisture

Foliar moisture as a percentage of dry weight was compared between tree species for each foliar component using a two-sample t-test with a two-tailed hypothesis ($\alpha = 0.05$) and the following null and alternative hypotheses:

H_0: Mean foliar moisture of Douglas-fir and tanoak are the same.

H_a: Mean foliar moisture of Douglas-fir and tanoak are *not* the same.

The objective of this test was to determine if higher foliar moisture content of sub-canopy tanoak trees may have a dampening effect on fire behavior, which would suggest that these trees have the opposite function of sub-canopy conifers which typically serve as ladder fuels aiding vertical fire spread.

Fire Severity

The objective of this study was to compare fire severity of overstory trees, so descriptive statistics of fire damage variables are reported only for trees with dbh > 24 cm. This diameter criterion was determined by comparing dbh distributions of thinned and untreated plots. Fire damage in treatments was then compared using trees as replicates. Burn severity class data were analyzed using a chi-square test ($\alpha = 0.05$) for homogeneity on 3 x 3 contingency tables (Zar 1999), with the following null and alternative hypotheses:

H_0: The proportion of trees in each burn severity class is the same for all treatments.

H_a: The proportion of trees in each burn severity class is *not* the same for all treatments.

Tree mortality was tested in the same way but with 3 x 2 contingency tables and the following null and alternative hypotheses:

H_0: The proportions of dead and live trees are the same for all treatments.

H_a: The proportions of dead and live trees are *not* the same for all treatments.

Contingency tables were compared separately for the two sites and further subdivided and tested again when significant differences were found between treatments (Zar 1999). The Yates correction for continuity was used whenever a subdivision created 2 x 2 contingency tables.

Continuous tree damage variables (bole char height, crown scorch height and percent crown scorch) were tested using one-way analysis of variance (ANOVA) ($\alpha =$

0.05). The two sites were tested separately, and multiple comparisons were made using the Tukey HSD test (Zar 1999) when significant differences were found. A block design was not used because the sites did not contain the same treatments. Residuals were examined to ensure statistical test assumptions were met, and percentage data were divided by 100 then transformed with the arcsin square-root transformation.

Finally, I used a logistic regression function of the form:

$$CS = 1 / (1 + \exp(b_0 + b_1 x_1))$$

where CS is the proportion crown scorch, the *b*'s are the regression coefficients and the *x*'s are the independent variable, to estimate proportion crown scorch as a function of fuel structure for each of the five 18 x 18 m square tree plots per treatment (n=30). The independent variables tested were fine wood loading, sound and rotten coarse wood loading, tree density, CBH and CBD. The significance of each independent variable was tested by comparing the reduction in deviance to a chi-square distribution with degrees of freedom equivalent to the reduction in degrees of freedom when the variable is added to the model ($\alpha = 0.05$). The hypotheses for this test are:

H_0: The independent variable and crown scorch are not correlated.

H_a: The independent variable and crown scorch are correlated.

A deviance test was used to test for satisfactory model fit ($\alpha = 0.05$) (Neter et al 1996). If the logistic model is a satisfactory fit, and the sample size is large, then the model deviance will approximately follow a chi-square distribution with degrees of freedom equal to the residual degrees of freedom from the model. The hypotheses for this one-tailed test are:

H_0: The logistic model is a satisfactory fit.

H_a: The logistic model is insufficient.

Therefore *large p-values* mean H_0 cannot be rejected, and the conclusion is 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, the same chi-square homogeneity test that was used for the burn severity class data was also used to test if the proportion of dead and live trees differed between treatments as described above. Second, the fire damage variables (percentage crown scorch, crown scorch height, and number of dead cambium samples) were used along with dbh to construct models that predict mortality for Douglas-fir trees (dbh ≥ 10 cm). I used a logistic multiple regression function of the form:

$$P_m = 1 / (1 + \exp (b_0 + b_1 x_1 + \ldots + b_i x_i))$$

where P_m is the probability of mortality, the b's are regression coefficients and the x's are the independent variables. The significance of each independent variable was tested with the same variable fitting procedure listed above. 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 probability of mortality (P_m) ≥ 0.5 in order to compare model predictions to observed mortality (1 or 0). The number and direction (predicted dead but observed alive or predicted alive but observed dead) of incorrect predictions were tallied for each model.

Results

Forest Structure and Composition

Species composition was similar in all treatments within a site but different between sites prior to the thinning treatment (Figure 4). Douglas-fir (85% of total) dominates all dbh classes in treatments at Panther Lake. The larger dbh classes include some knobcone pine (5% of total), and the small dbh classes include two hardwood species: chinquapin and tanoak (10% of total). Species composition in all treatments at Meadow Creek was similar prior to thinning, but the Meadow Creek site had a larger component of hardwood species than the Panther Lake site. Prior to treatment, Meadow Creek was composed of 50% Douglas-fir, 45% tanoak, 5% knobcone pine and occasional Pacific madrone and canyon live oak (*Quercus chrysolepis* Liebm) with conifer species dominating the larger dbh classes and hardwood species dominating the smaller dbh classes.

After the thinning treatment, species composition was similar in three of the thinned plots, which had approximately 85% Douglas-fir, 10% knobcone pine and 5% hardwood species (Figure 4). However, the thin only treatment at Meadow Creek still had a large component of tanoak (60%) in the smallest dbh classes, and Douglas-fir (35%) and knobcone pine (5%) in the larger dbh classes (Figure 4).

Stand structure variables for all treatments before and after thinning are shown in Table 3. Dbh (dead and live trees) and tree density (dead and live trees) were similar for all treatments and both sites prior to thinning, but Meadow Creek plots had lower basal area, CBD and CBH than Panther Lake plots. The thinning treatment decreased tree density (dead and live trees), basal area, and CBD, and increased CBH and mean dbh of live trees in all thinned plots. The thinning increased the CBH more in the thinned plots at Meadow Creek (10.2 – 17.5 m) than at Panther Lake (4.3 – 5.5 m). The thin only treatment plot at Meadow Creek had a lower reduction in live tree density and less of an increase in mean dbh than the other thinned plots, because some sub-canopy hardwood trees were not removed in the thinning (Figure 4).

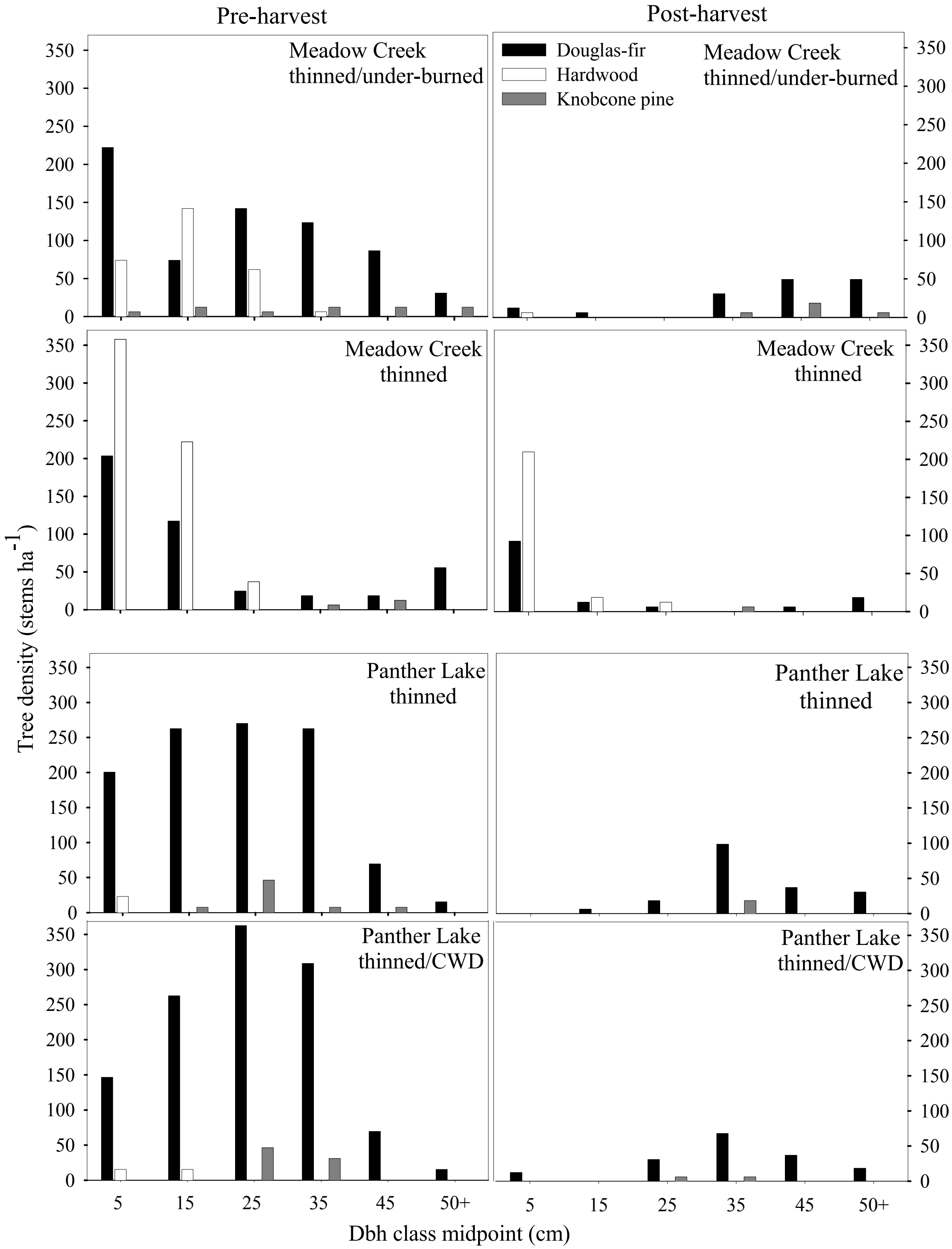

FIG 4. Tree density by species and dbh class in thinned treatments pre and post thinning.

Table 3. Means and (standard deviations) of pre and post-thinning stand structure variables.

Site: Meadow Creek

	Pre-harvest			Post-harvest	
	Untreated	Thinned	Thinned/ under-burned	Thinned	Thinned/ under-burned
Mean dbh (cm) live	17.4 (4.3)	16.2 (5.8)	22.7 (6.1)	26.6 (27.5)	42.4 (8.0)
Mean dbh (cm) dead	13.0 (2.8)	12.9 (2.6)	13.5 (6.2)	19.6 (2.1)	6.0[b] —[b]
Tree density (stem ha^{-1}) live	1395 (296)	1074 (345)	1025 (233)	383 (341)	185 (31)
Tree density (stem ha^{-1}) dead	611 (209)	512 (299)	407 (329)	68 (88)	6 (14)
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)
Canopy bulk density (kg m^{-3})	0.090 (0.030)	0.047 (0.025)	0.104 (0.026)	0.020 (0.011)	0.058 (0.015)
Canopy base height (m)	5.4 (1.9)	6.2 (5.7)	7.0 (3.2)	23.7 (22.3)[a]	17.2 (1.1)

Site: Panther Lake

	Pre-harvest			Post-harvest	
	Untreated	Thinned	Thinned/ high CWD	Thinned	Thinned/ high CWD
Mean dbh (cm) live	24.5 (1.3)	23.5 (4.6)	24.5 (5.3)	35.3 (5.0)	38.4 (3.1)
Mean dbh (cm) dead	10.7 (1.4)	13.1 (2.5)	11.5 (2.9)	16.9 (15.1)	15.3 (5.5)
Tree density (stem ha^{-1}) live	1247 (236)	1180 (274)	1273 (271)	185 (44)	210 (40)
Tree density (stem ha^{-1}) dead	944 (314)	818 (339)	903 (177)	37 (14)	74 (35)
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)
Canopy bulk density (kg m^{-3})	0.174 (0.046)	0.185 (0.051)	0.215 (0.050)	0.050 (0.023)	0.094 (0.014)
Canopy base height (m)	8.2 (0.9)	9.7 (4.7)	8.7 (3.5)	14.0 (1.2)	14.2 (1.4)

[a] The standard deviation is large for CBH in the thin only treatment at Meadow Creek, because CBD did not exceed the critical threshold in one tree plot, so the plot was assigned a CBH value of 200.

[b] Only one tree plot had dead trees after the thinning.

Surface Fuels

Surface fuel loading was calculated before and after the thinning and after the Biscuit Fire for all thinned treatments. For the thinned and under-burned treatment, surface fuel loading values are reported for before and after the thinning, after the under-burn and after the Biscuit Fire. Data collected after the Biscuit Fire are reported for the post under-burn conditions, and no change is reported for the post Biscuit Fire conditions. This is because an inventory was not done after the prescribed burn, and the Biscuit Fire did not spread into this treatment.

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 Mg ha^{-1} at Meadow Creek and from 14.9 to 31.6 Mg ha^{-1} at Panther Lake. Rotten coarse wood was less abundant than sound coarse wood in all treatment plots, ranging from 0 to 2.4 Mg ha^{-1} at Meadow Creek and was not present at Panther Lake (Table 4).

All thinned treatment plots had greater fine wood and rotten coarse wood loading after the thinning (Figure 5). Fine wood increased by 15.2 to 27.0 Mg ha^{-1}, and rotten coarse wood increased by 1.7 to 6.2 Mg ha^{-1}. Sound coarse wood loading decreased by 0.9 to 5.8 Mg ha^{-1} in all thinned treatment plots except the thinned plot with high CWD which had an increase in sound coarse wood of 10.7 Mg ha^{-1}. In the thinned and under-burned treatment, fine wood decreased after the prescribed burn by 16.6 Mg ha^{-1}, so there was a net decrease in fine wood after both the thinning and under-burn treatments (Figure 5).

Consumption of fine wood was high during the Biscuit Fire, and it was higher in the thinned plots than in the untreated plots at both sites (Figure 6). Rotten coarse wood was almost completely consumed in both treated and untreated plots (Figure 6). A smaller portion of sound coarse wood (25% - 34%) was consumed compared to other fuel types, except in the thin only treatment at Meadow Creek, which had about 65% consumption of sound coarse wood. Consumption of surface fuels is measured by the change in loading between post-thin and post-fire samples. Coarse wood that was partially burned and had a diameter < 7.6 cm after the fire was included in the post-fire fine wood sample, so consumption of sound coarse wood may be slightly over estimated and consumption of fine wood may be slightly underestimated. New woody surface fuels recruited after the fire, such as fallen snags, were not included in the post-fire sampling.

Table 4. Means (standard deviations) of surface wood loading.

		Meadow Creek			Panther Lake		
		Untreated	Thinned	Thinned/ under-burned	Untreated	Thinned	Thinned (high CWD)
Pre-treatment	Fine wood	9.3 (3.6)	9.0 (4.8)	10.1 (10.8)	18.4 (5.9)	21.6 (7.7)	18.0 (5.4)
	Sound coarse wood	17.4 (11.1)	24.1 (24.7)	34.7 (35.8)	18.6 (18.6)	31.6 (34.4)	14.9 (13.3)
	Rotten coarse wood	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
Post-treatment	Fine wood	8.9 (6.7)	27.3 (29.4)	25.9[a] (23.0) 4.7[a] (4.5)	29.7 (18.0)	36.8 (16.5)	45.0 (26.4)
	Sound coarse wood	14.5 (7.2)	23.1 (14.1)	28.9[a] (18.4) 19.3[a] (11.1)	8.8 (3.9)	15.4 (10.2)	25.6 (23.4)
	Rotten coarse wood	5.1 (7.2)	3.4 (6.1)	2.3[a] (2.1) 0.8[a] (0.9)	2.9 (2.7)	4.4 (3.5)	6.2 (5.0)
	Total	25.4	47.7	51.3[a] 24.8[a]	31.2	48.2	66.8
Post-wildfire	Fine wood	1.2 (1.8)	0.6 (1.3)	4.7[b] (4.5)	3.6 (5.3)	1.7 (4.3)	0.1 (0.2)
	Sound coarse wood	9.6 (4.7)	7.3 (5.3)	19.3[b] (11.1)	4.4 (3.0)	11.4 (7.7)	19.2 (5.9)
	Rotten coarse wood	0.4 (0.4)	0.6 (0.3)	0.8[b] (0.9)	1.1 (0.7)	0.0 (0.0)	0.6 (1.0)
	Total	11.2	8.1	24.8[b]	9.1	13.1	19.9

[a] The values for each fuel class in the thinned and under-burn treatment of Meadow Creek are for after the thinning and after the under-burning.

[b] Fire did not spread into the thinned and under-burned treatment, so post-wildfire fuel loading is the same as after the under-burn.

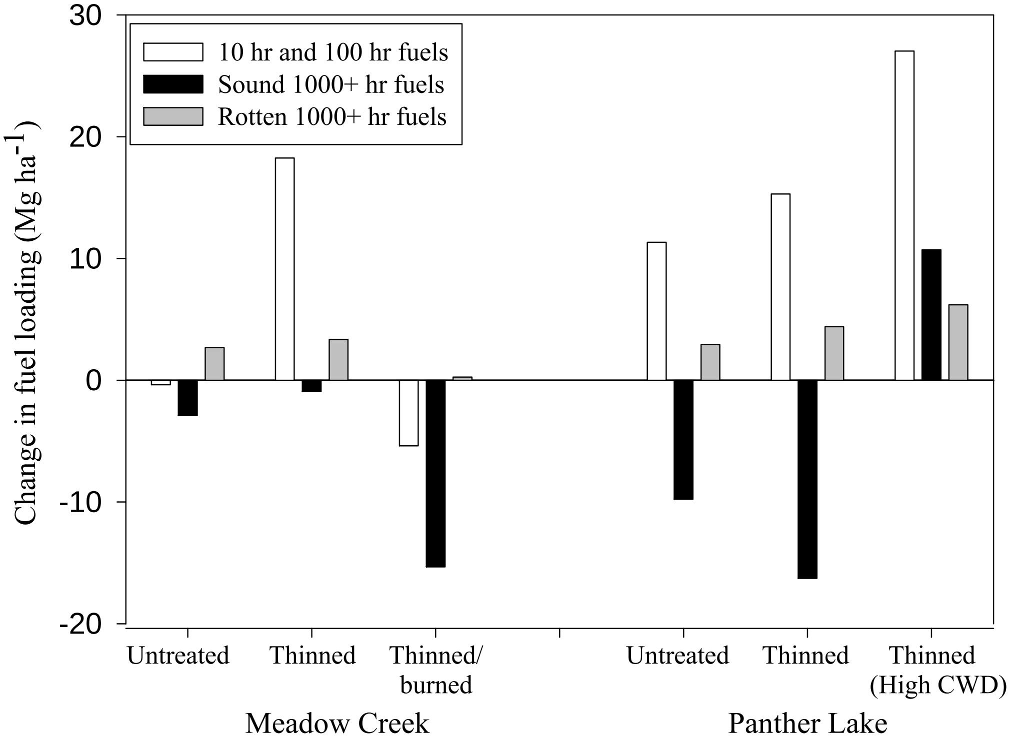

Fig 5. Post treatment change in fuel loading by decay and size class.

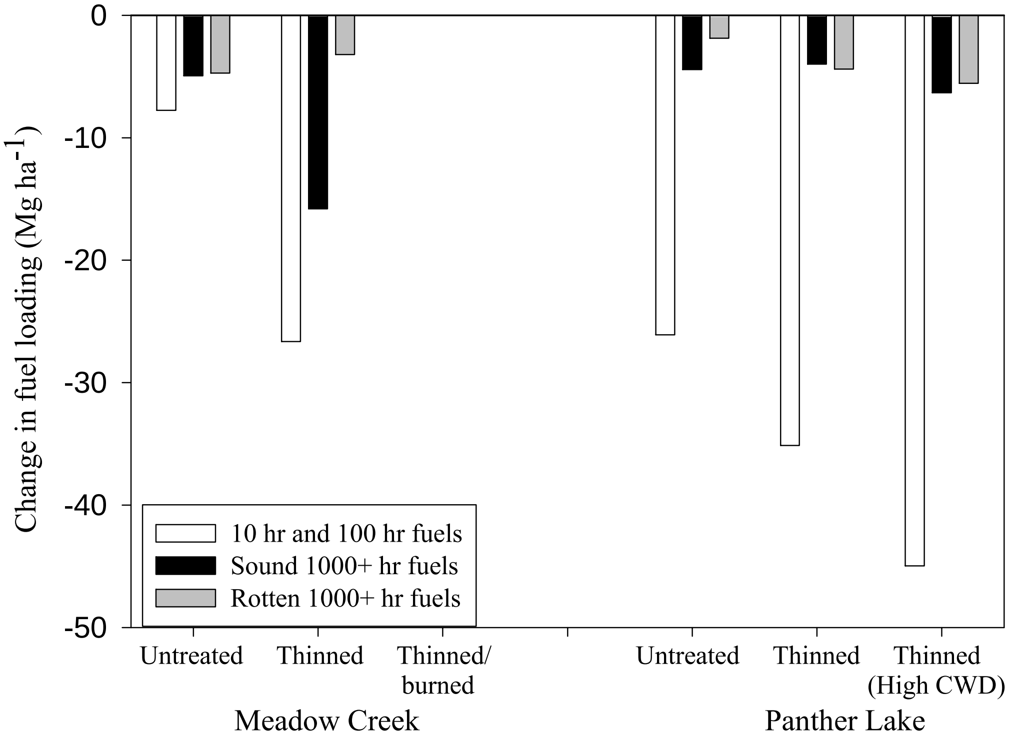

Fig 6. Post-wildfire change in fuel loading by decay and size class.

Foliar Moisture

The foliar moisture of new foliage and fine twigs was not different for the dominant two sub-canopy tree species, but old foliage was significantly different (Table 5). Mean foliar moisture content of tanoak old foliage was 91%, and mean foliar moisture content of Douglas-fir old foliage was 147%.

Table 5. Sample sizes (n), means and standard errors of the mean (sem) of August foliar moisture of two tree species in southwestern Oregon

	Douglas-fir			Tanoak		
Foliar component	n	mean	sem	n	mean	sem
New foliage	10	137	(12)	9	144	(18)
Old foliage	10	147[a]	(6)	9	91[a]	(2)
Fine twigs (0.0 -0.6 cm)	10	88	(6)	9	90	(6)

[a] Within row means are significantly different (p = 0.001)

Potential Fire Behavior

The Panther Lake site had greater potential for severe fire behavior than the Meadow Creek site prior to treatment. The predicted fire type for Meadow Creek was surface fire under the 98th percentile weather conditions, and the torching index (km hr^{-1}) was above realistic wind-speeds for all treatments (Table 6). Actual CBH values exceeded target CBH values, limiting the possibility of crown fire initiation. The predicted fire type for the Panther Lake site was border-line conditional surface fire under the 98th percentile weather conditions in all treatment plots (Table 6). At Panther Lake the actual CBH exceeds the target CBH for the 98th percentile weather conditions, and the torching index was above any realistic wind-speed making the transition from surface fire to crown fire unlikely, as at Meadow Creek. However, the actual CBD values were very close to target CBD values, so with a crowning index of 20 to 23 km hr^{-1} horizontal crown fire spread would be possible under the 98th percentile weather conditions. The pre-thin plots at Panther Lake could be susceptible to crown fire if an active crown fire spread into the stand, but not if a surface fire spread into the stand.

Potential fire behavior was similar in thinned treatment plots at both sites after the thinning. The target CBH increased, but the actual CBH also increased in all thinned treatment plots, so the torching index (km hr^{-1}) remained similar or slightly increased. The crowning index (km hr^{-1}) increased in all thinned plots (Table 6). At Panther Lake the thinning reduced the actual CBD to below the target CBD, so the potential fire type under the 98th percentile weather conditions was surface fire in the thinned treatments at Panther Lake. The crowning index increased by at least 26 km hr^{-1} in all thinned plots, so wind-speeds would need to be at least double the 98th percentile wind-speeds in order for crown fire to spread. In the thinned and under-burned site at Meadow Creek, the target CBH decreased to 0.5 m under the 98th percentile weather conditions and the torching index was very high for the conditions present after the under-burn.

Table 6. Potential fire behavior before and after thinning.

		Pre-thinning							Post-thinning						
Site	Treatment	actual CBH (m)	target CBH (m)	actual CBD (kg m^{-3})	target CBD (kg m^{-3})	Fire type	Torching index (km hr^{-1})	Crowning index (km hr^{-1})	actual CBH (m)	target CBH (m)	actual CBD (kg m^{-3})	target CBD (kg m^{-3})	Fire type	Torching Index (km hr^{-1})	Crowning Index (km hr^{-1})
Meadow Creek	Untreated	5.4	1.2	0.09	0.16	S	177	38	—	—	—		—	—	—
	Thinned	6.2	1.2	0.05	0.16	S	212	62	23.7	3.1	0.02	0.16	S	311	116
	Thinned/ under-burned	7.0	1.0	0.10	0.16	S	260	38	17.2	0.5	0.06	0.16	S	5202	53
Panther Lake	Untreated	8.2	1.6	0.17	0.18	S	163	23	—	—	—		—	—	—
	Thinned	9.7	1.7	0.19	0.18	C	187	22	14.0	3.3	0.05	0.18	S	141	60
	Thinned/ High CWD	8.7	1.8	0.22	0.18	C	161	19	14.2	3.5	0.09	0.18	S	141	40

Note: S = surface fire, C = conditional surface fire

Fire Severity

All trees showed some evidence of burning but with variable severity (Table 7). Trees in the thinned treatments had the greatest burn severity as measured by the relative proportion of trees in higher burn severity classes. Trees in the thinned and under-burned treatment had the lowest burn severity, and trees in the untreated treatment had moderate burn severity. The proportion of trees in each class was different for untreated and thinned treatments when the sites were combined. However, the proportion of trees in each class was different for the two sites (excluding trees from the thinned and burned site) indicating that treatments should be compared within sites separately. At Meadow Creek the only treatment with significantly different proportions of burn severity class was the thinned and under-burned treatment (Table 7). At Panther Lake the only treatment with significantly different proportions of burn severity classes was the untreated (Table 7).

Table 7. Overstory trees classified by burn severity class

			Burn severity class				
	Treatment description	n	(low) 1	2	3	4	5 (high)
Meadow Creek [a]	Untreated [c]	45	0	0	21	24	0
	Thinned [c]	6	0	0	2	4	0
	Thinned/under-burned [d]	26	0	25	1	0	0
Panther Lake [b]	Untreated [e]	82	0	26	16	40	0
	Thinned [f]	27	0	0	2	25	0
	Thinned (high CWD) [f]	32	0	0	0	32	0

Note: Burn severity results for the thinned and under-burned treatment are from the under-burn.
Different superscripts indicate significant differences within sites (α = 0.05)

At Meadow Creek fire damage was lowest in the thinned and under-burned treatment and highest in the thin only treatment, but not all differences between the untreated and the thin only treatment were significant (Table 8). All measures of fire damage had the greatest variability in the untreated plot. Bole char height was higher in the thin only treatment, but there was no difference between the untreated and the thinned and under-burned treatment. Crown scorch height was different for all treatments; the thinned treatment having the highest crown scorch and the thinned and under-burned treatment having the lowest. The untreated and thin only treatments did not have significantly different percentage crown scorch, although percentage crown scorch ranged from 15% to 100% in the untreated and from 75% to 100% in the thin only.

Fire damage was lowest in the untreated treatment and similar in the thinned and thinned (high CWD) treatments at Panther Lake. The untreated had significantly different bole char height, crown scorch height and percentage crown scorch compared to the thinned and thinned (high CWD) treatments, but there were no significant differences between the two thinned treatments. As at Meadow Creek, the untreated plot at Panther Lake had the largest range of percentage crown scorch, from 0 to 100% compared to 65% to 100% in the thinned treatment and 95% to 100% in the thinned (high CWD) treatment (Table 8).

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, but abundance of knobcone pine was low for all treatments, so results are reported for only Douglas-fir (Table 9). Ryan et al. (1988) found that mortality was likely for trees with two or more dead cambium samples, so this criterion is used to classify trees as girdled. Approximately 25% of Douglas-fir trees in all treatments at Panther Lake had two or more dead cambium samples. The untreated plot at Meadow Creek also had approximately 25% of Douglas-fir trees with two or more dead cambium samples, but the thinned and under-burned treatment had 5% and the thin only treatment had 100%. Cambial damage of knobcone pine was similar in all treatments and sites with all trees having two or more dead samples except one tree in the untreated plot at Meadow Creek.

Table 8. Means (standard deviations) and ranges of tree damage variables for overstory trees.

			dbh (cm)	Bole char height (m)			Crown scorch height (m)			Crown scorch (%)		
Site	Treatment	n	mean	mean	SD	range	mean	SD	range	mean	SD	range
Meadow Creek	Untreated	45	39.1	7.9 ^{a}	(3.7)	0.3 – 22.1	24.5 ^{a}	(4.3)	16.7 – 34.7	83 ^{a}	(26)	15 – 100
	Thinned	6	57.9	22.7 ^{b}	(8.3)	11.4 – 35.2	30.8 ^{b}	(7.2)	20.3 – 41.9	94 ^{a}	(11)	75 – 100
	Thinned/ under-burn	26	50.0	5.9 ^{a}	(3.0)	0.6 – 12.2	0.4 ^{c}	(1.9)	0.0 – 9.5	0.1 ^{b}	(0.4)	0 – 2
Panther Lake	Untreated	77	36.8	10.6 ^{d}	(5.8)	0.0 – 29.4	17.4 ^{d}	(12.6)	0.0 – 31.3	59 ^{d}	(47)	0 – 100
	Thinned	27	37.9	17.0 ^{e}	(3.3)	11.2 – 27.8	24.5 ^{e}	(3.5)	17.9 – 31.3	98 ^{e}	(7)	65 – 100
	Thinned (high CWD)	32	39.2	15.3 ^{e}	(4.8)	6.5 – 27.8	24.6 ^{e}	(3.2)	13.9 – 30.8	100 ^{e}	(1)	95 – 100

Note: The thinned and under-burned treatment did not have added tree damage from the Biscuit Fire.
Different superscripts indicate means are significantly different within sites ($\alpha = 0.05$).

Table 9. Number of dead cambium samples for overstory Douglas-fir.

	Treatment	n	Number of dead samples 0	1	2	3	4	Percent girdled trees
Meadow Creek	Untreated	38	17	11	5	4	1	26
	Thinned	5	0	0	2	2	1	100
	Thinned/under burned	22	20	1	0	0	1	5
Panther Lake	Untreated	77	48	13	13	1	2	21
	Thinned	26	11	8	2	4	1	27
	Thinned (high CWD)	32	14	11	5	0	2	22

Note: The burn severity results for the thinned and under-burned treatment are from the under-burn.

Trees are considered to be girdled if two or more cambium samples are dead.

Fire Severity and Fuel Structure

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

$$CS = 1/\ (1 + \exp^{(0.800 - 0.0998\ (FWD)})$$

A test on model deviance showed the model to have sufficient fit (p = 0.85). However, the percent reduction in deviance is 23%, and the residual deviance is still high (analogous to a low R^2 value for linear regression). The relationship between CS and FWD also suggests a threshold, with all plots that have > 30 Mg ha^{-1} of fine wood having complete crown scorch.

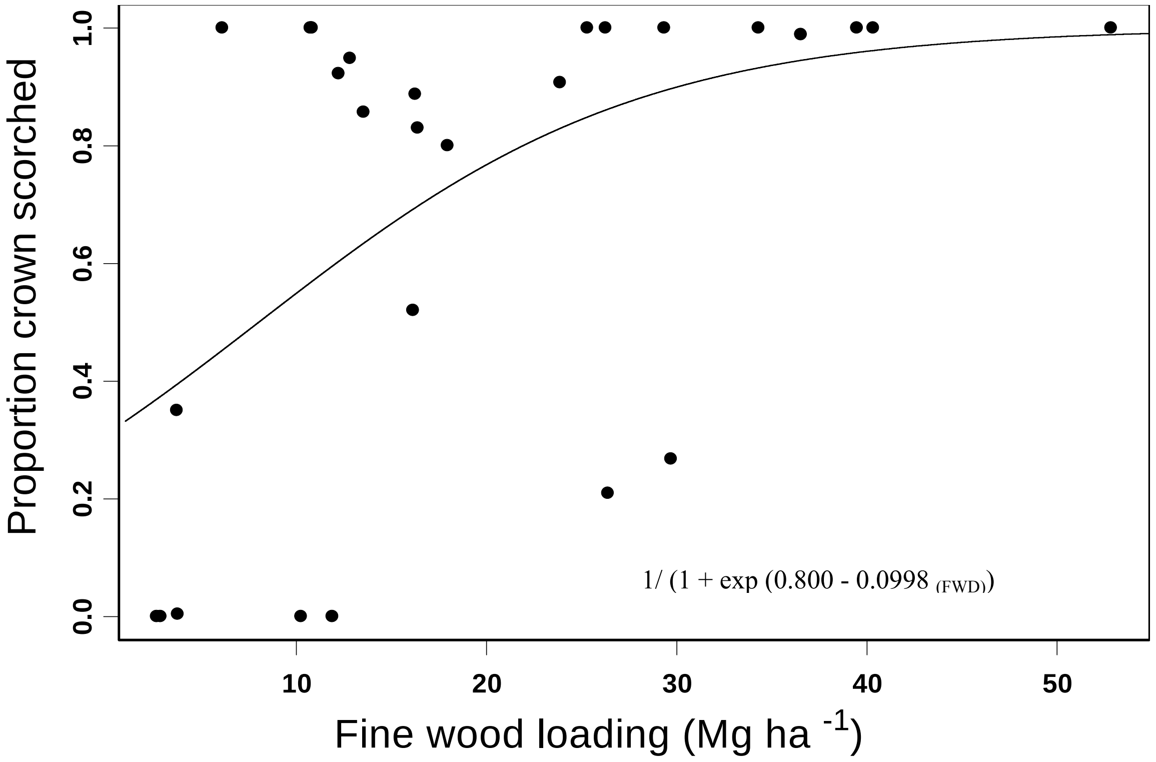

Fig 7. Crown scorch as a function of fine wood fuel loading.

Mortality

Mortality of overstory Douglas-fir trees was highest in thinned treatments, lowest in the thinned and under-burned treatment, and moderate in the untreated. Mortality was 53 - 54% in untreated treatments, 80 – 100% in thinned treatments and 5% in the thinned and under-burned treatment (Table 10). Mortality of knobcone pine trees was almost 100% regardless of treatment. Mortality of sub-canopy (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 under-burned treatment) was different for 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 is the thinned and under-burned treatment ($p = 0.001$). At Panther Lake the untreated is significantly different from the two thinned treatments ($p = 0.001$).

Table 10. Mortality status of overstory Douglas-fir trees two years post-fire.

			Tree Status		
	Treatment description	n	Dead	Live	Mortality (%)
Meadow Creek	Untreated ^{a}	38	20	18	53
	Thinned ^{a}	5	4	1	80
	Thinned/under-burned ^{b}	21	1	20	5
Panther Lake	Untreated ^{c}	78	42	36	54
	Thinned ^{d}	25	24	1	96
	Thinned (high CWD) ^{d}	30	30	0	100

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

All four independent variables -- diameter (DBH), percentage crown scorch (CS), crown scorch height (CSHT) and number of dead cambium samples (NDEAD) -- were significant ($p = .001$) predictors of overstory tree mortality. All models with single predictor variables had sufficient fit (Table 11). Models with all four predictor variables were compared (24 models). NDEAD and CS were significant in all models, but DBH was not significant in any model that includes CSHT and CS, and CSHT was not significant in any model that includes DBH or CS. CSHT was highly correlated with CS ($r = 0.94$) and DBH ($r = 0.70$), so models with these combinations were not considered further. All multiple-regression models were highly significant (Table 11), but the large number of degrees of freedom ($n = 265$ trees) makes it difficult to use this criterion to compare the relative effectiveness of the different models.

Table 11. Logistic models for the probability of mortality (P_m) ($n = 265$ trees)

Model	b_o	b_1 DBH	b_2 CS	b_3 CSHT	b_4 NDEAD	Resid. df	Resid. Dev.	p (χ^2)
1	-3.423	0.073				265	282	0.23
2	2.668		-0.050			265	168	0.99
3	1.062			-0.114		265	250	0.74
4	0.243				-1.449	265	247	0.78
5	-0.014	0.072	-0.050			264	144	0.99
6	-2.013	0.058			-1.447	264	226	0.96
7	3.571		-0.050		-1.158	264	136	0.99
8	1.278	0.064	-0.053		-1.078	263	121	0.99

Note: $P_m = 1 / (1 + \exp(b_0 + b_1 x_1 + \ldots + b_i x_i))$
Large p-values indicate sufficient model fit

Therefore, the prediction errors -- the model predicts a tree to be dead when it is observed live ($P_D O_L$) and live when it is observed dead ($P_L O_D$) -- were compared for several models (Table 12). For the single-regression models, NDEAD had the greatest number of prediction errors and CS has the least. The model with NDEAD predicted mortality if a tree had 1 or more dead cambium samples. The model with CS predicted mortality of any tree with > 60% crown scorch.

The multiple-regression model with the least total prediction errors was the model that includes DBH, CS and NDEAD, but this was only slightly better than the model that contained DBH and CS. The multiple-regression model with the least net prediction errors contained DBH and NDEAD, but this model had the highest total errors.

Table 12. Prediction errors for mortality models (n = 265 trees).

Model	Variables	P_L O_D	P_D O_L	Total errors	Net errors
1	DBH	17	42	59	25
2	CS	8	23	31	15
3	CSHT	8	35	43	27
4	NDEAD	51	11	62	-40
5	DBH, CS	8	19	27	11
6	DBH, NDEAD	25	28	53	3
7	CS, NDEAD	5	17	22	12
8	DBH, CS, NDEAD	3	15	18	12

Note: A tree is predicted to be dead if $P_m \geq 0.5$.

Discussion

Forest Structure and Potential Fire Behavior

The thinning treatment 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 increased 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 sub-canopy Douglas-fir and evergreen broad-leaved trees that are not fire resistant and can be killed by low-intensity fires. Removing these sub-canopy trees also raised the CBH in all thinned treatments, eliminating the ladder fuels that can enable fire propagation from the surface stratum to the canopy stratum.

The potential for crown fire initiation and spread was low in all treatments at Meadow Creek prior to thinning, so the thinning had little effect on further reducing the potential for crown fire. Prior to thinning, the predicted fire type at Meadow Creek under 98th percentile weather conditions was surface fire, and the wind-speed required to initiate crown fire was larger than any realistic wind-speed. The higher CBH after the thinning did not change fire hazard, because the predicted surface fireline intensity also increased (the torching index was only slightly higher). The thinning reduced CBD, which did decrease the potential for crown fire spread (crowning index for the thinned stands was 1.5 to 2 times greater), but the potential for crown fire spread was low even before the thinning.

Panther Lake had greater potential for crown fire spread than Meadow Creek before the thinning treatment. The predicted fire type under the 98th percentile weather was conditional surface fire, although plots were right at the border of this classification. Conditional surface fire 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 (Scott and Reinhardt 2001). Anecdotal evidence suggests the phenomenon is real, but more research is needed to confirm that it is not simply a modeling artifact caused by linking independently derived surface and crown fire spread models (Scott and Reinhardt 2001). The Panther Lake plots could theoretically experience crown fire if fire spread into the stand already as a crown fire, but not if the fire spread into the stand as a surface fire.

The thinning treatment reduced crown fire potential more in the thinned treatments at Panther Lake than at Meadow Creek. The higher CBH after the thinning had no effect on the torching index because surface fire intensity also increased, as at Meadow Creek. However, the thinning treatment reduced CBD to below the threshold required to sustain crown fire spread under the 98th percentile weather conditions, dropping the predicted fire type from conditional surface fire to just surface fire. The effect of lower CBD is also shown by the doubling of the crowning index to unlikely wind-speeds (over two times the 98th percentile wind-speed).

The combined thinning and under-burning treatment at Meadow Creek decreased crown fire potential more than thinning alone. The thinning had a similar effect on potential for crown fire spread in this treatment as it did in the thin only treatments, but the combined treatment also reduced the potential for crown fire initiation by both increasing CBH and decreasing surface fuels. The reduction in surface fire intensity decreased the target CBH to less than a meter, and increased the torching index above that of the thin only treatments.

Forest Structure and Fire Severity

Crown damage to overstory trees in the Biscuit Fire was extensive despite the absence of crown fire, and the low predicted crown fire potential before and after the fuel treatment. Crown fire is not a prerequisite for high fire severity, because crown scorch from high intensity surface fires can also cause overstory mortality (Ryan and Reinhardt 1988, Ryan et al.1988). Evaluating fuel treatments based only on potential fire behavior may not adequately reflect treatment effects on fire severity caused by crown scorch.

Fire severity was greater in thinned treatments than untreated, and lowest in the thinned and under-burned treatment, with differences most extreme at Panther Lake. Three fire damage variables – percentage crown scorch, scorch height and bole char height – all followed this pattern. Mortality of overstory Douglas-fir, two years post-fire, showed the same treatment effect, with 80 – 100% mortality in thinned plots, 53% -54% in untreated and 5% in the thinned and under-burned plot. Fire damage to the cambium of overstory Douglas-fir trees was low regardless of treatment. Fire severity for the thinned and untreated plots was not significantly different at Meadow Creek, perhaps because relatively steep slopes contributed to more uniform fire severity across the site, or because the small number of overstory trees in the thin only treatment decreased the power of the ANOVA.

The untreated plots had the highest within treatment variability in fire severity. 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%, and patterns of individual tree damage and mortality were more specific to tree species and size. Mortality was higher for overstory knobcone pine trees than overstory Douglas-fir, and mortality of Douglas-fir trees decreased with increasing tree size. Mortality was high for sub-canopy broad-leaved and conifer trees, but the broad-leaved trees sprouted following the fire. These species specific effects are characteristic of the life-histories of each species (Agee 1993). The high mortality of Douglas-fir throughout the area of thinned treatments and regardless of tree size is greater than would generally be expected for forests dominated by 100-year-old Douglas-fir in this region.

The additional fine wood left from the thinning operation (despite whole-tree yarding) most likely caused higher fire intensity and severity in the thinned treatments. The high damage to tree crowns and low damage to cambial tissue suggests that most tree injury was caused by a faster moving fire with high flame heights; fire behavior that would be expected in stands with abundant dry fine fuels. Surface fire consumed more fine wood in thinned treatments than in untreated treatments during the Biscuit Fire. The two 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 can cause more crown scorch of overstory trees (Van Wagner 1973).

Bole char measurements on overstory trees also suggest that fireline intensity was higher in thinned treatments compared to untreated, and lowest in the thinned and under-burned treatment. Bole char height can be used as an indicator of flame height and fireline intensity (Agee 1993), but it can over estimate fireline intensity if the bark of the bole is flammable and fire spreads up the bole itself.

The low vegetation, litter and ground fuel strata were not quantified for this study, and those fuels may also contribute to the total biomass consumption and affect fireline intensity (Sandberg et al. 2001). The sub-canopy broad-leaved trees sprouted after the thinning treatment and grew to a dense layer of woody vegetation during the five years between the thinning and the Biscuit Fire. This woody vegetation was also consumed during the fire, but this consumption could not be quantified because sampling was completed one year after the thinning and not again before the fire. An estimate of the tanoak was included in the custom surface fuel models used for the fire behavior predictions to account for these fuels.

The importance of fine wood loading as a control over fire severity is also shown by the fire behavior in the thinned and under-burned treatment during the Biscuit Fire. The Biscuit Fire spread to the edge of this treatment but not into the treatment. The under-burn reduced fine wood loading to below the pre-thin levels, eliminating much of the fine fuels on which surface fire spread depends. After the under-burn most of the remaining surface fuels were in the 1000+ hr size class and these larger fuels are generally not considered to contribute to the spread of surface fires (Rothermel 1991). However, the effects of prescribed burns can decrease rapidly with time since treatment (Kilgore and Sando 1975); the effectiveness of this treatment may be due to the short time interval between the under-burn and the Biscuit Fire (only one year).

Rotten coarse wood loading increased after the thinning, and was almost completely consumed in the Biscuit Fire, but both the pre-fire abundance and consumption of rotten coarse wood was relatively small compared to fine wood. The lower dead tree density after the thinning suggests that one consequence of the treatment was to fall standing rotten snags that then contributed to the woody fuel stratum. These rotten fuels typically have high moisture content and require a long burning duration to decrease moisture before consumption can occur, so consumption of large rotten wood will have different fire effects than consumption of fine wood. Smoldering of rotten wood near tree boles can be an important cause of cambial damage, but the lack of cambial damage in these stands suggests that rotten coarse wood was not sufficient enough to affect tree damage, despite increases after thinning. However, the greater consumption of rotten coarse wood in the thinned treatments can have other consequences for smoke production and loss of wildlife habitat.

Microclimatic changes that are a consequence of thinning may have also contributed to higher fireline intensity in the thinned plots; however, the lack of fire in the thinned and under-burned treatment suggests that fine wood loading was a more important control over fireline intensity. Previous studies show that reducing tree density creates a more open stand that can have higher wind-speeds, temperatures, and solar radiation (Weatherspoon 1996 and Scott 1998). A greater percentage of pre-fire fine wood was consumed in the thinned plots than in the unthinned plots during the Biscuit fire suggesting that fine fuel moisture may have been lower in the thinned plots. The surface fire in the thinned plots may have also been more intense due to greater wind-speeds and temperatures, but this was not measured directly. More empirical data are needed to quantify the microclimatic changes associated with different thinning levels in a variety of forest types.

Foliar Moisture and Fire Severity

Foliar moisture content can affect fire severity, but the results of this study suggest that fine wood loading was a more important control over fire severity. Crown fire initiation is a function of the abundance and arrangement of sub-canopy fuels (CBH) and the foliar moisture content of these fuels (Van Wagner 1977). The role of a sub-canopy tree layer in fire propagation is to lower CBH often creating sufficient ladder fuels to facilitate vertical fire spread to the upper canopy. However, the Biscuit Fire was observed to have more moderate fire behavior in stands with a sub-canopy tree layer compared to more open stands, suggesting that the sub-canopy trees did not function as ladder fuels. The relationship between ladder fuels and crown fire initiation was developed for coniferous species (Van Wagner 1977) and may not be applicable to a sub-canopy layer composed of primarily tanoak. Higher foliar moisture of broad-leaved species could have dampened fire behavior, inhibiting rather than aiding crown fire initiation.

The comparison of foliar moisture content in sub-canopy Douglas-fir and tanoak trees in this study does not indicate that tanoak has higher foliar moisture content than Douglas-fir. Foliar moisture of new foliage and small branches in late August was not different between tanoak and Douglas-fir, and old foliage of tanoak trees was drier than Douglas-fir trees. The moisture samples were collected in August 2004 and may differ slightly from foliar moisture conditions in August 2002 when the Biscuit Fire burned, although previous studies have shown that foliar moisture stabilizes late in the summer season in the American Pacific Northwest (Agee 2002).

Predicting Post-fire Mortality

This study provided an opportunity to evaluate the relative importance of different variables in predicting fire-caused tree mortality. These models are applicable to Douglas-fir with dbh ranging from 10 cm to 60 cm and crown scorch from 0% to 100%. Percentage crown scorch was the most important variable for predicting mortality of Douglas-fir trees following this high intensity surface fire. The predictive ability of a model with crown scorch can be slightly improved by adding dbh or the number of dead cambium samples.

These results corroborate previous studies that indicate percentage crown scorch is a better predictor of mortality than crown scorch height (Peterson 1985, Peterson and Arbaugh 1986, Ryan et al. 1988). Crown scorch height and percentage crown scorch are highly correlated, so if mortality is a primary interest in post-fire sampling, effort can be saved by measuring only percentage crown scorch.

The relative importance of cambium damage compared to percentage crown scorch differs from the study of Ryan et al. (1988) who found the number of dead cambium samples to be the most important predictor of Douglas-fir mortality. In my study, the number of dead cambium samples had the lowest predictive ability. Cambial tissue sampling requires the most effort of all damage variables measured, and the poor results for this variable relative to others does not justify the added effort. My study included more trees with extensive crown scorch and fewer trees with extensive cambial damage than in the study by Ryan et al. (1988), and most trees with any cambial damage also had extensive crown scorch. My study also differs in that mortality models were developed following a wildfire rather than a prescribed fire. Crown damage may be a greater indictor of tree mortality than cambial damage under wildfire conditions, but the opposite may be true under prescribed-fire conditions.

Management Implications

Efforts to reduce canopy fuels through thinning treatments may be rendered ineffective if not accompanied by adequate reduction in surface fuels. Surface fuels were a more important control over fire severity than canopy fuels under conditions of extreme drought but moderate wind-speeds. Fine fuel loading was the only fuel structure variable significantly correlated with crown scorch. Despite the reductions in crown fire potential associated with lower CBD, higher CBH and lower tree density, these variables were not significantly correlated with crown scorch. This study shows the need for fire hazard reduction treatments to simultaneously address multiple fuel strata in order to adequately reduce fire severity.

This study also suggests the need to establish acceptable levels of fire severity following wildfires in mixed-severity fire regimes. Does the fire severity in the untreated stands (about 50% mortality) exceed desired future conditions? Are the costs and effort of fuel treatments justified? These are management questions that depend on more than just fire hazard reduction. The acceptable level of fire damage in a mixed-severity fire regime such as the mixed-evergreen forest of southwestern Oregon will vary for areas with different management objectives (e.g. wildlife habitat, timber production, recreation). Fuel treatment options should be considered within the context of other management objectives.

At the scale of a large wildfire such as the Biscuit Fire (202,000 hectares), it is important to consider the size and position of fuel treatments in the landscape (Agee 1996, Finney 2001). Treatment plots in this study were 6-8 hectares. This treatment size may not be large enough to modify fire spread and reduce fire severity in a large wildfire because heat from adjacent areas could affect the treated areas. However, lack of fire spread into the thinned and under-burned treatment suggests that 6-8 hectares can be an effective treatment size under severe fire-weather conditions if all strata of fuel structure are sufficiently modified.

The thinned and under-burned treatment effectively reduced fire severity on slopes of 20 to 35%. Slope plays an important role in both fire behavior and the application of thinning treatments. Steeper slopes are typically associated with more extreme fire behavior, so treatments may be less effective at reducing fire hazard on steep slopes. Steeper slopes (>35%) also present logistical difficulties for administering thinning treatments with mechanized equipment, so fuel treatments that include thinning are generally appropriate on flat to moderate slopes. This study suggests that thinning treatments, followed by sufficient reduction of activity fuels, can effectively reduce fire severity at the upper level of steepness that is still feasible to treat by thinning.

Study Limitations and Further Research

This was a retrospective study and therefore has several limitations. Treatments were not replicated elsewhere in the Biscuit Fire or other wildland fires, so inferences are limited, and results may be specific to the site topography, species composition, and the weather conditions at the time the sites burned. Other areas in the Biscuit Fire experienced crown fire and higher fire severity. The treatment effects could have been different and fire severity more homogeneous in locations where the Biscuit Fire burned as a crown fire due to weather or topographic controls. More information is needed on relative fire severity in forests with different species composition, stand structure, and management histories within the Biscuit Fire perimeter. This information will help determine where and how fire hazard reduction treatments can be most effective in future wildfires in mixed-severity fire regimes.

Some reconstruction of pre-fire forest structure was necessary, and the effects of some fuel strata were not quantified because pre-fire data were unavailable. Despite the large data set for the canopy strata, some assumptions were made to calculate CBH and CBD that may have introduced additional error in the potential fire behavior assessment. The extensive data for woody fuels enabled the development of custom fuel models, which provided more site specific descriptions of surface fuels than the standard fuel models. However, some assumptions were made about surface fuels in order to quantify all the variables required for simulating surface fire behavior. Quantification and monitoring of changes to fuel structure as treatments are administered on public lands will provide essential information about treatment effects if these areas burn in future wildfires.

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 bottom-up controls (fuel structure) of fire severity at small scales (Raymond and Peterson 2004). 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 study site is a mature forest that established after a stand replacing fire in 1881 and is in a mixed-severity fire regime with a fire return interval of 90 – 150 years. The time since fire and the fire effects in the untreated stands are characteristic of a mixed-severity fire regime. Fire effects in the thinned treatments are more typical of a high-severity fire regime, and fire effects in the thinned and under-burned treatments are more typical of a low-severity fire regime. However, 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 may control the size and relative abundance of patches within the mosaic. More data are needed on the relative importance of controls over fire severity in mixed-severity fire regimes and the scales at which these controls operate.

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Appendix A. Layout of sampling plots within treatments

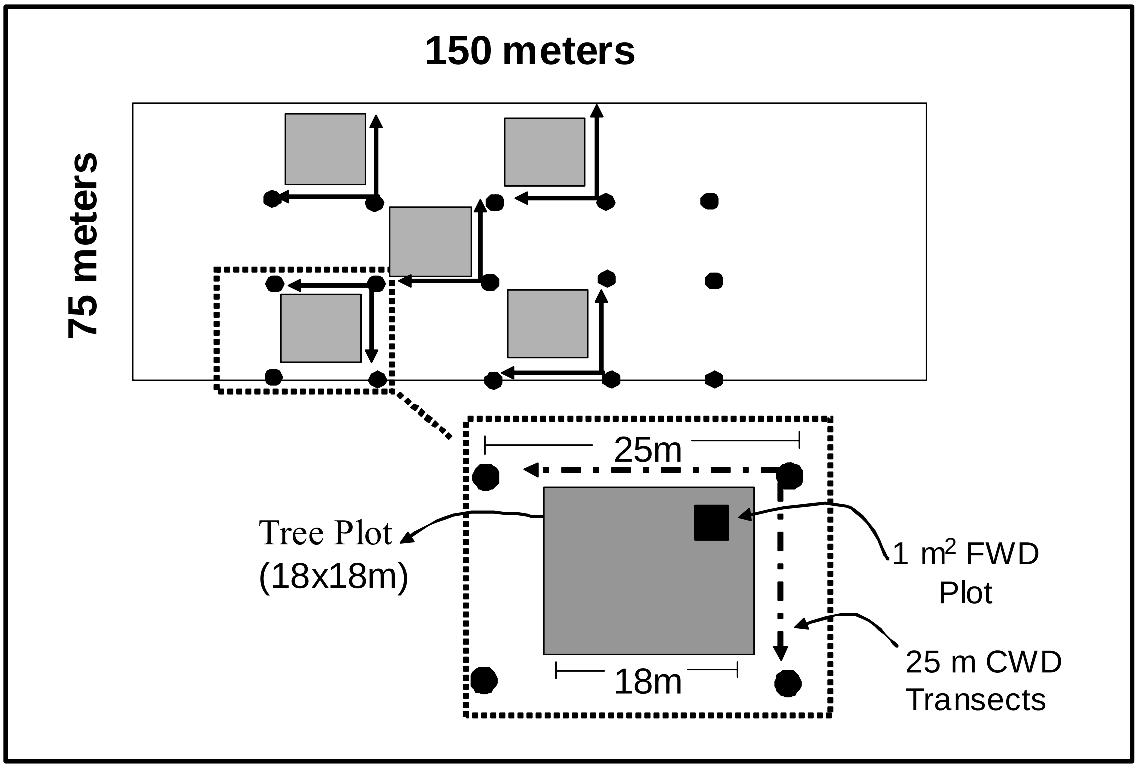

Fig 8. Layout of sampling plots and transects within each treatments.

Appendix B. Crown base height and total height calculations

Regression models were necessary to complete tree height and crown base height variables for use in calculations of CBH and CBD. I developed four regression models to generate complete tree list data for (1) total height (dbh > 7 cm), (2) total height (dbh < 7 cm), (3) crown base height for trees in untreated stands, and (4) crown base height for trees in thinned stands. Diameter-height regression equations have been extensively studied, and Curtis (1967) showed that linear regression equations that use dbh as an independent variable and height as a dependent variable perform differently for large and small diameter trees. Therefore, the trees were divided into two dbh size classes. I also tested relationships between diameter and crown base height, but the equations performed poorly, and I determined total height to be a better predictor for crown base height. I separated trees in untreated plots and thinned plots to account for any change in crown base height caused by a more open stand post-thin. All variables were tested for significance using a t-test and $\alpha = 0.05$. I tested additional variables, species and crown class, but both were not significant in all the models.

Equations for Total Tree Height

I generated the model for total height of large trees (dbh > 7cm) using a representative subset (two trees per crown class per plot) of total height measurements ($n = 972$) from all pre-thin and untreated plots post-thin. The residuals showed evidence of nonlinearity and included extreme values for diameter, so I used a natural log transformation of dbh to linearize the data. The best fitting equation for larger trees was (Figure 9):

$$\text{Total height} = -25.0700 + 14.4007 (\ln (\text{diameter}))$$

$$R^2 = .83$$

The diameter coefficient was highly significant ($p = 0.001$). Confidence bands for predicted values were calculated for $\alpha = 0.05$.

The above logarithmic equation has been shown to perform well for large trees, but can give negative estimates for small trees (Curtis 1967). I generated a model for total height of small trees using a representative subset of total height measurements ($N = 93$) from all pre-thin plots and untreated plots post-thin. Restricting the equation to pass through the natural origin (1.37, 0) (Curtis 1967) was not necessary because the unrestricted equation did not predict negative height values for the dbh values of interest (> 3.5 cm). The natural log transformation of diameter was used. The best fitting equation for small trees was (Figure 10):

$$\text{Total height} = -1.7491 + 3.7713 \ln(\text{diameter})$$

$$R^2 = 0.30$$

The diameter coefficient was highly significant ($p = 0.001$). Confidence bands for predicted values were calculated using $\alpha = 0.05$.

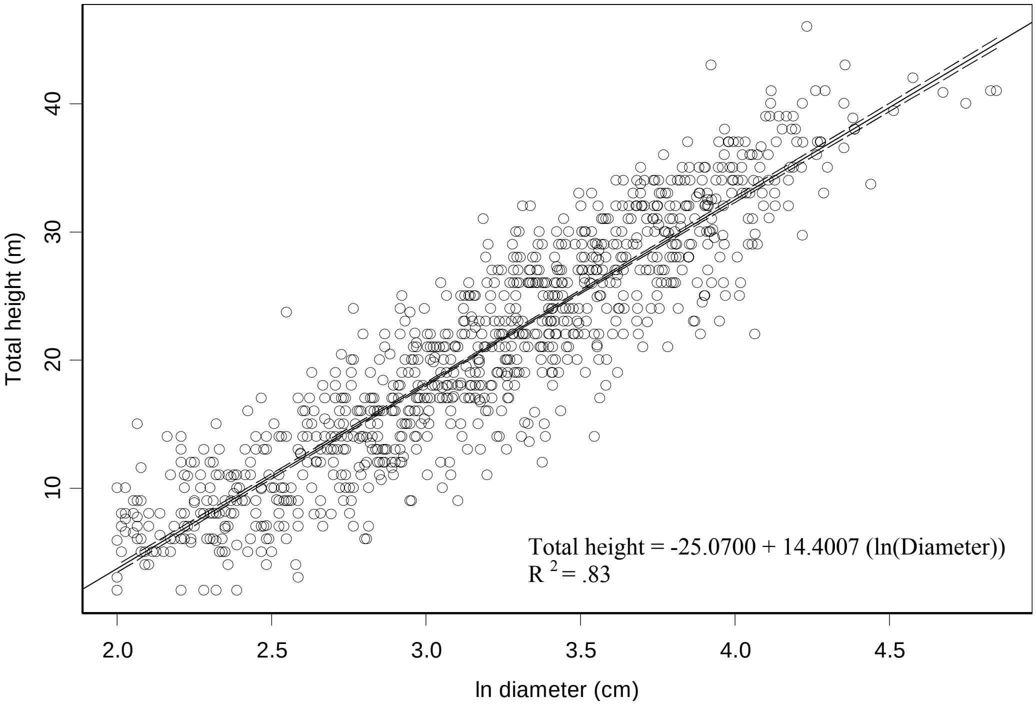

Fig. 9. Total height as a function of ln (diameter) for large trees.
Regression line is solid. Confidence bands for predicted values are dashed.

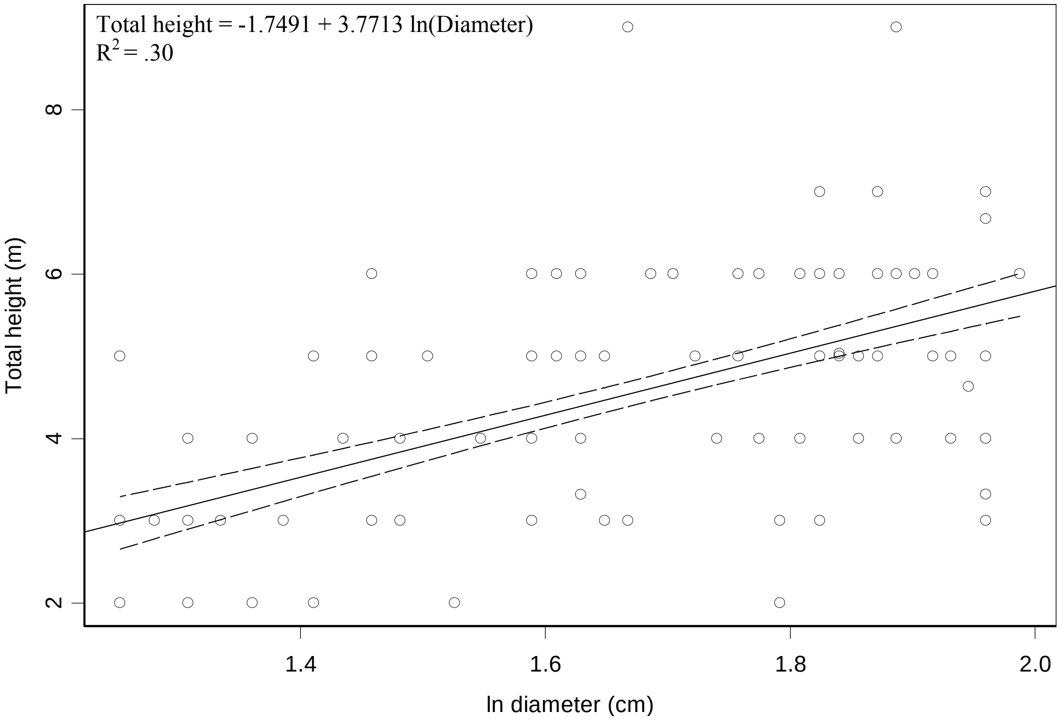

Fig. 10. Total height as a function of ln (diameter) for small trees.
Regression line is solid. Confidence bands for predicted values are dashed.

Equations for Height to Base of Live Crown

I also generated models for determining crown base height for all trees in the tree plots. Total height was a dependent variable in the equations above, but I only used measured values for developing the model for crown base height as a function of total height. However, this model is then used to predict the crown base height for trees with predicted values for total height. The introduced error is assumed to be minimal due to the narrow confidence bands for predicted values of total height (Figure 9 and 10), but the error will be greater for small trees. The relationship between total height and live crown base height was not different for different size trees, unlike the data for total height, so I combined the dbh size classes. I developed two models, one for trees in untreated plots and one for trees in thinned plots.

The model for crown base height in the untreated plots was developed from the same subset of trees from all plots pre-thin and untreated plots post-thin for which crown base height was measured. The residuals showed evidence of non-constant variance, so I used a square root transformation. The best fitting equation for crown base height of trees in untreated stands was (Figure 11):

$$\sqrt{}\,(\text{crown base height} + 1) = 1.147 + 0.1557(\text{Total height}) - 0.0018\,(\text{Total height})^2$$

$$R^2 = 0.78$$

Total height is significant ($p = 0.001$) and total height^2 was significant ($p = 0.001$).

I generated a model for crown base height for trees in the thinned plots post-thin using a subset of trees ($n = 74$) for which crown base height was measured. I used the same transformation as in the equation above to mitigate non-constant variance. The best fitting equation for crown base height of trees in thinned stands was (Figure 12):

$$\sqrt{}\,(\text{Live crown height} + 1) = 1.0039 + 0.1729(\text{Total height}) - 0.0022(\text{Total height})^2$$

$$R^2 = 0.89$$

Total height was significant ($p = 0.001$) and total height^2 was significant ($p = 0.001$).It is important to note that use of the quadratic function requires that predictions be limited to the maximum height used to generate the model, total height = 43 m.

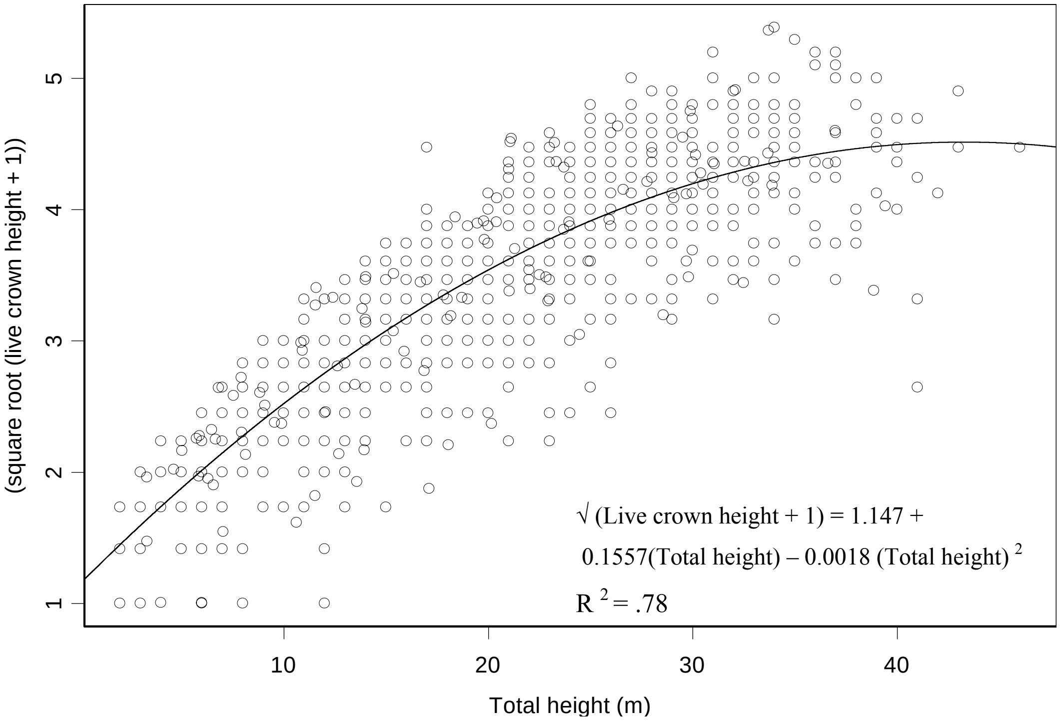

Fig 11 Crown base height as a function of total height for trees in untreated plots.

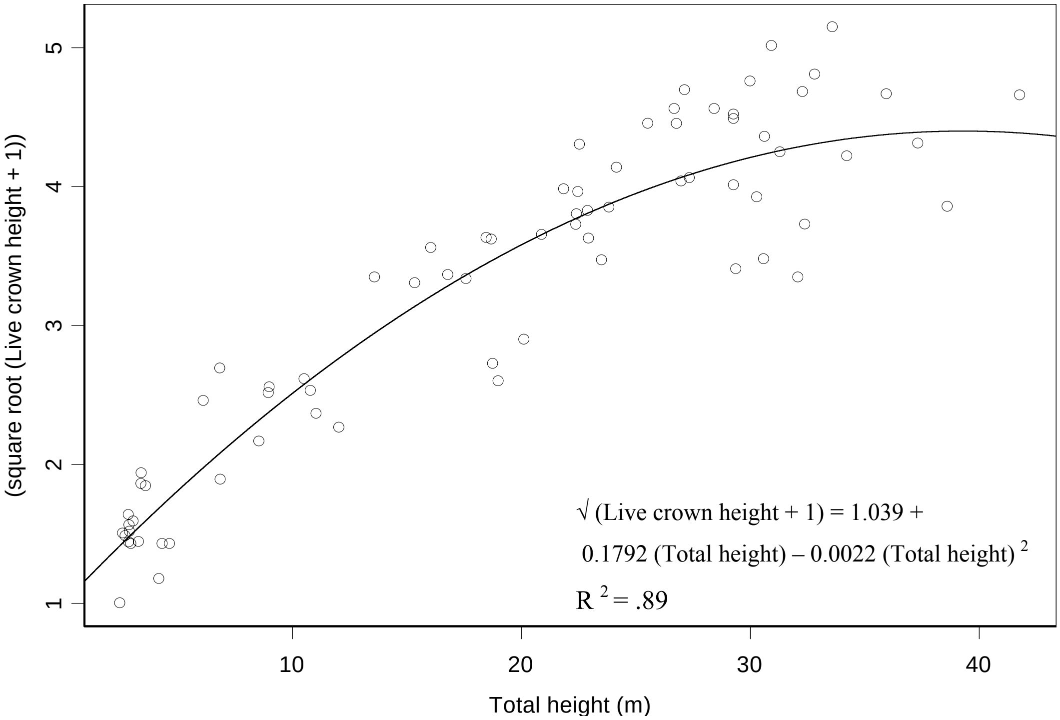

Fig. 12. Crown base height as a function of total height for trees in thinned plots.

Appendix C. Fuel moisture assumptions

The post-thin fine wood sampling in the three Panther Lake treatments was measured between July 27 and August 7, 1999. Fuel moistures of fine fuels (< 7.6 cm) can be assumed to reach stable moisture content during mid-summer in southwestern Oregon given the lack of summer precipitation and variability in daily temperature and relative humidity. Archived 100-hr fuel moisture data for the area show that moisture levels were stable between July 27 and August 7 for 2000 through 2003 (Available online NFDRS www.fs.fed.us/land/wfas/wfas10.html). Fuel moisture for 100-hr fuels ranged from 6% to 15% based on dry weight. Data for 1999 are unavailable, but given the consistency of fuel moistures for the subsequent four years, I assumed the range of 6% to 15% to be appropriate for 1999 as well, and used this range to calculate the dry weights of fine fuels (Table 13). The changes in fuel loading associated with this range of moisture levels only minimally affect the magnitude of results, so the middle value of 10% was selected for analysis.

Table 13. Means and (standard deviations) of fine wood loading for a range of fuel moistures.

	Fine wood loading (Mg ha^{-1})				
Treatment	Pre-thin	Post-thin (6% FM)	Post-thin (10% FM)	Post-thin (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 (CWD)	18.0 (5.4)	46.7 (27.4)	45.0 (26.4)	43.1 (25.3)	0.1 (0.2)

Appendix D. Fine wood size class adjustments

Proportions of fine wood by size class were calculated so fine wood samples that combined all wood between 1.0 cm and 10.0 cm could be divided into time-lag size classes for fire behavior simulations and surface fuel analysis (Table 14). Additional samples were taken in unburned LTEP plots to calculate the proportion of fine wood between 0.0 cm and 0.6 cm, and between 0.6 cm and 1.0 cm (Table 15). Size-class proportions were calculated separately for thinned and untreated plots and these proportions were applied to post-thin fine wood samples collected in thinned and untreated plots that burned during the Biscuit Fire.

Table 14. Proportions of clip-plot samples by size class from unburned sites.

Treatment	partial 10 hr (0.6 – 2.5 cm)	100 hr (2.5 – 7.6 cm)	1000 hr (7.6 – 10 cm)
Untreated	0.58	0.39	0.03
Thinned	0.38	0.50	0.12

Table 15. Fine wood proportions for the smallest size classes.

Treatment	1 hr (0.6 – 2.5 cm)	100 hr (2.5 – 7.6 cm)
Untreated	0.44	0.45
Thinned	0.40	0.26

Appendix E. Fuel model parameters for fire behavior modeling

Table 16. Fuel model parameters used for surface fire modeling in NEXUS.

		Pre-treatment							Post-treatment						
		Fuel loading (Mg ha^{-1})					fuelbed		Fuel loading (Mg ha-1)					fuelbed	
Site	Treatment	1 hr	10 hr	100 hr	live herb	live wood	depth (m)	MOE (%)	1 hr	10 hr	100 hr	live herb	live wood	depth (m)	MOE (%)
Meadow Creek	Untreated	1.21	4.11	4.83	1.21	0.00	0.30	25	—	—	—	—	—	—	—
	Thinned	1.21	2.18	7.49	1.21	0.00	0.30	25	3.63	10.90	13.05	0.00	4.83	0.50	30
	Thinned/under-burned	1.21	3.63	4.83	1.21	0.00	0.30	25	0.01	1.45	3.50	0.00	0.00	0.06	20
Panther Lake	Untreated	4.35	6.77	8.70	1.21	0.00	0.30	25	—	—	—	—	—	—	—
	Thinned	5.08	9.18	8.94	1.21	0.00	0.30	25	5.32	16.92	17.40	0.00	4.83	0.50	20
	Thinned/High CWD	4.59	6.04	8.70	1.21	0.00	0.30	25	6.53	20.54	21.51	0.00	4.83	0.50	20

Note: MOE = Dead fuel moisture of extinction

Appendix F. Weather input for fire behavior modeling.

Table 17. Fuel moistures used for fire behavior modeling.

Fuel class	Moisture (%)
1 hr	3
10 hr	4
100 hr	6
live herb	30
live wood	78
tree foliar	100

The 98th percentile wind-speed from the Red Mound RAWS station is 23 km hr^{-1}.