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Changes in fuelbed characteristics and resulting fire potentials after fuel reduction treatments in dry forests of the Blue Mountains, northeastern Oregon

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Abstract

In many fire-prone forests in the United States, changes occurring in the last century have resulted in overstory structures, conifer densities, down woody structure and fuel loads that deviate from those described historically. With these changes, forests are presumed to be unsustainable. Broad-scale treatments are proposed to reduce fuels and promote stand development on trajectories toward more sustainable structures. Yet little research to date has identified the effects of these treatments, especially in low elevation dry ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) forests. We report initial fuelbed conditions and changes immediately and 4–6 years after fuel reduction treatments in an operational-scale, replicated ($N = 4$), completely randomized experiment in northeastern Oregon. Treatments included a single entry thin from below conducted in 1998, a late season burn conducted in 2000, a thin followed by burning (thin + burn), and a no action treatment which served as a control. Between 1998 and 2004, litter mass declined about 4.4 Mg ha^{-1} in thin units, about 4.1 Mg ha^{-1} in thin + burn units, and about 1.5 Mg ha^{-1} in burn units. Duff mass did not change with treatment. Mass of woody fuels in the 1 and 10 h timelag classes increased in thin units immediately after treatment, but fell to nearly pre-treatment levels by 2004. Mass of woody fuels in the 100 h timelag class increased about 1.6 Mg ha^{-1} in thin units, and decreased about 0.7 Mg ha^{-1} in burn units and about 0.1 Mg ha^{-1} in thin + burn units. There was no difference in the change in total woody fuel mass among all treatments. About 62% of the residual trees in the burn and the thin + burn units were charred; charring extended up the bole about 1.1 m. About 50% of the residual trees in the burn and thin + burn units had scorched lower crowns. Mean scorch height was 4.3 m. Log density was greater in control units compared to actively treated units and greater in the thin units compared to burn or thin + burn units. We used the Fuel Characteristic Classification System (FCCS) to construct a representative fuelbed for each unit from inventoried data and to calculate three indices of fire potential as measures of the change in fire hazard resulting from our treatments: surface fire behavior, crown fire behavior, and fuels available for consumption. Projected flame length, rate of spread, and reaction intensity are derived as metrics of future surface fire behavior. These results are discussed in the context of management options for restoration of ecosystem health in similar low elevation dry ponderosa pine and Douglas-fir forests.
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1. Introduction

Many fire-prone forests in the United States, especially those with historically short-interval, low- to moderate-severity fire regimes, contain more small trees and fewer large trees, greater accumulations of down woody debris, and higher fuel loading compared to conditions under historical fire regimes (Kilgore and Taylor, 1979; Agee, 1993; Covington and Moore, 1994; Caprio and Swetnam, 1995; Arno et al., 1997; Taylor and Skinner, 1998; Heyerdahl et al., 2001; Wright and Agee, 2004; Hessburg et al., 2005). In low elevation dry forests of the Pacific Northwest, these altered fuelbeds and shifts in forest structure and composition have primarily been caused by fire exclusion and also past grazing and timber harvesting practices, and

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changes in climate (Steele et al., 1986; Dolph et al., 1995; Arno et al., 1997). Collectively, these altered structural conditions may contribute to increased probability of unnaturally severe wildfires, susceptibility to uncharacteristic insect outbreaks, and drought-related mortality (Wickman, 1992; Mutch et al., 1993; Stephens, 1998).

Prior to the 20th century, low severity surface fires burned frequently in low elevation dry forests in the Pacific Northwest (Everett et al., 2000; Heyerdahl et al., 2002; Youngblood et al., 2004; Arabas et al., 2006). Ignitions were predominantly caused by lightning and coincided with the time of year when moisture content of fine fuels was lowest (Agee, 1993; Rorig and Ferguson, 1999). Under historical disturbance regimes, frequent surface fires consumed litter, duff, and down wood, controlled establishment of fire-intolerant species, reduced density of small-diameter stems, opened the stands to increased sunlight, led to vertical stratification of fuels by eliminating fuel ladders between the forest floor and the overstory canopy, and maintained early seral plant associations. Crown fires occurred rarely under these natural disturbance regimes. Consequently, the structure in these stands consisted of open, predominantly widely spaced medium to large and old trees, light and patchy ground fuels, and low and patchy cover of fire-tolerant shrubs and herbs (Wickman, 1992; Agee, 1994; Hessburg et al., 2005).

There is broad agreement that some form of fuel reduction is necessary to move stands from their current structure and developmental trajectory to conditions that more closely incorporate natural disturbance regimes under pre-Euro-American influences. Strategies for restoring forest structure and function include thinning live and dead trees to promote late seral structures and burning surface fuels to reduce the risk of severe surface and crown fires (Brown et al., 2004). Recent presidential initiatives such as the National Fire Plan, the 10-year Comprehensive Strategy, and the Healthy Forests Initiative, and legislation such as the Healthy Forest Restoration Act of 2003, have promoted large scale and strategically located thinning and burning to manage landscapes within the context of ecological processes (USDI and USDA, 2006). Current national assessments indicate that there are over 53,200 km^2 of forests in Washington, Oregon, and northern California in need of fuel reduction to return fuelbeds to pre-settlement conditions and restore ecosystem functionality (USDA, 2003). Land managers implementing these fuel reduction treatments often lack a full understanding of their ecological effects (Fiedler et al., 1992; Pollet and Omi, 2002; Noss et al., 2006). Reducing fuels and restoring forest structure and composition to some semblance of the conditions that prevailed prior to Euro-American influence assumes that reference conditions can be quantified, that departures from reference conditions can be measured, and that the efficacy of treatments designed to move stands toward reference conditions can be measured (Landres et al., 1999). While structural reference conditions exist for low elevation dry forests along the east slope of the Cascade Range (Youngblood et al., 2004), similar work is lacking for other portions of the Pacific Northwest containing dry forests. Lacking definitive reference conditions, fuel reduction treatments that incorporate thinning or burning may still be designed to reduce surface fuels, to decrease crown density while retaining large live and dead trees of fire resistant species, to increase the height to the live crown, and to decrease the risk of stand-replacement wildfire (Agee and Skinner, 2005).

Our work is part of the Fire and Fire Surrogate study (Weatherspoon, 2000), a national network of 13 long-term study sites established to evaluate the ecological and economic consequences of treatments intended to reduce fuels and restore forest ecosystems. The effects of thinning and burning treatments on vegetation, fuels, wildfire hazard, soils, wildlife habitat and use, insect population dynamics, and ecosystem structure and processes are being evaluated across 13 fire dependent ecosystems. A randomized and replicated study design and a common set of response variables were used to facilitate comparisons among sites. Details of the network, links to individual sites, listings of research products are available at the portal http://frames.nbii.gov/portal/server.pt.

We report initial fuelbed conditions and changes one, and 4–6 years after fuel reduction treatments at the Fire and Fire Surrogate study site in low elevation dry ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) forests of the Blue Mountains in northeastern Oregon. Changes in overstory structure, including basal area, tree density, diameter distribution, and crown ratio; understory vegetation, including diversity metrics, community composition, and presence of invasive species; and residual log characteristics such as log cover and size were previously described (Youngblood et al., 2006). Our overarching ecological hypothesis in analyzing fuels was that manipulative treatments such as thinning and burning create distinctly different fuelbeds and down woody structure in the short-term (<5 years post-treatment) when compared to non-manipulated or control treatments. The following objectives are addressed in this paper: (1) quantify changes in fuelbed characteristics that result from each treatment and how these changes differ among treatments. (2) Relate the differences in surface fuel composition to potential fire behavior and effects from a future fire. (3) Relate this information to ecological restoration of ponderosa pine and Douglas-fir in low-elevation dry forests of the Pacific Northwest.

2. Methods

2.1. Study area

This study was conducted in the northern Blue Mountains of northeastern Oregon, USA. The study area (lat., 45°40′N; long., 117°13′W) includes almost 9400 ha of plateaus, benches, and deeply incised drainages formed in highly fractured ancient Columbia River basalt. Forest composition and structure in the study area is representative of warm and dry biophysical environments common throughout the upper Columbia Basin of Washington and Oregon. North-facing plateau slopes, draws, and swales with relatively deep soils support grand fir (*Abies grandis*), Douglas-fir, ponderosa pine, and occasionally lodgepole pine (*Pinus contorta*). Warm and dry sites on gentle south-facing plateau slopes and ridge tops have thinner soils and support ponderosa pine and open, low shrub and grass-dominated communities. Discrete forest stands typically are ≤200 ha in size. Elevation ranges from about 1040 to 1480 m.

Soils are formed from weathering of the basaltic parent rock, and from accumulated or redeposited volcanic ash and wind-blown loess. Total soil depth varies with surface topography and often is greatest on north and east-facing slopes. Soils within the study area, from deep to shallow, include typic Vitrixerands, vitrandic Argixerolls, lithic ultic Haploxerolls, and lithic Haploxerolls.

The climate is strongly continental; mean annual temperature is 7.4 °C (Fig. 1). Frost can occur any month of the year. Two distinct periods of precipitation occur, as snow in November and as rain in March. Mean annual snowfall is 66 cm. Moisture within the growing season results from highly variable convection storms. Precipitation in this portion of the Blue Mountains is influenced at a regional scale by moisture moving eastward along the Columbia River and at a temporal scale in response to fluctuations in El Niño-Southern Oscillation (Heyerdahl et al., 2002). The closest weather station is in Enterprise, OR (lat., 45°42′N; long., 117°05′W) with continuous records since 1969. Annual precipitation at Enterprise averages nearly 500 mm. The Enterprise station is 100–400 m below the study site and may be in a rain shadow formed by adjacent high ridges of the Wallowa Mountains. Therefore it probably receives less precipitation than the study area.

Prior to the 20th century, ponderosa pine and Douglas-fir stands were dominated by late successional and old-growth structure in a mosaic pattern of large-diameter, single stratum, even-aged groups interspersed with non-forest communities across the landscape. Forest structure and processes during the 18th and 19th centuries were strongly influenced by frequent, low-intensity fires burning at intervals of ≤20 years (Heyerdahl et al., 2001; Hessburg et al., 2005). Under this disturbance regime, surface fires resulting from lightning ignitions thinned stands from below by killing small-diameter stems through a combination of cambial and root damage and crown scorch, consumed litter and down wood, opened the stands to increased sunlight, and led to vertical stratification of fuels by eliminating ladder fuels represented by saplings of fire-sensitive conifers such as grand fir. Other disturbances were caused by bark beetle populations (*Dendroctonus brevicomis* and *D. ponderosae*), usually at endemic levels. As a result of more recent human-caused disturbances, especially harvest of large trees, grazing practices, and exclusion of wildfire, most of the study area currently is in the stem exclusion-closed canopy structural stage of development (O'Hara et al., 1996). These stands mainly occur as 70–100-year-old even-aged ponderosa pine and Douglas-fir pole and small-diameter sawtimber that regenerated after extensive partial cutting. Overtopping this cohort is a stratum of scattered large and old remnants of the previous stand that were not harvested earlier. At least two entries within the past several decades reduced densities in some stands. During the 1990s, the study area was affected by high levels of bark beetles, especially *D. ponderosae* and *Ips pini*.

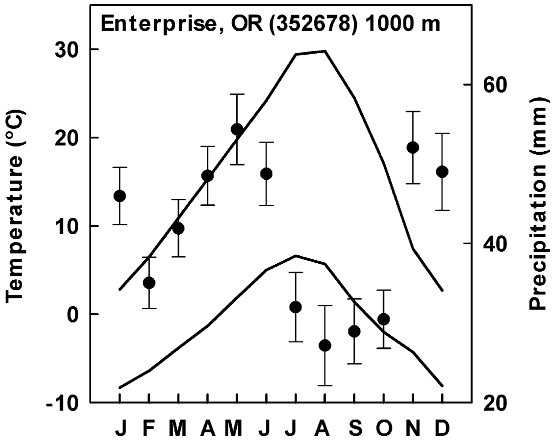

Fig. 1. Climatic features near the Fire and Fire Surrogate fuel reduction study area in northeastern Oregon. Pattern of mean monthly maximum temperature and mean monthly minimum temperature (left axis and solid lines), with the pattern of mean monthly precipitation (right axis, dots with standard error bars) for the period of 1969–2004 at Enterprise, OR.

Understory vegetation is dominated by relatively few shrubs and graminoids. Plant associations are named for the preponderance of ponderosa pine or Douglas-fir and the presence of *Spirea betulifolia*, *Symporicarpos albus*, *Calamagrostis rubescens*, *Festuca idahoensis*, or *Pseudoroegneria spicatum* (Johnson and Simon, 1987) [Nomenclature follows the Plants Database USDA, NRCS (2007)]. In addition, *Arnica cordifolia* and *Carex geyeri* commonly occur. These plant associations represent a majority of the variation in dry forests of the Blue Mountains.

2.2. Treatment implementation

We randomly selected 16 units from a population of 37 stands with similar topographic features and stand structure (Table 1), for an operational experiment with a completely randomized design consisting of four treatments replicated four times. Experimental units ranged from 10 to 20 ha in size. Treatments included: (1) thin – a single entry thin from below; (2) burn – a single underburn; (3) thin + burn – a single entry thin from below followed by an underburn; (4) control – untreated or no action. As part of the Fire and Fire Surrogate network, the primary objective of the active treatments (thin, burn, and thin + burn) was to modify stand structure such that 80% of the dominant and co-dominant trees in the post-treatment stand would be expected to survive a wildfire modeled under 80th percentile weather conditions (Weatherspoon, 2000). Active treatments were designed to reduce the total basal area from about 26 to about 16 $m^2\ ha^{-1}$ and reduce surface fuel mass in the 0–7.62 cm timelag classes to ≤4.5 Mg ha^{-1}.

Thinned treatment units were cut-tree marked, leaving dominant and codominant crown classes and accepting irregular or clumped spacing. Overall, ponderosa pine was favored for retention over other species under a land management objective of increasing the proportion of fire tolerant species across the landscape consistent with a restoration goal.

Table 1
Environmental setting and initial stand conditions of experimental units across four fuel reduction treatments in northeastern Oregon

Unit	Treatments	Size (ha)	Elevation (m)	Aspect (°)	Slope (%)	Number of plots	Live density (trees ha^{-1})	Live basal area (m^2 ha^{-1})	Plant association[a]
6A	Thin	14.4	1361	283	11	26	827	24.7	Pseudotsuga menziesii/ Calamagrostis rubescens
7	Thin	11.9	1305	292	21	25	868	30.4	Pseudotsuga menziesii/ Symphoricarpos albus
9	Thin	9.1	1235	51	12	23	711	15.5	Pinus ponderosa/ Agropyron spicatum
22	Thin	8.8	1380	286	8	28	386	17.2	Pseudotsuga menziesii/ Spirea betulifolia
8B	Burn	10.1	1170	82	8	23	287	17.1	Pinus ponderosa/ Festuca idahoensis
10B	Burn	8.4	1920	50	8	21	219	12.4	Pinus ponderosa/ Festuca idahoensis
21	Burn	10.4	1373	230	18	30	265	19.4	Pseudotsuga menziesii/ Calamagrostis rubescens
24	Burn	8.4	1260	84	9	23	374	12.8	Pinus ponderosa/ Festuca idahoensis
6B	Thin + burn	12.1	1388	221	15	29	695	19.3	Pseudotsuga menziesii/ Calamagrostis rubescens
8A	Thin + burn	10.4	1174	297	9	23	285	18.3	Pinus ponderosa/ Festuca idahoensis
10A	Thin + burn	15.9	1186	297	13	24	330	12.3	Pinus ponderosa/ Festuca idahoensis
1112	Thin + burn	11.0	1185	274	9	27	282	15.6	Pinus ponderosa/ Festuca idahoensis
245	Control	13.8	1286	218	11	21	452	14.4	Pinus ponderosa/ Symphoricarpos albus
15	Control	15.1	1113	108	18	10	425	29.4	Pseudotsuga menziesii/ Calamagrostis rubescens
18	Control	7.5	1333	296	26	19	567	19.7	Pseudotsuga menziesii/ Calamagrostis rubescens
23	Control	12.0	1379	345	10	28	432	17.7	Pseudotsuga menziesii/ Calamagrostis rubescens

[a] A relatively stable plant community of definite composition growing in a uniform habitat; see Johnson and Simon (1987).

All live trees ≥53 cm in diameter at breast height (dbh; 1.37 m above the ground) representing late and old seral structural characteristics were retained and competing conifers within 9 m of dominant ponderosa pine were removed. The thin treatment employed a cut-to-length harvesting system featuring a single-grip harvester and forwarder to remove merchantable live trees and standing dead and down material. Forwarders used the same trail system as the harvesters, operating on top of the accumulated limbs and tree tops within trails that ran up or down slope within each unit. All thinning occurred from July through October 1998, after pre-treatment sampling.

Experimental units to which the burn treatment was assigned had individual burn plans developed to account for differences in site physical features and fuel accumulations. Burn prescriptions were developed by using fuel model 2 (grass with timber overstory) and fuel model 8 (timber litter) as a basis for predicting fire behavior and effects. Mortality targets for trees between 20 and 51 cm dbh were ≤30% for ponderosa pine, ≤40% for Douglas-fir, and ≤70% of the grand fir. Basal area of ponderosa pine ≥51 cm dbh was to be reduced by ≤20%, with similarly large Douglas-fir reduced by ≤30% and grand fir ≤50%. Burns were planned for fall 1999 to allow limbs and tops to cure, but were postponed until mid-September 2000 because of weather. Ignition was by hand-carried drip torches, generally beginning in the early afternoon and completed by 1800 h. Both backing and strip head fires were used to ignite each burn unit under weather and fuel moisture conditions conducive to low flame heights (Table 2).

Table 2
Burning conditions (mean ± standard error) for a set of fuel reduction treatments in northeastern Oregon

Treatment	Ambient temperature (°C)	Relative humidity (%)	Wind speed (m s^{-1})	Graminoid moisture (%)	Litter moisture (%)	Duff moisture (%)	10-h fuel moisture (%)	100-h fuel moisture (%)	1000-h fuel moisture (%)
Burn	23.0 ± 0.7	28.5 ± 2.6	2.4 ± 0.1	52.7 ± 8.6	13.0 ± 0.9	31.5 ± 4.4	13.5 ± 0.6	21.5 ± 3.3	52.5 ± 4.7
Thin + burn	23.0 ± 0.7	28.2 ± 2.7	2.7 ± 0.3	43.2 ± 6.7	13.5 ± 1.3	29.5 ± 0.9	16.2 ± 1.2	25.0 ± 2.3	35.7 ± 3.6

Experimental units to which the thin + burn treatment was assigned first were thinned from below (as described above) in 1998 and then were burned (as described above) in 2000. Burn prescriptions were developed by using fuel model 11 (light logging slash). While the same targets for residual structure were applied, actual on-site application of fire required manipulation of burn strips and fire behavior to treat accumulations of cured tree branches and tops.

If the characteristics of all units were identical before treatments were randomly assigned, the no-action treatment would have represented a true control. Differences in site and disturbance history, however, resulted in differences in stand structure that were recognized before treatments were applied. The term ‘‘control’’ is used here for ease of interpretation.

2.3. Vegetation sampling

Experimental units (treatment units) were whole, discrete stands or portions of larger stands, all having irregular boundaries. Before treatments were applied, a systematic grid of sample points was established along compass lines within each unit, with sample points 50 m apart and ≥50 m from stand boundaries. Within the 16 experimental units, 380 sample points was established, with each point permanently marked and geo-referenced by GPS. At each sample point, aspect was estimated to the nearest 1° azimuth by using a compass, slope was estimated to the nearest 1% inclination by using a clinometer, and elevation was estimated to the nearest 15 m from USGS 7.5′ series contour maps.

Pre-treatment measurements of vegetation were taken in 1998 with circular 0.02-ha plots centered at each sample point. Overstory canopy cover was estimated within each plot by taking measurements at five regularly spaced points with a GRS densitometer (Ganey and Block, 1994). On each plot, all standing trees ≥1.37 m in height were inventoried by species, noted as live or dead, and their height measured to the nearest 0.1 m using either a telescoping height pole or clinometer. Diameter was measured at 1.37 m above the ground with a diameter tape. Crown ratio, defined as the percent of bole with live foliage, was ocularly estimated to the nearest 5% for all live trees. Cover of dominant vascular plant species on each plot was ocularly estimated to the nearest 1% for values up to 10% and to the nearest 5% for all values >10%. We assigned a cover value of 0.3% to those species present in trace amounts. Post-treatment vegetation measurements were repeated in 1999, 2001, and in 2004, the sixth growing season after the thin treatment and the fourth growing season after the burn treatment. Beginning in 1999, circular 0.04-ha plots were centered on each grid point; this larger plot conformed to Fire and Fire Surrogate guidelines for sampling intensity.

2.4. Ground and surface fuel sampling

Ground and surface fuels were sampled prior to treatment (1998) in all 16 units, after the initial thinning treatment in thin + burn units (1999), after all treatments (2001) except in controls, and again in all 16 units (2004). Ground and surface fuels were sampled with three transects at each of the 380 sample points using the planar intercept method (Brown, 1974). The direction of the first transect at each sample point was based on a random bearing and the second and third transects were 120° on either side. The same transects (i.e., the same starting and ending points) were used for all pre-treatment and post-treatment sampling. Ten-hour (0.64–2.54 cm) woody fuels were sampled from 0 to 3 m, and 100 h (2.54–7.62 cm) and 1000 h (>7.62 cm) fuels were sampled along each entire 20-m transect. Diameter, species, and decay class (sound or partially decayed) of each 1000 h log was noted. Depth above mineral soil of freshly fallen conifer litter and duff (older decaying needles and humus) was measured by strata at 6, 12, and 18 m along each planar intersect transect in thin and control units. Litter and duff depth was measured at 16 random points surrounding each sample point in burn and thin + burn units. Steel duff pins were pounded into mineral soil with the head flush with the top of the litter layer. After burning, each pin was relocated and the distance measured from the top of the pin to the top of the remaining forest floor and to mineral soil. To determine wood volume lost through combustion, between 21 and 31 pieces of large woody debris (1000-h fuels) of varying species and decay status, scattered throughout the treatment unit, were measured for circumference and wrapped with high-temperature wire to determine the volume lost through combustion. Total woody fuel depth was recorded in 2004.

In addition to these measures of woody fuel, estimates of log density (2001 and 2004) were made by using the strip-plot method (Bate et al., 2004). The middle of a 4 m × 40 m strip plot was centered over each sample point, with the strip oriented at a bearing determined randomly. Only logs that had a large end diameter ≥15 cm and a length ≥1 m were included.

To better understand fire behavior during the burning, tile pyrometers (ceramic tiles with 25 different temperature-sensitive lacquer spots) (Omega Engineering, Inc.) were staked at 2 m directly south of each sample point at 0.3 and 1.2 m above the forest floor in burn and thin + burn units. These tile pyrometers provided a measure of the maximum instantaneous temperature during the passage of the flaming front within the constraints of the 25 different lacquer spots, but provided no indication of duration. Work with similar tile pyrometers has indicated that this method may underestimate maximum temperatures relative to those recorded by thermocouple, yet is sufficiently precise and accurate for characterizing fire behavior (Iverson et al., 2004; Kennard et al., 2005). Heat sensitivities of the lacquer spots ranged from 40 to 900 °C with about 20 °C intervals between 40 and 400 °C and 75 °C intervals >400 °C. When individual tile pyrometers indicated no change from ambient, we assumed a uniform 23 °C temperature.

Tree damage from the passing fire front was assessed by both bole and crown components (Fowler and Sieg, 2004): the height of bole char was measured to the nearest 0.1 m and the height of crown scorch was estimated as a percentage of tree height to the nearest 5%.

To measure fuel moisture immediately before burning, we gathered multiple samples of live and dead aboveground graminoid biomass, litter and duff, 10 h, and 100 h fuels throughout the fuel profile and the unit and placed them in air-tight plastic bags for evaluation in the lab. Samples of 1000 h fuels were cut from logs scattered throughout the treatment unit and were classified by species, decay status, and size. A 2–3 cm cross-sectional disk was cut from near the end of each identified log. These biomass samples were weighed while still ''wet'', oven-dried at 100 °C for a minimum of 48 h, and then reweighed to determine gravimetric moisture content.

2.5. Data analysis

Pyrometer tile, observed fire weather, and fire behavior data were summarized for the four burn units and four thin + burn units. A two-sample *t*-test was used for paired comparisons between the mean temperature observed at each of the two-pyrometer tile heights for burn and thin + burn units, under the assumption of unequal variances. Tree density was summarized for six size classes—(1) seedlings: <1.37 m in height; (2) saplings: 0.1–9.9 cm in diameter at breast height (dbh); (3) small trees: 10.0–24.9 cm dbh; (4) medium trees: 25.0–39.9 cm dbh; (5) large trees: 40.0–54.9 cm dbh; (6) very large trees: ≥ 55 cm dbh. The percentage of trees with bole char and with crown scorch were calculated based on the total number of live trees and the number of live trees in each size class. These percentages were arcsine square root transformed prior to analysis. Mean bole char and crown scorch height were based only on trees with bole char or crown scorch. Log density (number ha^{-1}) was computed for each treatment unit separately for 2001 and 2004 by summing the number of logs having the center of their large ends present within the strip plot, and this value converted to logs ha^{-1}, then transformed to the natural log before comparing treatment means. Litter and duff depth measurements were converted to mass using bulk density values of 2.64 $\text{Mg ha}^{-1}\,\text{cm}^{-1}$ for conifer needle litter, 3.82 $\text{Mg ha}^{-1}\,\text{cm}^{-1}$ for litter containing moss, 4.49 $\text{Mg ha}^{-1}\,\text{cm}^{-1}$ for litter containing lichens, 10.65 $\text{Mg ha}^{-1}\,\text{cm}^{-1}$ for conifer needle duff, and 16.46 $\text{Mg ha}^{-1}\,\text{cm}^{-1}$ for partially decayed wood duff (Ottmar et al., 1998). Mass of woody fuels <7.62 cm in diameter was based on the proportional abundance of different species of logs > 7.62 cm in diameter in each unit. Specific gravity values of 0.48 for sound Douglas-fir, 0.40 for sound ponderosa pine, and 0.30 for all partially decayed material were used (Brown, 1974; Forest Products Laboratory, 1999). We used non-horizontal angle correction factors and squared average quadratic mean diameters specified in Brown (1974) for slash (new activity fuels) and non-slash particles of different species.

Primary response variables were the difference between pre-treatment (1998) and post-treatment (2004) litter depth, duff depth, litter mass, duff mass, 10 h, 100 h, 1000 h sound, 1000 h partially decayed timelag fuel mass, and total woody fuel mass, and treatments were compared with a one-way analysis of variance (ANOVA) of treatment means. One-hour (0–0.64 cm) fuels, likely less important for fire behavior compared to larger fuels, were computed as 60% of 10 h fuels according to Bevins (1978) because of time constraints; these values are presented only as tabular results and were not considered in analysis of treatment differences because of the complete correspondence with 10 h fuels. Treatment means and standard errors are presented for all response variables. Fine structure differences in changes in fuel loading among treatments were examined by using *a priori* single degree-of-freedom tests within the context of the ANOVA. The five contrasts were specified as (1) the difference between the control and the three active treatments; (2) the difference between the mean of the thin and the burn treatments and the single thin + burn treatment (thus assessing the interaction effect of the combined treatments); (3) the difference between the thin and the burn treatment; (4) the difference between the burn and the thin + burn treatment; (5) the difference between the thin and the thin + burn treatment. A statistical significance level of $P < 0.05$ was used for all univariate tests. Assumptions of normality and equal variances were tested with the Shapiro-Wilk normality test and normal probability plots (Quinn and Keough, 2002). In addition to testing for the effect of treatment on each response variable, we also were interested in the overall change in fuel components, and used multivariate analysis of variance (MANOVA) to test for a simultaneous effect of treatment on the combination of changes in litter, duff, 10 h, 100 h, and 1000 h sound and partially decayed timelag fuel mass. This is a test of the null hypothesis that the effect of the treatment is zero with respect to all linear combinations of response variable. Pillai's trace was computed as the test statistic (Quinn and Keough, 2002).

2.6. Interpretation of results

We used the Fuel Characteristic Classification System (FCCS) (Sandberg et al., 2001; Sandberg, in press; Ottmar et al., 2007) to construct fuelbeds with quantitative fuel characteristics (physical, chemical, and structural properties) and probable fire parameters for each unit from inventoried data for each year sampled (total 48 fuelbeds). We used our measured fuelbed characteristics from each treatment unit to obtain synthesized properties and predictions of fire potentials from FCCS. The FCCS fire potentials are a set of relative values or indices that rate the intrinsic physical capacity of a wildland fuelbed to release energy and to spread, crown, consume, and smolder under a benchmark set of wind speed and fuel moisture conditions. The FCCS calculates each of the fire potentials on a scale of zero to nine in a three-digit integrated fire potential. The first digit represents relative potential surface fire behavior, the second digit represents relative crowning potential, and the third digit represents the fuels available for consumption.

The surface fire behavior potential uses the concepts and basic spread equations that form the basis of the Rothermel (1972) spread model that is in widespread use for fire management decision support in the United States, but uses a model reformulation that allows simulated or inventoried real-world fuelbed properties as direct input. Crown fire potential is based on Van Wagner (1977) and Scott and Reinhardt (2001) but utilizes a conceptual model by Schaaf et al. (2007) that is more flexible with regard to fuelbed characteristics and canopy structure. The conceptual crown fire model retains the limiting assumption that crown fire initiation occurs only as a result of surface fire energy release from the propagating front. Available fuel potential currently represents the mass of fuel present within the outside shell of layers of surface, ground, and canopy fuel elements that are potentially combustible under extremely dry conditions.

Briefly, the process for characterizing fuelbeds by using FCCS was first to access a database or library of existing FCCS fuelbeds through seven selection criteria: location, vegetation form, structural class, cover type, change agent, condition class, and fire regime condition class. In all cases, our unique fuelbeds are based on ''Interior ponderosa pine - Douglas-fir forest (Fire exclusion)'' (FCCS fuelbed 067) Next, we customized each fuelbed by using unique values for overstory, midstory, and understory tree cover and density, herbaceous and graminoid cover, and fuel mass and depth measurements (Table 3).

Each fuelbed included six horizontal strata: (1) ground fuels (duff), (2) litter, lichen and moss, (3) woody fuels (consisting of sound and rotten wood, piles, and stumps), (4) herbaceous (non-woody) vegetation, (5) shrubs, and (6) tree canopies consisting of both live and dead trees (snags) and ladder fuels associated with them. The first three strata contribute to smoldering and long-duration fires, the second, third, and fourth strata contribute to surface fires, and the fifth and sixth strata contribute to crown fires. Ground fuels were defined by duff depth measurements and were divided evenly between an upper and lower layer. The litter stratum was defined by litter depth measurements and the relative proportions of each of three types of litter (long needles, short needles, and hardwood) that were encountered. The woody fuels stratum was based on the mass of 1, 10, 100, and 1000 h sound and partially decayed fuels, and the density of sound stumps as a result of thinning. Because thinning involved mechanical equipment that repeatedly passed over new activity fuels (slash), we assumed that these fuels did not occur in large piles. The herbaceous stratum was based on unit level mean cover values for graminoids and forbs with literature values for their mean heights in primary and secondary layers. The shrub stratum used similar unit level mean shrub cover values cover and height values from the literature. Needle drape was not included. The canopy stratum used tree density, diameter, and height by tree species in

Table 3
Data source and measurement unit by input variable used to build FCCS fuelbeds to represent a set of fuel reduction treatments in northeastern Oregon

Input variables	Data source	Measurement units
Fuelbed FCCS067: Interior ponderosa pine - Douglas-fir forest (fire exclusion)	FCCS fuelbed library	
Total overstory cover	Vegetation sampling in 0.04-ha plots centered on each grid point	%
Overstory tree cover, height, density, diameter at breast height, and height to live crown	Mean value for treatment unit from measured values at 0.04-ha plots centered on each grid point	%, feet[a], number acre^{-1}, inches, feet
Midstory tree cover, height, density, diameter at breast height, and height to live crown	Mean value for treatment unit from measured values at 0.04-ha plots centered on each grid point	%, feet, number acre^{-1}, inches, feet
Understory tree cover, height, density, diameter at breast height, and height to live crown	Mean value for treatment unit from measured values at 0.04-ha plots centered on each grid point	%, feet, number acre^{-1}, inches, feet
Snag density, diameter, and height; snag classes include recently created and predominately sound snags, older snags without fine branches but coarse branches and bark intact, and old snags that are predominately rotten with no bark intact	Mean value for treatment unit from measured values at 0.04-ha plots centered on each grid point; assumed 20%, 40%, 40% class distribution of snags	Number acre^{-1}, inches, feet
Ladder fuels	Used default for FCCS067 except for post-thin and post-thin + burn where ladder fuels flagged as not present	Present or not present
Shrub cover, height, and percentage live	Mean cover value for treatment unit from measured values at 0.04-ha plots centered on each grid point; used default height and percentage live for FCCS067.	%, feet, %
Herbaceous cover height, and percentage live	Mean cover value for treatment unit from measured values at 0.04-ha plots centered on each grid point; used default height and percentage live for FCCS067.	%, feet, %
Non-woody fuel loading	Percentage of default for FCCS067 based on measured herbaceous cover	Tons acre^{-1}
Fine fuel loading	Mean mass value for treatment unit from measured fuels transects centered on each grid point	Tons acre^{-1}
Large fuel loading	Mean mass value for treatment unit from measured fuels transects centered on each grid point	Tons acre^{-1}
Rotten fuel loading	Mean mass value for treatment unit from measured fuels transects centered on each grid point	Tons acre^{-1}
Sound stump density	Difference in pre-and post-treatment density of overstory and midstory trees	Stumps acre^{-1}
Litter depth, duff depth, and duff cover	Measured forest floor depth, divided into litter and duff based on litter to duff depth for FCCS067, duff cover based on FCCS067	Inches, inches, %

[a] FCCS currently is configured only for English units; conversion to metric units occurred outside of FCCS.

overstory, midstory, and understory layers. Height to live crown for each tree was derived from the live crown ratio. We used the FCCS to calculate potentials for surface fire behavior, crown fire, and available fuel consumption based on the intrinsic characteristics of fuels assuming benchmark environmental conditions of 1 h fuels at 6%, 10 h fuels at 7%, 100 h fuels at 8%, graminoids and forbs at 60%, and shrubs at 90% fuel moisture content, zero slope, and 1.8 m s^{-1} wind speed. In addition, three metrics of probable surface fire behavior were computed: flame length, rate of spread, and reaction intensity.

2.7. Data quality

Because this study was established as a long-term experiment, with monitoring and evaluation of treatment effects repeated at future intervals and the same treatments reapplied in perhaps 10 years, data quality and documentation of meta-data were emphasized from study inception. Data and the respective meta-data for all measurement variables and the derived response variables were converted to a single database to facilitate error checking. In addition, all data were submitted to an independent database populated with common data from all 13 Fire and Fire Surrogate sites. All values in this national database were subjected to three independent forms of error checking, including conformance to experimental variable definitions, consistency in known or expected relationship between multiple measurement variables, and conformance within pre-established measurement variable limits.

3. Results

3.1. Fuel moisture and fire behavior

All eight units in which fire was applied (burn and thin + burn treatments) were burned within individual prescriptions of relative humidity, ambient air temperature, wind speed and direction, and fuel moisture to accommodate site and fuel loading differences, although weather and fuel moisture were generally similar throughout the burning periods (Table 2). Winds were all from the north, northwest, or northeast. Live and dead aboveground graminoid moisture content averaged 48.0 ± 5.3%. Moisture content of duff averaged 35.5 ± 2.1%, of litter averaged 12.2 ± 0.7%, of 10 h fuels averaged 14.9 ± 0.8%, and of 100 h fuels averaged 23.2 ± 2.0%. Large woody fuels (1000 h) in burn units had higher gravimetric moisture content compared to thin + burn units ($P = 0.03$).

Flame lengths varied between 0.5 and 0.9 m for all eight units. Maximum temperature at 0.3 m above the forest floor (low level) was ≥316 °C in one burn unit and 816 °C in one thin + burn unit, but did not differ between treatments ($P = 0.09$). The overall mean maximum temperature was ≥129.7 ± 16.3 °C. Elevated low level temperature was recorded at 85% of the sample points, suggesting relatively homogeneous spatial patterns in burning. Similarly, maximum temperature at 1.3 m above the forest floor (high level) was ≥260 °C in one burn unit and ≥371 °C in one thin + burn unit yet did not differ between treatments ($P = 0.19$). The overall mean maximum high level temperature was ≥80.1 ± 7.4 °C. Elevated high level temperature was recorded at 85% of the sample points. Sample points that lacked evidence of elevated temperature appeared to be randomly distributed across treatment units.

3.2. Changes in large woody fuels

Before treatment, mean total woody fuel mass across all treatments was 15.6 ± 2.2 Mg ha^{-1} (Table 3) (Fig. 2). Of this, 11.5 ± 1.7 Mg ha^{-1} (74%) was sound and partially decayed woody fuel >7.62 cm in diameter. About 39% of the large woody fuel (1000 h) was considered decayed. Mass of decayed wood in this timelag fuel class tended to decrease with active treatments (thin, burn, and thin + burn) and increase in control units, while mass of sound wood tended to decrease in all but thin units, yet overall these differences were not significant. Overall, treatments had no effect on mass of either sound or partially decayed large woody fuels (Table 4).

Mean log density was 88 ± 24 logs ha^{-1} in 2001, but differed by treatment (Table 3). Log density was greater in control units compared to actively treated units and greater in the thin units compared to burn or thin + burn units (Table 5). By 2004, log density increased to an overall mean of 116 ± 22 logs ha^{-1}. Log density was greater in control units compared to actively treated units and greater in the thin units compared to burn or thin + burn units. In addition, log density was greater in thin + burn units compared to burn units, reflecting the nearly doubling of log density in thin + burn units as result of falling snags (Table 6).

3.3. Changes in fine woody fuels, litter, and duff

The target for fine woody fuels (≤7.62 cm, or 1, 10, and 100 h woody fuels) after active treatments was ≤4.5 Mg ha^{-1}. Woody fuel mass in the 1 h and 10 h timelag class increased in thin units immediately after treatment, but fell to nearly pre-treatment levels by 2004. Overall, mass of 1 h and 10 h woody

Fig. 2. Low shrubs and graminoids, scattered logs, and clumps of ponderosa pine and Douglas-fir seedlings and saplings contribute to fuels in untreated ponderosa pine forests in northeastern Oregon.

Table 4
Mass (Mg ha^{-1}) (mean ± standard error) by fuel categories, and log density (number ha^{-1}) associated with four fuel reduction treatments in northeastern Oregon.

Treatment	1 h (<0.64 cm)	10 h (0.64–2.54 cm)	100 h (2.54–7.62 cm)	1000 h sound (>7.62 cm)	1000 h decayed (>7.62 cm)	Total woody fuel	Litter	Duff	Log density
1998[b]									
Thin	0.55 ± 0.12	0.92 ± 0.20	2.52 ± 0.60	4.12 ± 1.17	5.52 ± 1.49	13.64 ± 2.46	6.00 ± 0.82	29.44 ± 5.49	n.a.[a]
Burn	0.26 ± 0.04	0.44 ± 0.07	1.83 ± 0.16	3.16 ± 1.01	5.45 ± 1.59	11.15 ± 2.27	4.19 ± 0.43	17.89 ± 3.60	n.a.
Thin + burn	0.26 ± 0.16	0.44 ± 0.27	2.19 ± 0.48	5.08 ± 1.31	5.91 ± 1.90	13.95 ± 3.17	5.97 ± 0.17	16.44 ± 4.74	n.a.
Control	0.94 ± 0.20	1.56 ± 0.33	4.16 ± 0.59	9.63 ± 3.46	7.31 ± 2.512	23.81 ± 6.43	5.90 ± 0.97	22.27 ± 7.52	n.a.
1999									
Thin	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Burn	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Thin + burn	1.99 ± 0.17	3.33 ± 0.28	5.39 ± 0.71	5.65 ± 0.41	5.40 ± 2.07	21.77 ± 2.96	4.45 ± 0.34	17.13 ± 2.65	n.a.
Control	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
2001									
Thin	1.99 ± 0.43	3.31 ± 0.72	5.30 ± 1.00	5.83 ± 1.02	3.39 ± 0.85	19.82 ± 3.39	5.57 ± 0.86	26.36 ± 5.18	110 ± 21
Burn	0.20 ± 0.04	0.34 ± 0.06	0.97 ± 0.19	1.59 ± 0.37	0.45 ± 0.09	3.53 ± 0.53	2.10 ± 0.22	14.15 ± 2.25	23 ± 1
Thin + burn	0.78 ± 0.10	1.30 ± 0.17	1.67 ± 0.11	2.29 ± 0.55	0.47 ± 0.15	6.51 ± 1.04	2.18 ± 0.21	14.44 ± 1.64	35 ± 3
Control	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	114 ± 18
2004									
Thin	0.55 ± 0.17	0.92 ± 0.28	4.11 ± 1.06	4.96 ± 0.78	3.24 ± 0.61	13.79 ± 2.60	1.57 ± 0.25	28.36 ± 5.48	156 ± 37
Burn	0.19 ± 0.01	0.32 ± 0.03	1.15 ± 0.10	2.26 ± 0.42	0.44 ± 0.10	4.37 ± 0.47	2.71 ± 0.43	10.85 ± 1.67	30 ± 5
Thin + burn	0.35 ± 0.10	0.59 ± 0.17	2.10 ± 0.39	4.23 ± 1.02	0.60 ± 0.03	7.87 ± 1.64	1.90 ± 0.20	9.68 ± 1.79	61 ± 8
Control	0.37 ± 0.12	0.64 ± 0.21	3.04 ± 0.67	8.88 ± 4.26	7.97 ± 0.61	20.86 ± 5.03	3.74 ± 0.44	25.48 ± 7.03	195 ± 22

[a] Data not available.

[b] Values for 1998 are pre-treatment; values for 1999 are for the thin component of thin + burn treatment; values for 2001 are after all active treatments; values for 2004 are 6 years after thinning and 4 years after burning.

Table 5

Results of an ANOVA of the change (difference between pre-treatment in 1998 and post-treatment in 2004) in fuel loading (mass, Mg ha^{-1}) by category after four fuel reduction treatments in northeastern Oregon

Response variable	Mean square error	*F*	Contrast	*P*
10 h (0.64–2.54 cm)				
Treatment	0.92	3.59		0.046
Control vs. active			2.802	0.008
Thin and burn vs. thin + burn			0.425	0.506
Thin vs. burn			0.112	0.759
Burn vs. thin + burn			0.269	0.467
Thin vs. thin + burn			0.156	0.670
100 h (2.54–7.62 cm)				
Treatment	5.63	6.56		0.007
Control vs. active			4.164	0.023
Thin and burn vs. thin + burn			−1.102	0.350
Thin vs. burn			2.270	0.005
Burn vs. thin + burn			0.584	0.390
Thin vs. thin + burn			−1.686	0.024
1000 h sound (>7.62 cm)				
Treatment	2.80	0.34		0.800
1000 h decayed (>7.62 cm)				
Treatment	30.93	2.39		0.119
Total woody load				
Treatment	40.35	1.67		0.226
Litter				
Treatment	2.85	2.47		0.111
Duff				
Treatment	96.90	2.71		0.092

fuels increased with active treatment and declined in control units (Table 4). Most (67%) of the pre-treatment fine woody fuels mass was represented by 100 h fuels (2.54–7.62 cm). Mass of 100 h woody fuels increased about 0.3 Mg ha^{-1} in actively treated units and declined about 1.1 Mg ha^{-1} in control units. Thinning increased mass of 100 h fuels about 1.6 Mg ha^{-1}, while mass of 100 h fuels was decreased about 0.7 Mg ha^{-1} with burning in burn units and about 0.1 Mg ha^{-1} in thin + burn units. Overall, mass of fine woody fuels remained below the target except in thin units where mass increased to 5.6 Mg ha^{-1}.

Total woody fuel depth, measured in 2004, ranged from 20.3 ± 0.9 mm burn units to 46.0 ± 7.6 mm in control units. Actively treated units had lower woody fuel depth (26.7 ± 3.5 mm) compared to control units (46.0 ± 7.6 mm) ($P = 0.014$).

Pre-treatment litter depth was variable and averaged 21.6 ± 0.5 mm in thin + burn units, 21.2 ± 3.4 mm in control units, 20.8 ± 2.6 mm in thin units, and 15.2 ± 1.3 mm in burn units. Average litter depth remained unchanged immediately after thinning in thin units, but was reduced about 6 mm with thinning in thin + burn units (Fig. 3). Burning reduced average litter depth about 8 mm in burn units and an additional 8 mm in thin + burn units. Despite these short-term variations, there was little evidence of any difference among treatments by 2004 ($P = 0.066$), because litter depth declined from pre-treatment conditions about the same in all treatments. Litter depth averaged 9.4 ± 1.2 mm across all treatments in 2004.

Pre-treatment duff depth was more variable than litter depth and averaged 26.7 ± 5.1 mm in thin units, 18.8 ± 6.2 mm in control units, 15.7 ± 2.6 mm in burn units, and 14.7 ± 4.1 mm in thin + burn units (Fig. 4). Wide variation at the unit level, however, resulted in an overall average duff depth of 18.9 ± 2.4 mm. Overall, there was no detectable treatment effect ($P = 0.104$); duff depth increased 3 mm in control units, decreased 2 mm in thin units, and decreased 6 mm in both burn and thin + burn units between 1998 and 2004. Duff depth averaged 23.0 ± 3.5 mm across control and thin units and 9.5 ± 1.0 mm across burn and thin + burn units post-treatment in 2004.

Pre-treatment litter mass did not differ among treatments and averaged 5.5 ± 0.4 Mg ha^{-1} (Table 3). Litter mass declined 4.4 ± 0.8 Mg ha^{-1} in thin units and 4.1 ± 0.8 Mg ha^{-1} in thin + burn units compared to 1.5 ± 0.8 Mg ha^{-1} in burn units (Table 4). Litter mass declined with each measurement period in thin + burn units, but did not decline immediately after thinning

Table 6

Results of an ANOVA of the natural log of log density (number ha^{-1}) in 2001 and 2004 after four fuel reduction treatments in northeastern Oregon

Response variable	Mean square error	*F*	Contrast	*P*
Log density 2001				
Treatment	2.30	29.1		0.001
Control vs. active			2.809	0.001
Thin and burn vs. thin + burn			0.717	0.061
Thin vs. burn			−1.490	0.001
Burn vs. thin + burn			−0.386	0.078
Thin vs. thin + burn			1.104	0.001
Log density 2004				
Treatment	2.73	22.2		0.001
Control vs. active			3.372	0.001
Thin and burn vs. thin + burn			0.153	0.729
Thin vs. burn			−1.604	0.001
Burn vs. thin + burn			−0.726	0.014
Thin vs. thin + burn			0.879	0.005

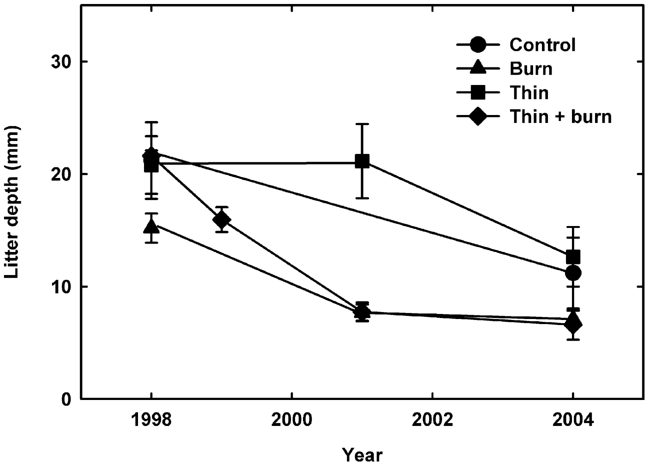

Fig. 3. Change in litter depth (mean ± standard error) with four fuel reduction treatments in northeastern Oregon.

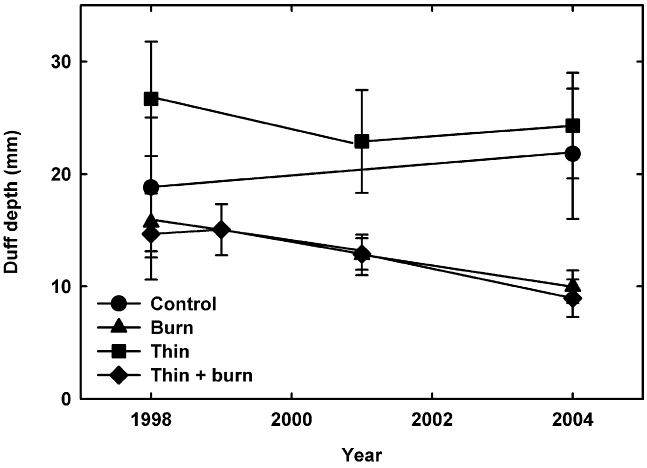

Fig. 4. Change in duff depth (mean ± standard error) with four fuel reduction treatments in northeastern Oregon.

in thin units. In general, the pattern of litter mass decline matched the pattern of litter depth decline.

Pre-treatment duff mass ranged from 16.4 ± 4.7 Mg ha^{-1} in thin + burn units to 29.4 ± 5.5 Mg ha^{-1} in thin units (Table 3) yet did not differ across all treatments. The overall pre-treatment duff mass was 21.5 ± 2.8 Mg ha^{-1}. Duff mass tended to increase about 3 Mg ha^{-1} in control units, decline about 7 Mg ha^{-1} in burn and thin + burn units, and decline about 1 Mg ha^{-1} in thin units, yet there were no detectable differences among treatments. The pattern of change in duff mass followed the same pattern of change for duff depth, but differed from relative changes in litter mass in all but the thin + burn units.

3.4. *Changes across multiple fuel categories*

Total woody fuel mass declined between 1998 and 2004 across all treatments except the thin treatment. Total woody fuel mass in 2004 tended to be about 61% less than in 1998 in burn units and about 44% less in 2004 than in 1998 in thin + burn units, while total woody fuel mass in thin units increased slightly, yet there were no differences among treatments.

Multivariate analysis of the change among treatments across the combination of forest floor, fine woody fuels, and large woody fuels (mass of litter, duff, 10 h, 100 h, 1000 sound, and 1000 decayed fuels) did not provide additional insights into relevant response variables. The null hypothesis of all linear combinations of the response variables equal to zero was rejected (Pillai's trace = 1.861, $P = 0.008$) indicating that there was at least one linear combination that represented a difference among treatments. Fine structure differences examined by using the five *a priori* contrasts statements for changes in fuel loading among treatments was inconclusive; all values of Pillai's trace were nonsignificant ($P \geq 0.063$). The integrated response variables were uncorrelated; the highest correlation was the change in 10 h and 100 h woody fuel mass (coefficient = 0.543, $P = 0.055$). Univariate ANOVA results were deemed sufficient to describe treatment differences because the response variables proved to be uncorrelated.

3.5. *Char and scorch*

Char occurred on the lower bole of 68 ± 8% of the trees in burn units and 55 ± 11% of the trees in thin + burn units, although a t-test failed to detect a significant difference between treatment means ($P = 0.409$). Charring was noted on about 60 to 80% of the ponderosa pine across all diameter classes, while Douglas-fir with larger diameters tended to be charred more frequently than Douglas-fir with smaller diameters (Fig. 5). Char height averaged 0.83 ± 0.15 m in burn units and 1.29 ± 0.30 m in thin + burn units ($P = 0.218$). Char exceeded 2 m in height only in thin + burn units, although there was no difference in char height by treatment. Char height increased with tree diameter with the exception of trees with diameter >55 cm (Fig. 6).

Scorching of live foliage occurred in 48 ± 16% of the trees in burn units and 53 ± 17% of the trees in thin + burn units, yet there was no difference between treatments ($P = 0.959$). Ponderosa pine tended to be more frequently scorched compared to Douglas-fir in burn units, while ponderosa pine and Douglas-fir >25 cm in diameter were scorched in similar proportions in thin + burn units (Fig. 7). Scorch height averaged 3.9 ± 0.9 m in burn units and 4.7 ± 0.3 m in thin + burn units, although there was no difference by treatment ($P = 0.449$). Scorch was higher in ponderosa pine than in Douglas-fir across all size classes and treatments (Fig. 8).

3.6. *Change in fire potentials*

Surface fire behavior potentials were all ≤2.0 (on a scale from 0 to 9) and did not differ before treatment ($P = 0.873$) or after treatment ($P = 0.426$) (Fig. 9). In addition to the overall surface fire potential index, three metrics of probable surface fire behavior were computed: flame length, rate of spread, and reaction intensity. Mean flame length, the average length of the flame front from the ground to the flame tips, was 0.74 m and

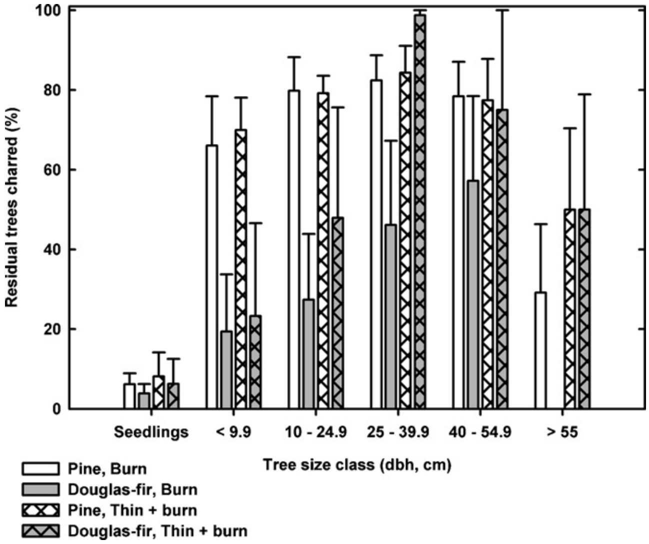

Fig. 5. Percentage of residual trees with bole charring (mean ± standard error) by tree size and species after the burn and thin + burn treatments in northeastern Oregon.

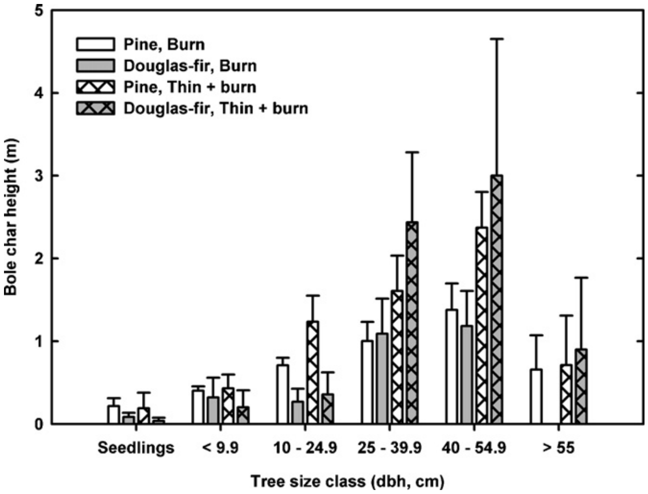

Fig. 6. Height of bole charring (mean ± standard error) by tree size and species after the burn and thin + burn treatments in northeastern Oregon.

did not differ among pre-treatment fuelbeds ($P = 0.2$) (Fig. 10). Mean flame length increased in thin units with treatment, then declined to about the same as below by 2004. Mean flame length in burn units declined slightly with treatment. Mean flame length in thin units was projected to be about twice that in burn units in 2004 ($P = 0.016$). Projected rate of spread, the speed of forward movement of a fire, was 1.82 m min^{-1} for all pre-treatment units (Fig. 11). Although the rate of spread in thin units increased slightly and the rate of spread in burn and thin + burn units decreased slightly immediately after treatments, mean rate of spread averaged 1.65 m min^{-1} across all treatments and did not differ among treatments by 2004 ($P = 0.315$). Mean reaction intensity was 211.4 kW m^{-2} min and did not differ among pre-treatment units (Fig. 12). Reaction intensity increased with the addition of activity fuels added during thinning, and declined slightly with burn and thin + burn

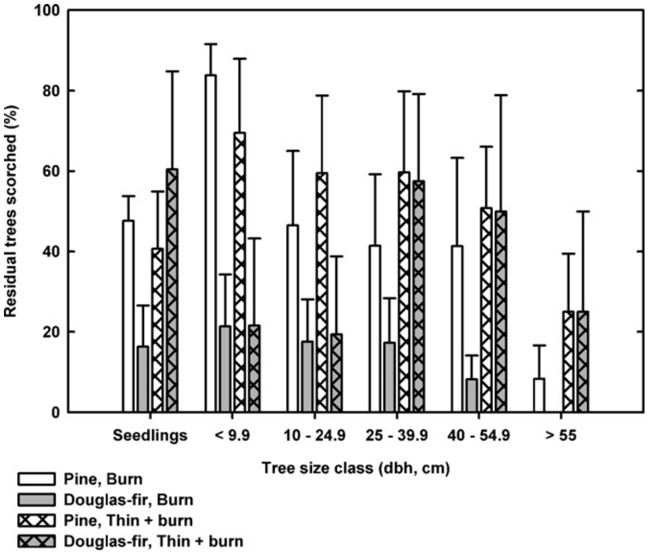

Fig. 7. Percentage of residual trees with crowns scorched (mean ± standard error) by tree size and species after the burn and thin + burn treatments in northeastern Oregon.

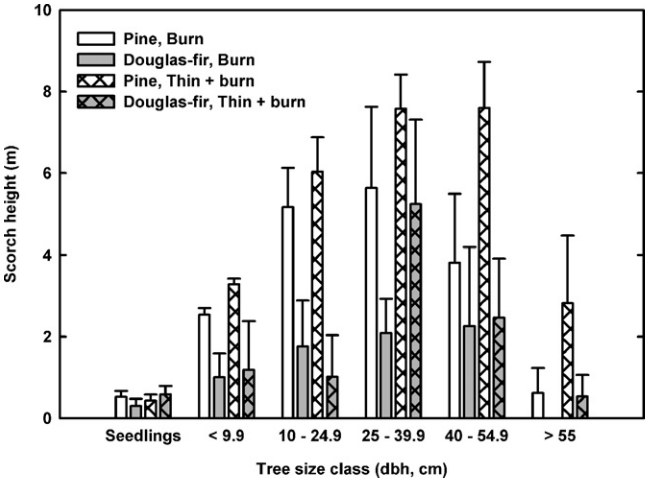

Fig. 8. Height of crown scorch (mean ± standard error) by tree size and species after the burn and thin + burn treatments in northeastern Oregon.

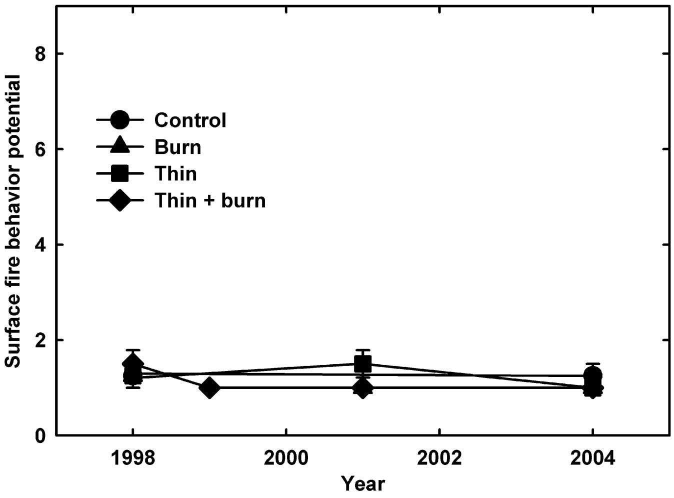

Fig. 9. Surface fire potential (mean ± standard error) projected by the Fuel Characteristic Classification System for a set of fuelbeds associated with four fuel reduction treatments in northeastern Oregon.

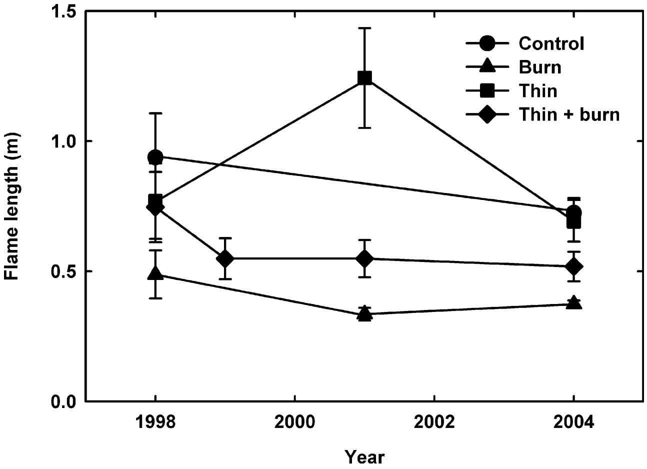

Fig. 10. Flame length (mean ± standard error) projected by the Fuel Characteristic Classification System for a set of fuelbeds associated with four fuel reduction treatments in northeastern Oregon.

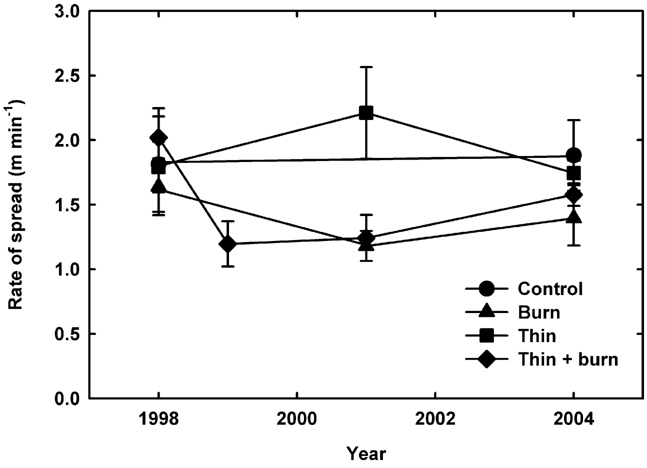

Fig. 11. Rate of fire spread (mean ± standard error) projected by the Fuel Characteristic Classification System for a set of fuelbeds associated with four fuel reduction treatments in northeastern Oregon.

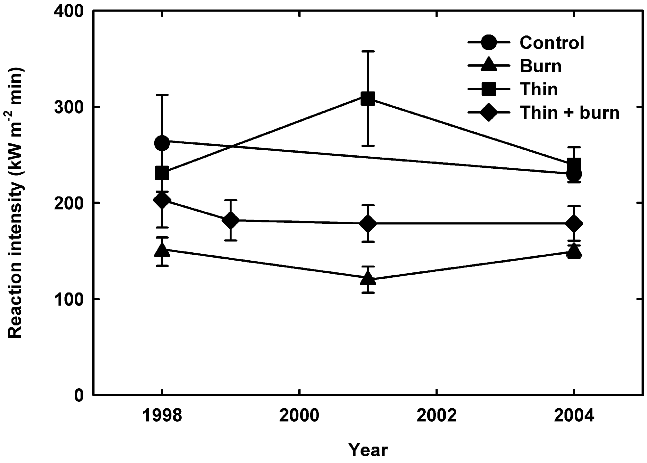

Fig. 12. Reaction intensity of fire (mean ± standard error) projected by the Fuel Characteristic Classification System for a set of fuelbeds associated with four fuel reduction treatments in northeastern Oregon.

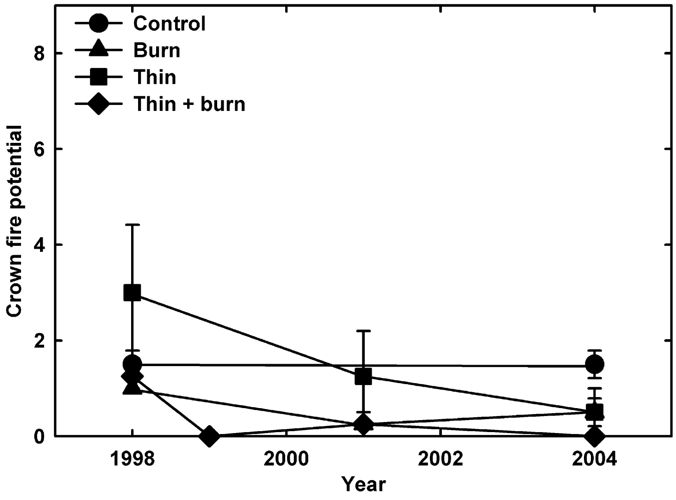

Fig. 13. Crown fire potential (mean ± standard error) projected by the Fuel Characteristic Classification System for a set of fuelbeds associated with four fuel reduction treatments in northeastern Oregon.

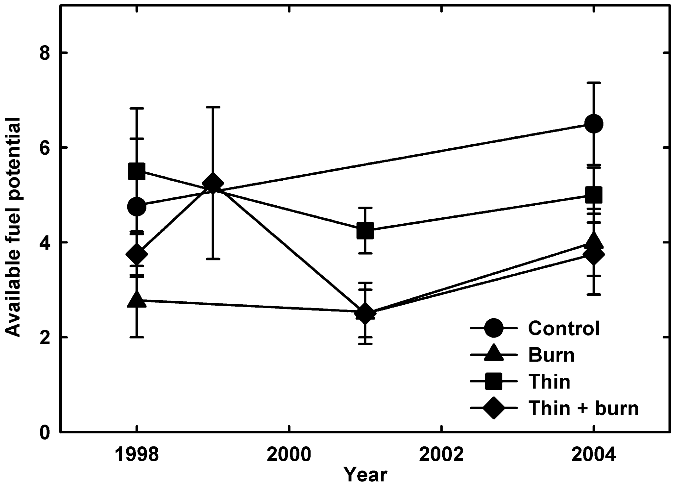

Fig. 14. Available fuel potential (mean ± standard error) projected by the Fuel Characteristic Classification System for a set of fuelbeds associated with four fuel reduction treatments in northeastern Oregon.

treatments. By 2004, burn units average 149.4 kW m^{-2} min and thin units averaged 239.6 kW m^{-2} min ($P = 0.005$). Reaction intensity in actively treated units was not lower than control units ($P = 0.079$).

Crown fire potential did not differ before treatment ($P = 0.263$) and averaged 1.7. Active treatments tended to decrease slightly the crown fire potential in the short-term, and thinning likely had the greatest effect in reducing crown fire potential. By 2004, crown fire potential in actively treated units was marginally lower than in control units ($P = 0.059$) (Fig. 13).

Available fuel potential ranged from 5.5 in thin units to 2.75 in burn units before treatments were applied, however, there was no difference among units ($P = 0.337$). The overall mean pre-treatment fuel potential was 4.2. Activity fuels associated with the thinning may have led to a short-term increase followed by a slight decrease in the available fuel potential, especially evident in the thin + burn treatment. This effect was transitory. By 2004, mean available fuel potential was 4.8 and did not differ among treatments ($P = 0.911$) (Fig. 14).

4. Discussion

4.1. Treatment justification

Thinning, burning, and the combination of thinning and burning used in this study each modified fuelbed characteristics. Yet the changes noted herein appear minor compared to those reported after stand-replacement wildfires (Passovoy and Fulé, 2006) and after similar treatments in other ecosystems (Knapp et al., 2005; Stephens and Moghaddas, 2005). While we used unusual care in selecting experimental units that were similar in aspect, slope, and elevation, were located close to each other, and were reasonably consistent in their overstory composition, age, and basal area, pre-treatment differences in fuel accumulation were evident among treatment units. We view this as an acceptable consequence of conducting ecological studies at an operational scale. We based our analysis of treatment differences not on the absolute quantity of fuel remaining on site after treatment, but rather on the change between pre-existing conditions and the conditions after treatment. Variation in fuel accumulation by treatment was thus the combination of variation in stand structural attributes, past disturbances, and differences directly attributable to treatment implementation. Slight declines in the estimates of litter mass, and slight increases in the estimates of 1, 10, and 100 h timelag classes suggests that while the treatments were considered an operational success, they did little to modify the arrangement and structure of the fuelbeds, and that changes caused by our treatments were minor within the context of natural disturbances that occur within this portion of northeastern Oregon forests.

Silviculturists and fuels managers throughout the western United States are increasingly being asked to design fuel reduction treatments for low-elevation landscapes that historically supported high frequency, low severity fires. Historical structure in ponderosa pine forests has been described as open and park-like, dominated by large, typically uneven-aged trees with recruitment into the overstory occurring at small spatial and long temporal scales (White, 1985; Arno et al., 1997; Kaufmann et al., 2000; Wright and Agee, 2004; Youngblood et al., 2004; Brown and Cook, 2006). While reference conditions for stand structure that are derived from the legacy contained in tree rings and historical records may suggest tree densities and diameter and age distributions, we have little to guide the development of reference conditions for fuels other than knowledge of the frequency and severity of past burns. Thinning and burning are often used to reduce stand basal area and density of small trees, remove fire-sensitive trees, reduce accumulations of woody fuels, increase height to live crowns, and create more fire-resistant forest structure. There is broad agreement that these management practices should move forests in the direction of historical structures and disturbance regimes (Youngblood et al., 2004) and contribute to process-centered restoration goals (Falk, 2006). A more conservative approach to management, that questions the feasibility and desirability of emphasizing seral conditions, was advocated by Tiedermann et al. (2000).

Thinning is designed to improve growth of the residual trees, to enhance forest health, or to recover potential mortality in immature forests. Thinning also may be used to develop or protect vertical and horizontal forest structure, to develop larger trees, snags, and down wood for terrestrial habitat, and to promote late-successional characteristics (Powell et al., 2001). Broad scale application of mechanical thinning has been suggested as a management strategy for low elevation dry forests in northeastern Oregon in part because thinning avoids air quality degradation issues (Mutch et al., 1993). Increasingly, thinning has been suggested for making forests more resistant to uncharacteristically severe fire (Miller and Urban, 2000). In the context of fuel reduction treatments, thinning may be most appropriate when trees are sufficiently large and dense that the structure of the stand is changed by density reduction, and when treatments with fire would kill too many overstory trees (Brown et al., 2004). We used a low thinning (thinning from below) that removed lower canopy trees and retained larger codominant and dominant trees, aiming to mimic mortality caused by tree-to-tree competition or surface fires under historical conditions (Graham et al., 1999).

Large scale use of prescribed fire has been recommended as a primary means for removing undesirable fuel accumulations, for controlling unwanted dense regeneration that serves as ladder fuels, for increasing forage production, for converting organically bound nutrients to forms more readily available for plant uptake, and for decreasing the risk of stand-replacement wildfire in low elevation dry forests (Mutch et al., 1993; Harrington, 1996). Burning as a fuel reduction treatment may have the desired attributes of being "natural" within the ecological system and may provide a full range of ecological effects because of varying intensities across burn units (Brown et al., 2004), yet is imprecise within the context of single tree effects. Perhaps the greatest impediments to increased use of burning in low elevation dry forests are legal and social constraints on smoke production. While broad scale prescribed burning likely produce less smoke than a large wildfire, the emissions associated with future burning treatments is projected to exceed current levels and to persist over longer times (Arno and Ottmar, 1994). Our treatments were purposely applied as late season or fall burns because at this time woody fuel, vegetation, and duff moisture levels are usually lower than during early season or spring burning periods and lower moisture levels enhance the uniform spread of fire allowing for more efficient application of fire on the treated landscape. In addition, we assumed that most plant species within our study area are adapted to a fire regime that featured frequent late season or fall wildfires.

Low elevation, dry forests in northeastern Oregon may be particularly suited to applications of thinning coupled with burning for reducing fuels and restoring and maintaining forest cover that is resistant to severe insect, disease, and wildfire damage (Mutch et al., 1993; Arno and Ottmar, 1994). In this study, the thin + burn treatment was considered a single treatment. Effects of the initial thin component of the thin + burn treatment were distinguished only to capture the short-term effect on fuel accumulation.

While treatments such as our thinning and burning are not new silvicultural practices in low elevation forests, better information is needed about both short- and long-term ecological consequences and tradeoffs of treatments (Weatherspoon, 2000). Current understanding of the effects of various fuel reduction treatments that modify both surface fuels and duff layers and their resident organisms and also modify the processes that link organic fuels with mineral soils such as fine root dynamics are especially lacking. Ectomycorrhizal fungi that aid in nutrient uptake by ponderosa pine had reduced species richness and live root biomass in burn and thin + burn units on our sites the first year post treatment (Smith et al., 2005). Repeated burning at 2-year intervals over a total of 20 years in Arizona produced similar reductions in fine root length, fine root biomass, and ectomycorrhizal root biomass, yet estimates of nutrient dynamics were similar in burned and unburned plots (Hart et al., 2005), suggesting that long-term site productivity and growth of ponderosa pine may be unaffected. Thinning increased the density of common small mammal species in ponderosa pine forests of northern Arizona, while burning reduced shrub cover, woody debris biomass, and small mammal densities (Converse et al., 2006). In the same study area in northeastern Oregon as reported here, Youngblood et al. (2006) reported that the thin, burn, and thin + burn treatments reduced the density, but not the basal area of live overstory trees, and thinning tended to decrease the abundance of shade tolerant, moist-site understory species, while increasing the dominance of common rhizomatous species of grasses and shrubs. In contrast, burning increased the frequency and average cover of shade tolerant perennial species associated with fine textured soils. Substantial effort is being devoted to increasing our understanding of short- and long-term ecological consequences and tradeoffs of thinning and burning treatments; however, there remains little agreement in treatment efficacy across broad regions or among multiple fire-dependent ecosystems for sustaining healthy forest ecosystems and regulating fuels (Stephens, 1998; van Wagtendonk, 1996; Weatherspoon, 2000). There is as yet no comprehensive comparison of effects across the many fire-dependent forest ecosystems to guide decision-makers. Innovative operational-scale experiments such as those of the Fire and Fire Surrogate study are essential for providing this comparison.

4.2. Thinning effects

In our study, mechanical thinning from below using a harvester-forwarder combination removed 59.7 ± 6.9 Mg ha^{-1} in both live and dead standing and down biomass (Matzka, 2003) (Fig. 15). Essentially all of this biomass was removed as standing trees, however, because the thinning treatment had little overall effect on large down woody biomass. Surprisingly, mass of 1000 h sound fuels initially increased about 40% within the thinned units before declining to a level that represented about a 20% overall increase after thinning, while mass of 1000 h partially decayed fuels was reduced about 40%. These modest declines in large partially decayed fuels most likely represent degradation of piece size due to mechanical disturbance (Torgersen, 2002). Thinning nearly doubled the mass of 100 h fuels, while smaller 1 and 10 h fuels increased initially with treatment, but returned to pre-treatment levels after several years. In our study, the doubling of mass in 100 h fuels probably represents branchwood and tree tops that failed to meet contract utilization standards. The initial increase in mass of 1 and 10 h fuels, followed by the return to pre-treatment levels, represents an initial flush of activity fuels that decays and is quickly incorporated into litter and duff layers even in the dry environment of northeastern Oregon. Consequently, total woody fuel load was greater the first year post-treatment compared to pre-treatment, but returned to initial loading level after 6 years. Our thin treatment failed to achieve the target of ≤ 4.5 Mg ha^{-1} for the combined 1, 10, and 100 h fuels. Litter mass was reduced about 75% in thinned units, but this decline was no different than other treatments. In contrast, duff was essentially unchanged with thinning. While we lack pre-treatment data for log resources, our thinning likely had little effect on log density. Log density after thinning was similar in 2001 and 2004 to log density in control units and higher than in burn and thin + burn units. These log resources provide important habitat for a host of small mammals, amphibians, and reptiles, primarily as escape cover, shelter, and runways (Bull et al., 1997) and our study documents the retention of these habitat features with thinning as a fuel reduction treatment.

Fig. 15. Abundant low shrubs and graminoids, scattered logs, and clumps of ponderosa pine and Douglas-fir saplings remain after reducing fuels by using a thin treatment in ponderosa pine and Douglas-fir in northeastern Oregon.

Thinning from below is commonly applied to reduce tree density in dry forests throughout the west, yet there is little documentation of empirical results of the effects of thinning from below with respect to fuel reduction. Pollet and Omi (2002) showed that in eastside ponderosa in the Lake Tahoe Basin, a thinning treatment resulted in lower fire severity and less crown scorch compared to untreated stands burned by wildfire. Our results are consistent with work by Agee and Skinner (2005), who postulated that harvester-forwarder operations increase surface fuels, while concentrating and compacting the fuels. Our work is difficult to compare to published work from other FFS study sites in the central Sierra Nevada where thinning in heavy fuels was coupled with mastication of surface fuels and small diameter trees (Stephens and Moghaddas, 2005), thus changing fuelbed configuration and distribution. Thinning in similar ponderosa pine and Douglas-fir forests on steep ground at the FFS Mission Creek site in the eastern Cascades also increased 10 h fuels (Agee and Lolley, 2006).

4.3. Burn effects

In this study, late season burns reduced the mass of 1000 h sound fuels nearly 30% and reduced the mass of 1000 h partially decayed fuels over 90% (Fig. 16). Burning reduced the mass of 100 h and smaller fuels somewhat less, yet the comparison between changes in mass of 100 h fuels with burning and with thinning was the only comparison with

Fig. 16. Dense cover of graminoids and forbs with little large woody fuels after reducing fuels by using a burn treatment in ponderosa pine in northeastern Oregon.

statistical significance. Overall, mass of woody fuels was reduced about 60% with burning. The burn treatment achieved the target of $\leq$4.5 Mg ha^{-1} for the combined 1, 10, and 100 h fuels. Burning resulted in decreases in both litter and duff depth and <40% reduction in litter and duff mass. Scorch and char heights suggest that few if any trees would be expected to have high probability of delayed mortality, based on regional guides for assessing survival of fire-injured trees (Scott et al., 2002). Latent mortality of overstory trees caused either directly from burning or from the interaction of burning, insects, diseases, and environmental conditions may continue for years (Swezy and Agee, 1991; Busse et al., 2000; Agee, 2003).

We expected a greater reduction of surface fuels than the burns produced, yet the modest reduction of surface fuels is not unusual. Burns conducted for this study were carefully tailored to each burn unit to consume small surface fuels yet prevent movement of the flame into overstory canopies. Thus, consumption of large woody fuels and fire-causes changes to overstory structural attributes were limited. More aggressive burning prescriptions would likely achieve greater amounts of fuel consumption, coupled with greater scorching of live tree canopies and more tree mortality, with correspondingly greater risk that the burning front would transition from surface to crown fire. Greater scorching and tree mortality would ultimately result in inputs of woody fuels to the surface fuelbeds. Our burns were the first in what is likely to require multiple entries in order to return fire to these stands at their historical frequency and severity.

A growing body of literature addresses the effects of underburning in ponderosa pine forests in the western United States. Pollet and Omi (2002), working with eastside ponderosa pine in the Lake Tahoe Basin, showed that an underburning treatment could lower fire severity and reduce crown scorch compared to untreated stands burned by wildfire. Late season burns in Sierra Nevada mixed conifer forests that differed from our stands in the smaller component of ponderosa pine and the order of magnitude greater pre-treatment fuel loads were successful in reducing fuel mass across all timelag classes, but did not effect log density (Knapp et al., 2005). In ponderosa pine and Gambel oak forests outside Grand Canyon National Park that resemble our pre-treatment fuel loadings, recent work showed that fuel loadings measured 5 years after underburning were about one-third of untreated stands (Fulé et al., 2005). Burning on steep ground in the eastern Cascades reduced the mass of 1 and 10 h fuels and forest floor mass and depth, but had little effect on reducing simulated wildfire behavior (Agee and Lolley, 2006).

4.4. Thin + burn effects

Mechanical thinning from below, using a harvester-forwarder combination, removed 93.6 ± 10.1 Mg ha^{-1} in both live and dead standing and down biomass as the first part of the thin + burn treatment (Matzka, 2003) (Fig. 17). We have no direct measure of the woody mass on the forest floor that was removed as merchantable volume. Total woody fuel loading actually increased 56% during the thinning, primarily as a result of increased mass of 10 and 100 h fuels. In contrast, 1000 h sound fuels increased about 10% and 1000 h partially decayed fuels declined about 10%. This suggests that the mechanical harvester-forwarder combination was ineffective in reducing down woody biomass. The burning component of the thin + burn treatment was more effective than the thinning component in overall fuel reduction; nearly 65% of the existing total woody biomass was consumed during the burns. This reduction was not uniform across timelag classes; 10 and 100 h fuels increased slightly with treatment, 1000 h sound fuels decreased about 17%, and 1000 h partially decayed fuels declined about 90%. Our thin + burn treatment achieved the target of retaining $\leq$4.5 Mg ha^{-1} of fuels in the combined 1, 10, and 100 h timelag classes. This treatment also resulted in modest decreases in both litter and duff depth and in litter and duff mass.

While we detected no differences in char and scorch heights between the burn and the thin + burn treatments, our results do suggest that for some ranges of tree diameters, charring and scorching in the thin + burn units occurred at greater heights than in units that were only burned. Bole charring was

Fig. 17. Widely spaced trees, lush graminoids, scattered low shrubs, and freshly fallen logs after reducing fuels by using a thin + burn treatment in ponderosa pine in northeastern Oregon.

especially prevalent on medium and large Douglas-fir (diameters between 25 and 54.9 cm) and extended up to 3 m in height. Small, medium, and large ponderosa pine (diameters between 10 and 54.9 cm) were scorched nearly 8 m above the ground. This suggests that some activity fuels were added to fuelbeds during the harvester-forwarder operations and may have increased fire intensity.

Similar thin + burn treatments have not been as widely applied across the west as have underburn or thin treatments. Somewhat similar results were found in southwestern ponderosa pine and Gambel oak forests outside Grand Canyon National Park, where thinning to emulate pre-fire-exclusion conditions followed by prescribed burning left fuel loadings after 5 years nearly the same as untreated stands, presumably because of greater mortality of residual trees (Fulé et al., 2005). Preliminary results from the eastern Cascade FFS site in Washington, with only two thin + burn units, suggest that this treatment may produce more varied results that depend, in part, on the amount of fuels added during the thinning portion of the treatment (Agee and Lolley, 2006).

4.5. Implications for management and further research

A broad range of changes resulted from our four fuel reduction treatments. The three active treatments (thin, burn, thin + burn) are first steps in the process of restoring historical fuelbed and forest structure conditions and reestablishing ecosystem processes that may reduce the risk of uncharacteristically severe wildfire (Fiedler et al., 1998; Harrod et al., 1999; Spies et al., 2006). Managers are cautioned to use our results as indicative of only the first in a series of planned treatments. It is unlikely that any single treatment or entry will mitigate the nearly 80 years of fire exclusion and fuel accumulation in low elevation dry forests. A second treatment application in 10–15 years may provide greater efficacy and a greater reduction in the risk of uncharacteristically severe wildfires while continuing to shape the forest structure.

We base our interpretation of treatment effects with respect to future wildfire on the Fuel Characteristic Classification System and the measures of fire hazard: surface fire behavior potential, crown fire potential, and the fuels available for consumption. These potentials provide managers a means of comparing and communicating the degree of fire hazard of any unique fuelbed to evaluate the effectiveness of fuel treatments. As a component of surface fire behavior, we used the FCCS to derive three additional metrics of surface fire behavior: flame length, rate of spread, and reaction intensity. Note that reaction intensity (kW m^{-2} min) appears similar but is not equivalent to fireline intensity (kW m^{-1}).

The surface fire behavior potential is a derived index reflecting the maximum of the latent reaction intensity or energy released per unit area and time, the latent rate of spread in surface fuels, and the latent fireline intensity or flame length. It is based on measured fuelbed characteristics and the work of Rothermel (1972) as modified by Sandberg et al. (2007a, 2007b). In this study, surface fire behavior potential was initially rated low (≤ 2 across all treatments in all years. Interestingly, there was no spike in surface fire behavior potential suggestive of increased fuel loadings of activity fuels. Thus, our results suggest that no elevated risk of more severe fire behavior related to activity fuels.

Crown fire potential is a derived index incorporating potential surface fire intensity, the physical gap between the surface fuels and the overstory canopy, the presence of fuel ladders, and the canopy closure. Crown fire potential reflects a combination of the potential for individual crown ignition, the potential for a surface fire to reach and carry through the overstory canopy, and the potential for fire to carry through a canopy independent of surface fire. Our estimates of pre-treatment crown fire potential were relatively low (≤ 2) for all treatments except for the thin treatment. Crown fire potential either declined (with active treatments) or remained low (in control units). Thinning increased the gap between the surface fuels and the forest canopy by reducing the density of small diameter Douglas-fir that originally bridged the gap. Presumably the burn and the thin + burn treatments had a somewhat similar effect, although the overall effect was negligible because of low initial crown fire potential.

Available fuel potential is a derived index that is a sum of the expected consumption of fuel loads under oven-dry conditions during the flaming, smoldering, and residual smoldering phases of combustion. Partitioning of combustion into the flaming, smoldering, and residual smoldering phases reflects fuel loading of fuel particles of different size, heat content, surface area-to-volume ratio. Our estimates of available fuel potential indicated little change among treatments and years; available fuels increased in control units with stand development through tree mortality, branch and litter fall, and duff development, while available fuels declined with active treatment, but quickly returned to pre-treatment levels. This suggests that future management actions in these stands may require more aggressive fuel treatments to maintain the available fuel within desired limits.

What are the avenues for future research of fuel dynamics in low elevation, dry forests dominated by ponderosa pine and Douglas-fir? We report evidence that fuel reduction treatments, conducted in the context of restoring both forest structure and historical processes, resulted in differential short-term changes in fuelbeds. These findings provide a necessary foundation for future and ongoing assessments of vegetation dynamics, treatment economics, and interactions among treatments, various avian guilds, and insect populations that lead to tree mortality. Further work with potentially more severe treatments, such as greater basal area reduction or greater mortality from burning, would aid in quantifying ecosystem resilience. When extended beyond this first set of treatments, our study will provide a foundation for assessing the effects of continued long-term restoration treatments for reducing fuels and accelerating the development of late-successional stand structure in low elevation dry ponderosa pine and Douglas-fir forests of northeastern Oregon. As part of the national Fire and Fire Surrogate study, this work identifies the nature and strength of ecological responses that cross ecosystem boundaries, and provides managers a framework for predicting the outcome of restoration treatments.

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