Restoration Treatment Effects on Stand Structure, Tree Growth, and Fire Hazard in a Ponderosa Pine/Douglas-Fir Forest in Montana

Carl E. Fiedler, Kerry L. Metlen, and Erich K. Dodson

Abstract: Crown fires that burned thousands of ha of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) forests in recent years attest to the hazardous conditions extant on the western landscape. Managers have responded with broad-scale implementation of fuel reduction treatments; however. because threats to pine forests extend beyond fire, so too must the approaches to address them. This western Montana study evaluated four treatments in a randomized complete block experiment for their effects on stand structural characteristics, growth increment, and crown fire potential. Evaluation of control, burn-only, thin-only, and thin-burn treatments showed that the combined thin-burn treatment had the greatest number of desired effects, the burn-only had the fewest, and the thin-only was intermediate. The thin-burn significantly reduced stand density, canopy cover, torching hazard, and crowning hazard and increased average diameter, height-to live-crown, and basal area increment; the thin-only reduced stand density, canopy cover, and crowning hazard and increased average diameter and basal area increment; and the burn-only reduced torching hazard and increased height-to-live crown. These structural and growth effects are related to or influence numerous stand/ecosystem properties at our site, including diameter distributions, species composition, large-tree development potential, overall tree vigor, potential for shade-intolerant tree regeneration, and resiliency to fire. Results demonstrate that well-designed restoration treatments can promote key short-term stand and ecosystem responses while significantly reducing crown fire potential. For. Sci. 56(1):18–31.

Keywords: basal area increment, crown fire, density, fuel reduction, mechanical, thinning

Historically, many pure ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) and pine-dominated dry coniferous forests were shaped by frequent, low-intensity fire. This disturbance regime sustained open, large-tree dominated structures with diverse and productive understory communities (Arno 1980, Hessburg and Agee 2003). However, over the last century, fire suppression, livestock grazing, and high-grade logging, among other factors, have altered the structure and function of dry coniferous forests across much of the American West. Dramatically higher stand densities and development of ladder fuels (Covington and Moore 1994a, Arno et al. 1995, Peterson et al. 2005) increase the risk of uncharacteristically severe wildfire (Everett et al. 2000, Friederici 2003), bark beetle infestations (Fettig et al. 2007), and in some areas, successional replacement by shade-tolerant competitors (Gruell et al. 1982, Mutch et al. 1993, Habeck 1994, MacKenzie et al. 2004).

Restoration treatments are increasingly being recommended in these forests to reduce fire hazard (Fiedler et al. 1996, Covington et al. 1997), sustain/recruit large trees (Covington and Moore 1994b, Fiedler et al. 2007, Kolb et al. 2007), enhance understory plant productivity and diversity (Griffis et al. 2001, Laughlin et al. 2004, Dodson et al. 2007), reduce proportional composition of Douglas-fir (*Pseudotsuga menziesii* [Mirbel] Franco var. *glauca* [Beissn.] Franco) or true firs (*Abies* spp. [Mill]), induce regeneration of ponderosa pine (Fiedler 2002), stimulate nutrient cycling processes (Gundale et al. 2005), and improve tree vigor (Kolb et al. 2007). Increased vigor has important indirect effects on forest structure by accelerating large tree development (Fiedler 2000a) and reducing vulnerability to bark beetle attack (Wallin et al. 2008). Bark beetles, in turn, influence forest structure and function by regulating aspects of primary production, nutrient cycling, vegetative succession, and the size, distribution, and abundance of trees (Fettig et al. 2007), but not necessarily in ways desired by forest managers (e.g., killing large trees).

Reference conditions representing the range of natural (or historical) variability of ecosystem structures and processes have been proposed as a reasonable restoration goal (Fulé et al. 1997, Harrod et al. 1999, Moore et al. 1999, Friederici 2003, Stephens and Fulé 2005). These conditions provide reasonable references or targets not because they are historical, per se, but because they have been sustainable (Fiedler 2000b). Restoration treatments that approximate desired conditions tend to create relatively open, large-tree dominated structures primarily composed of seral species. Such conditions favor regeneration of shade-intolerant pine and increase resistance to crown fires (Covington et al. 1997, Swetnam et al. 1999, Fiedler et al. 2001). Techniques to restore forest structure and function typically include some level of stand manipulation via silvicultural cutting, prescribed burning, or both (Fiedler et al. 1998, Moore et al. 1999, Friederici 2003, Hessburg and Agee 2003). In some areas, even herbicides have been used.

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Acknowledgments: We thank Tucker Bishop, Doug Bushey, Amber Harrison, Holly Miller, Robert Nelson, and Shelly Saras for field assistance, David Affleck for analytical consultation, and two anonymous reviewers for helpful comments on the manuscript. This is Contribution Number 90 of the National Fire and Fire Surrogate Project, funded by the US Joint Fire Science Program.

Manuscript received May 29, 2008, accepted July 10, 2009

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Managers, particularly on federal ownerships, broadly support restoration objectives of enhancing large-tree development, increasing overall tree vigor, and reducing crown fire hazard but have little research to draw on in terms of specific treatments and expected outcomes. Operational-level field experiments specifically focused on evaluating restoration treatments could provide managers with a stronger basis for designing treatments that better achieve their objectives. Despite the millions of ha of dry coniferous forests in the West rated at risk to unnaturally severe wildfire (General Accounting Office 1999), few studies to date (e.g., Fulé et al. 2001, Agee and Skinner 2005, Stephens and Moghaddas 2005) have focused on quantifying treatment effects on stand structure and fire hazard in these forests, especially in the northern portion of the range of ponderosa pine.

General approaches to fire hazard reduction include narrowly focused fuel reduction approaches, with the primary aim of reducing or changing the structure, kind, or volume of fuels, and broader restoration approaches (such as the one used in this study), with the aim of addressing stand density, structure, and species composition relative to insects, disease, tree vigor, understory productivity, nutrient cycling processes, and regeneration needs of desired tree species. Implicit in the second approach is that more comprehensive treatments that address a broader range of ecological concerns will create low-hazard, fire-resilient conditions as a byproduct of treatment, rather than as the primary focus of treatment (Fulé et al. 2001). Thinning and burning treatments can be viewed as a first step in the long-term process of broader ecological restoration (Arno and Fiedler 2005), increasing resource availability and facilitating reintroduction of disturbance processes. Specifically, treatments manipulate or indirectly influence key stand attributes such as density (trees [TR] ha^{-1} and basal area [BA] ha^{-1}), structure (diameter distribution [TR] ha^{-1} by diameter class), species composition, quadratic mean diameter (QMD), which is the diameter of the tree of average BA, canopy cover (CC), and height to live crown (HLC). Besides their integral association with structure, levels of one or more of these characteristics take on special significance in pine forests, given their relationship to bark beetle susceptibility (Larsson et al. 1983, Kolb et al. 1998, Fettig et al. 2007), regeneration of desired pine species (Guldin and Baker 1998, Fiedler 2000a), understory diversity and productivity (Laughlin et al. 2004, Metlen and Fiedler 2006), and crown fire potential (Fulé et al. 2001, Fiedler et al. 2004, Stephens and Moghaddas 2005).

This study was conducted at the University of Montana's Lubrecht Experimental Forest, located in west-central Montana. It is one of 12 sites in the nationwide Fire and Fire Surrogate (FFS) study network, which has an overall goal of evaluating the ecological consequences of wildfire hazard reduction treatments (Weatherspoon 2000). The primary objective of this study was to quantify treatment effects on stand structural characteristics and growth increment and to evaluate treatment effectiveness in reducing fire hazard. Specific objectives were to 1) evaluate the effectiveness of burn-only, thin-only, and thin-burn treatments in achieving target stand density levels (i.e., BA ha^{-1}), 2) evaluate treatment effects on stand structural characteristics, including QMD, HLC, and CC, 3) evaluate changes in diameter distributions resulting from treatments using multivariate tools, 4) evaluate treatment effects on BA increment (BAI) and height increment (HI), and 5) evaluate treatment effectiveness in reducing torching and crowning potential in relation to basic fuel reduction principles (as in Agee and Skinner 2005).

We hypothesized that all three active (noncontrol) treatments would significantly reduce stand BA but expected the burn-only to be less effective than the two treatments that included thinning. We also hypothesized that all active treatments would increase QMD and HLC but reduce CC and torching and crowning potential. We further hypothesized that the thin-only and thin-burn would increase BAI but not HI. Finally, we hypothesized that the thin-burn would elicit the greatest overall changes in stand structural attributes and modeled torching and crowning indices.

Methods

Study Area and Design

The study is located in a second-growth forest at the University of Montana's Lubrecht Experimental Forest in western Montana, approximately 50 km east of Missoula, MT (46°53′N, 113°26′W). The historical mean fire interval for the area was 7 years (range of 2 to 14 years), with 68% of the fires occurring in the early portion of the growing season (Grissino-Mayer et al. 2006). The area was heavily logged in the late 1800s and early 1900s, and the current forest was initiated soon afterward (Henry Goetz, pers. comm., University of Montana-Missoula, Aug. 23, 2005). Ponderosa pine and Douglas-fir comprise the majority of the overstory, with occasional lodgepole pine (*Pinus contorta* Douglas ex Louden) and western larch (*Larix occidentalis* Nutt) in mixture. Seedlings and saplings of shade-tolerant Douglas-fir are abundant in the understory, whereas similar-sized ponderosa pines occur mostly in scattered thickets. The entire study area is classified within the Douglas-fir habitat type series (Pfister et al. 1977). Elevation of the study area ranges from 1,263 to 1,388 m. Mean annual air temperature is 7°C, with mean annual maximum and minimum temperatures of 13 and 0°C, respectively (National Climatic Data Center 2003). Mean annual precipitation is 50 cm (Nimlos 1986), about half of which falls as snow.

This study used a randomized complete block design with three blocks and four treatments. Three 36-ha blocks were delineated in relatively homogeneous ponderosa pine/Douglas-fir forest conditions and divided into four square treatment units of 9 ha each. Each of four treatments was randomly assigned once in each of the three blocks. A 6 by 6 grid of 36 points was systematically established in each treatment unit, with 50-m intervals between points. We used a stratified random design to ensure dispersion of sample points throughout a treatment unit and selected 10 points within each treatment unit to serve as plot centers for 20 m × 50 m (0.1 ha) modified Whittaker plots (Keeley et al. 1995, Metlen and Fiedler 2006). Each row and column in the grid was required to have at least one plot assigned but no more than two. Each plot was subdivided into 10 subplots of 10 m × 10 m (100 m^2). Further details on study design and plot layout can be found in Metlen and Fiedler (2006).

Restoration Treatments

The treatment prescriptions and range of posttreatment target conditions developed for this study were derived from a variety of sources on ponderosa pine forest structure, ecology, and management in Montana and the Inland Northwest (Anderson 1933, Meyer 1934, Larsson et al. 1983, Fiedler et al. 1988, Menakis 1994, Arno et al. 1995, Morgan 2000). Stand reconstructions were not available for our site, nor did any large, "old-growth" trees remain on site. However, a reconstruction of 1906 forest conditions on similar sites in the nearby Bitterroot National Forest indicated approximately 50 large (>50 cm dbh) TR ha^{-1}, nearly all ponderosa pine (Menakis 1994). Descriptions by Anderson (1933) and Meyer (1934) profiled virgin ponderosa pine stands that were relatively open and many-aged, ranging from seedlings to 600-year-old trees. Larsson et al. (1983) reported that maintaining pine densities below 19 m^2 ha^{-1} to enhance tree vigor also reduced susceptibility to bark beetle attack. Fiedler et al. (1988) presented BA density guidelines ranging from 8 to 12 m^2 ha^{-1} for securing ponderosa pine regeneration in uneven-aged stands on drier habitat types (Pfister et al. 1977). Reconstructions of five dry-site stands on the Lolo and Bitterroot National Forests by Arno et al. (1995) showed clumpy, uneven-aged structures with densities ranging from 65 to 77 TR ha^{-1} (trees establishing before 1900). Arno et al. (1995) noted wide disparities in tree ages and arrangements among these stands, despite nearly identical fire histories, climate, and site conditions. Elsewhere in Montana, reconstructions by Morgan (1999) of five old-growth ponderosa pine stands found pre-1880 densities ranging from 17 to 44 TR ha^{-1}.

We used a broad rather than strict interpretation of these varied sources of historical reference conditions and contemporary research findings to guide our treatment prescription development. This approach is consistent with Allen et al. (2002) and Brown et al. (2004), who suggested that reconstructed historical conditions are most useful when used as general guides in prescription development, rather than as rigid restoration prescriptions, per se. Furthermore, the stands treated in this study are not old-growth stands that have been invaded by young trees since fire exclusion. Instead, these are second-growth stands that regenerated and gradually filled in after heavy cutting a century ago. Realistic treatment objectives in such conditions are to reduce density and modify species composition in ways that increase tree growth and vigor, reduce wildfire hazard, induce ponderosa pine regeneration, increase pine composition, increase average tree size, and expedite reintroduction of fire. Any reasonable resemblance to reference or historical conditions is many decades and multiple additional treatments into the future.

Based on broad interpretation of historical reference conditions and contemporary research findings, desired future conditions at our site would be uneven-aged, relatively open (i.e., BA from 8 to 20 m^2 ha^{-1}), dominated by large trees (i.e., >40 cm diameter at 1.37 m height [dbh]), primarily pine composition (i.e., ≥90% pine), and random to clumpy in arrangement. Achievement of these structural/compositional goals should create sustainable, fire-resilient forests, which is a primary management goal. In addition, national FFS network protocols specified that ". . . each noncontrol treatment shall be designed to achieve stand and fuel conditions such that, if impacted by a head fire under 80th percentile weather conditions, at least 80% of the basal area of overstory (dominant and codominant) trees will survive" (Weatherspoon 2000).

Four treatments (control, burn-only, thin-only, and thin-burn) were evaluated for their effectiveness in moving stands toward the desired range of conditions. The control treatment involved no thinning or burning. The burn-only treatment involved prescribed broadcast burning in the spring, but no thinning. Burning in unthinned stands was designed to significantly reduce surface fuel mass and sapling/pole ladder fuels. The treatment hereafter referred to as "thin-only" (for correspondence with FFS terminology) actually consisted of a low thinning and improvement/selection cutting, but no burning. The thin-burn treatment entailed thinning (as defined previously) with the same objectives as the thin-only treatment but was followed by broadcast burning the following year to reduce logging slash (i.e., tree tops and limbs) and existing surface fuels.

All treatment units were leave-tree marked to the target reserve density before treatments were assigned so that a subset of similar trees could be directly compared among treatments in the future. Leave-tree marking reserved a target BA averaging 11 m^2 ha^{-1} over the 9-ha experimental unit, although density varied considerably across any given hectare. Marking favored leaving larger (i.e., ≥40 cm dbh) trees in the following order of species preference: ponderosa pine, western larch, lodgepole pine, and Douglas-fir. Modest numbers (~100–150 trees ha^{-1}) of healthy medium-sized and smaller ponderosa pines were also marked for leave, if available, until the target reserve BA density was achieved and to make progress toward the desired uneven-aged structure.

A single-grip harvester was used to cut, limb, and buck trees into logs. Nonmerchantable material was left in place and trampled by the harvest equipment. Logs were decked by product in the woods and then moved to the landing area by a self-loading, rubber-tired forwarder. Harvesting and forwarding were conducted in the winter (January–March) of 2001 over a snowpack, resulting in no measurable soil compaction (Gundale et al. 2005).

Broadcast burning of the six units assigned the burning treatment, which included three unthinned units (burn-only) and three thinned units (thin-burn), was conducted during May and June 2002, a year after cutting and during the early growing season period characterized by the historical fire regime (Grissino-Mayer et al. 2006). Burning was conducted separately for each of the six burn treatment units. Relative humidity during burning ranged from 20 to 48% and averaged about 34%. Temperatures during burning ranged from 9 to 29°C and averaged approximately 18°C. Winds were generally light, ranging from 2 to 13 km h^{-1}, although the thin-burn unit in block 2 had gusts up to 21 km h^{-1}.

Field Sampling

Pretreatment tree data were collected in 2001 on each of the 10 0.1-ha plots in each treatment unit. All trees ≥10 cm dbh were tagged, recorded by species and treatment, and measured for dbh to the nearest 0.1 cm. For the subset of trees marked for leave, total height and HLC (balanced live crown base, not lowest live limb) were measured to the nearest 0.1 m using a laser measuring device (Impulse 200; Laser Technology, Centennial, Colorado). Posttreatment data were collected in the summer of 2005. Data for all treatments are therefore based on 4 years of growth from the pretreatment condition, but with 4 years of response to thinning and 3 years of response to burning, depending on treatment.

Saplings (0.1–10 cm dbh) were sampled on five randomly selected 100-m^2 subplots on each 0.1-ha plot and recorded by species and treatment. Pretreatment sapling data were taken in 2000 in the thin-only and thin-burn treatments and in 2001 in the control and burn-only treatments. Posttreatment sapling data were taken in 2003 for all treatments.

Tree CC data were collected in 2003 only. A densitometer was used to sample CC, with readings taken at each of the 18 subplot corners in each Whittaker plot. No pretreatment CC data were taken.

Surface fuels were sampled before and after treatment implementation using two 15.2-m long transects at each of the 36 grid points in each treatment unit for a total of 216 transects per treatment. Surface fuel loads (<7.6 cm) were estimated along each transect following Brown (1974) in terms of 100-h fuels (2.5–7.6 cm), 10-h fuels (0.6–2.5 cm), 1-h fuels (0–0.6 cm), and litter. Duff and litter were measured at two locations along each transect. Duff depth reductions due to burning were estimated by placing four 20-cm spikes around each of the 36 grid points in each treatment unit. Spikes were pushed level with the top of the duff layer before burning, and duff reduction was measured as the difference between the top of the spike and the top of the duff layer after burning. The cut-to-length harvest system used in the two thinning-related treatments removed the tops and limbs of trees where they were cut, resulting in somewhat clumpy concentrations of slash. For this reason, a supplemental fuel sampling protocol was developed for use where concentrations of slash made transect-sampling infeasible (Michael Harrington, pers. comm., US Fire Service Fire Sciences Laboratory, Missoula, MT, Sept. 19, 2001).

Data Analysis

Differences among blocks were not significant for any response variables, so all analyses were conducted with block excluded. This allowed all parametric variables to be averaged to the treatment-unit level for conservative statistical tests with the greatest possible inference. Therefore, all parametric analyses were conducted with a replication (n) of three. Assumptions of normality and homoscedasticity were evaluated using histograms and Levine's test of normality.

To accentuate pretreatment similarities, TR ha^{-1}, sapling density, and BA were tested among treatments within years using analysis of variance (ANOVA), with least significant differences (LSD) used to test for differences between treatments when a significant ($P < 0.05$) overall treatment effect was detected within a given year. Because pretreatment data were not available for CC, BAI, and annual HI, these variables were simply tested in 2005 using ANOVA as described above. High pretreatment variability among treatments for QMD and HLC necessitated analyses of posttreatment (2005) values using analysis of covariance (ANCOVA), with the pretreatment values used as the covariate. When significant ($P < 0.05$) overall treatment effects were detected, differences between treatments were tested using LSD on the adjusted values from the ANCOVA. All parametric analyses were conducted using SPSS 15.0.0.

All overstory trees >10 cm dbh were averaged for comparisons of TR ha^{-1}, BA ha^{-1}, QMD, CC, and HLC. Tree data were also summarized by 5-cm diameter class for a more detailed investigation and interpretation of TR ha^{-1}, BAI, and HI. Sapling data were summarized in terms of saplings ha^{-1} for all trees <10 cm dbh and >1.37 m in height. Individual tree diameter measurements were used to calculate associated BAs pre- and posttreatment and then were summed to obtain overall BA ha^{-1} by treatment. Quadratic mean diameter was calculated for all trees >10 cm dbh by treatment. Mean CC was calculated from the 18 canopy readings taken in each Whittaker plot and then were averaged across the 30 plots in each treatment.

Tree growth response was expressed in terms of average annual BAI (%) and average annual HI (m). BAI was calculated by converting pre- and posttreatment diameter measurements for each tree into BA and then subtracting pretreatment BA from posttreatment BA and dividing by the pretreatment value. The resulting value was then divided by the number of posttreatment growing seasons and multiplied by 100 to convert to average annual percent BAI. Height growth response was calculated by subtracting pretreatment tree height from height in 2005 and then dividing by the number of growing seasons to convert to average annual HI.

Overstory (trees >10 cm dbh) structural changes were also evaluated using multiresponse permutation procedures (MRPP) (Mielke 1984, Zimmerman et al. 1985) to determine whether the entire diameter distribution significantly changed among treatments or over time. This evaluation requires a multivariate statistical procedure, because diameter distributions cannot be meaningfully summarized into a single number. MRPP is a nonparametric multivariate analysis of variance that allows separation of among-treatment and between-year variation in the diameter distribution as a whole. In addition, a descriptive representation of the tree diameter distributions was generated using nonmetric multidimensional scaling (NMS) (Kruskal 1964, Mather 1976), a nonparametric ordination technique.

Both MRPP and NMS were run using pretreatment (2001) and posttreatment (2005) TR ha^{-1} grouped into 10-cm diameter classes averaged to the plot level ($n = 30$) using PC-ORD 4.28 (McCune and Mefford 1999). Data were square root-transformed before analysis, and Sorenson distance was used as the measure of distance among plots in multidimensional dataspace. Correlations between plot scores from the two primary axes of the ordination and a suite of stand characteristics were used to describe specific variables that could be driving the observed structural changes. These variables were TR ha^{-1}, BA ha^{-1}, QMD, HLC, percent ponderosa pine/other species composition, and heat load index (HLI) (McCune and Keon 2002).

Two fire hazard parameters, torching index (TI) and crowning index (CI), were estimated for posttreatment stand conditions using Fuels Management Analyst Plus (Carlton 2004). TI and CI are defined as the 6.1-m wind speed (km h^{-1}) needed to initiate torching into the main canopy (passive crown fire) or sustain an active crown fire, respectively. Stand conditions were evaluated at the 90th percentile (high) fire weather conditions. Thirty-six years (1966–2002) of fire season weather data (July 15–September 15) from the Missoula Mountain Remote Access Weather Station were analyzed with Fire Family Plus (Main et al. 1990) to estimate 90th percentile weather conditions (i.e., 33°C and 19% relative humidity). Burgan and Scott (2005) fuel models TL-01, TL-05, and SB-02 were used in the Fuels Management Analyst Plus modeling of fire behavior at our site (Stephens et al. 2009).

Surface and ground fuel loads were estimated using published conversions and equations (Brown 1974, Brown et al. 1982) and fuel depth-to-weight relationships were developed from the supplemental sampling protocols (Michael Harrington, US Fire Service Fire Sciences Laboratory, Missoula, MT, Sept. 19, 2001).

Results

Structural Characteristics

Density

There were no differences in live tree density (TR ha^{-1} >10 cm dbh) among treatments before treatment. However, tree numbers differed significantly among treatments by 2005 ($n = 3$, $F = 29.04$, $P < 0.001$), with far fewer trees in the thin-only and thin-burn treatments than in the control or burn-only (Table 1). However, no significant differences were observed between the thin-only and thin-burn or between the burn-only and control. Examination of density changes in these two thinning-related treatments shows that most of the trees removed were <40 cm diameter and Douglas-fir rather than ponderosa pine (Figure 1). The thin-only also significantly reduced tree density, but posttreatment density changed little in this treatment over the response period. The burn-only caused minor mortality in the four smallest diameter classes but had virtually no effect on density of trees >30 cm dbh. Tree density in the control actually increased slightly during the period.

Density of saplings (0.1–10 cm dbh) did not differ among treatments before treatment in 2001 but differed significantly by the posttreatment measurement in 2003 ($n = 3$, $F = 6.45$, $P = 0.016$) (Table 1). Two years after treatment, the thin-only had significantly fewer saplings than the control and the thin-burn had fewer than the control

Table 1. Mean and SE for trees ha^{-1} (>10 cm dbh), saplings ha^{-1} (>0.1 and <10 cm dbh), and BA m^2 ha^{-1} ($n = 3$)

Year	Treatment	Mean	SE	F	*P*
Trees ha^{-1}					
2001	Control	397.7	26.8	0.8	0.511
	Burn-only	442.0	51.0		
	Thin-only	390.0	35.7		
	Thin-burn	356.0	37.3		
2005	Control (a)	400.0	23.5	29.0	<0.001
	Burn-only (a)	386.3	44.4		
	Thin-only (b)	157.3	17.9		
	Thin-burn (b)	117.3	14.1		
Saplings ha^{-1}					
2001	Control	9946.7	2098.5	0.7	0.563
	Burn-only	10890.0	5643.5		
	Thin-only	6646.7	955.7		
	Thin-burn	5246.7	1425.4		
2003	Control (a)	11483.3	1757.3	6.4	0.016
	Burn-only (ab)	6550.0	2902.4		
	Thin-only (bc)	5293.3	684.2		
	Thin-burn (c)	706.7	444.4		
Basal area (m^2 ha^{-1})					
2001	Control	23.9	4.4	0.3	0.812
	Burn-only	22.8	2.1		
	Thin-only	20.6	0.7		
	Thin-burn	21.0	2.5		
2005	Control (a)	24.9	4.4	9.6	0.005
	Burn-only (a)	21.6	1.4		
	Thin-only (b)	12.1	0.8		
	Thin-burn (b)	9.9	0.4		

One-way ANOVA conducted within years, among treatments. When ANOVA was significant, LSD comparisons were conducted between treatments with different letters in parentheses indicating significant differences.

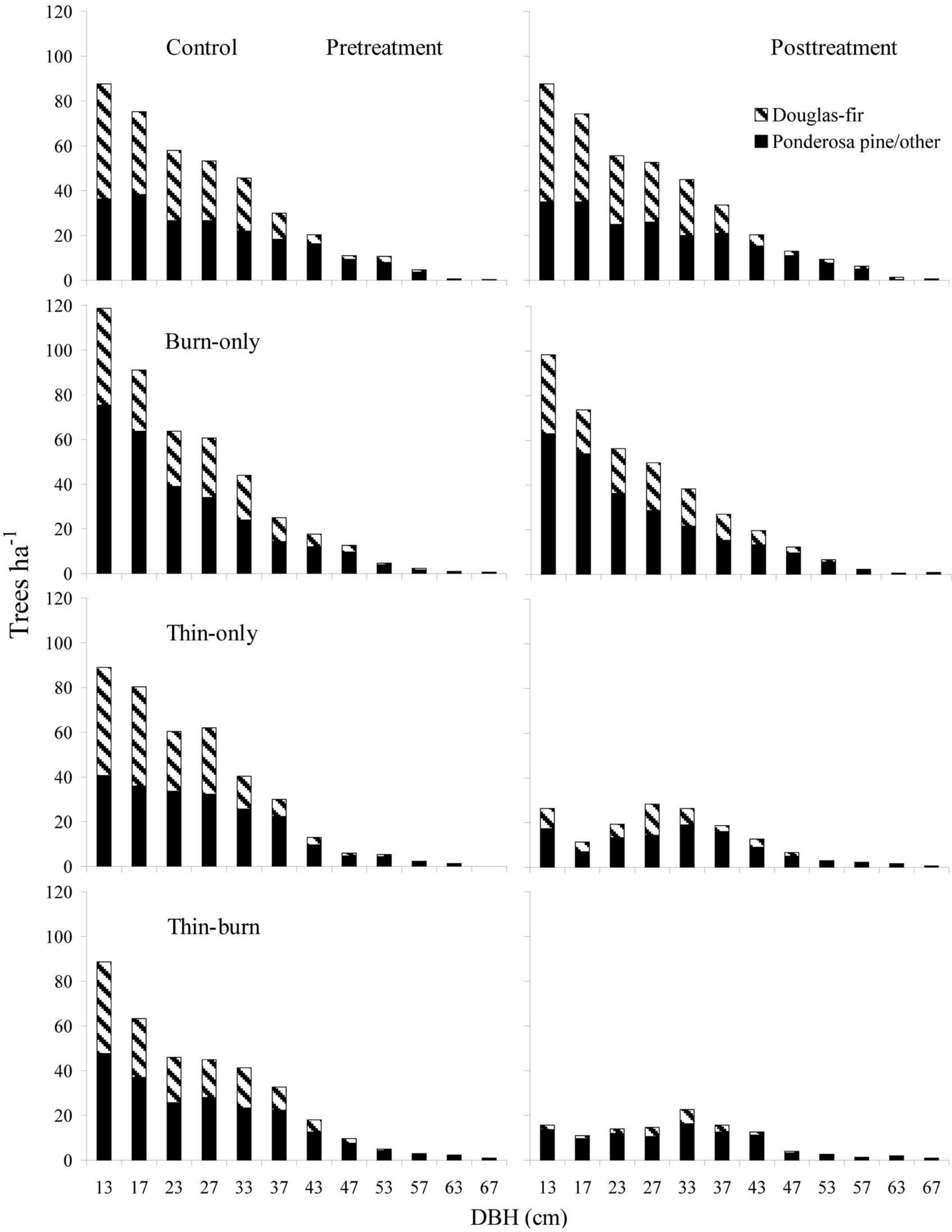

Figure 1. Pretreatment (2001) and posttreatment (2005) density of trees (>10 cm dbh), by 5-cm diameter classes and treatment.

and burn-only. No significant difference was observed between the thin-only and thin-burn.

No differences in BA were detected among treatments before treatment in 2001. However, posttreatment BA varied among treatments by 2005 (n = 3, F = 9.63, P = 0.005) (Table 1), with significantly lower densities in the thin-only and thin-burn than in the control and burn-only. No significant difference was observed between the control and burn-only.

Quadratic Mean Diameter

The two treatments that included thinning (thin-only and thin-burn) significantly increased the QMD of trees (>10 cm dbh) relative to the two treatments that did not (control and burn-only). The QMD of trees in the thin-only and thin-burn treatments were 33.2 and 34.0 cm, respectively, whereas the QMD of the control and burn-only were only 27.4 and 28.6 cm, respectively (Figure 2a). No significant differences in QMD were observed between the thin-only and thin-burn or between the burn-only and control.

Height to Live Crown

The burn-only and thin-burn treatments increased HLC, but the thin-only did not (Figure 2b). In 2005, the HLC of 9.0 m in the thin-burn was significantly greater than that for

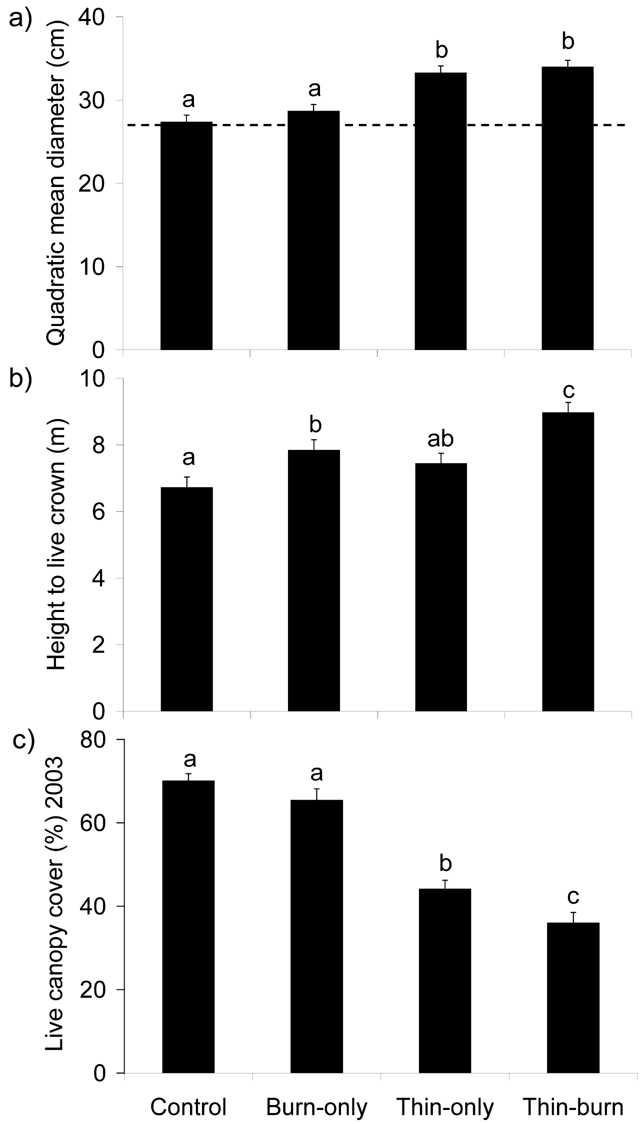

Figure 2. A, QMD in 2005, by treatment (ANCOVA, n = 3, F = 16.5, P = 0.0015), for trees >10 cm dbh. Values are adjusted to a common pretreatment QMD (2001; shown by dashed line). B, HLC in 2005, by treatment (ANCOVA, n = 3, F = 8.9, P = 0.0087), for trees >10 cm dbh. Values are adjusted to a common pretreatment HLC (2001). C, posttreatment live CC in 2003, 1 year after burning and 2 years after thinning, by treatment (ANOVA, n = 3, F = 34.8, P < 0.0001). In all instances, significant differences (LSD, P < 0.05) are indicated by differing superscripts. Whiskers are 1 SE.

the control, burn-only, and thin-only. The HLC in the burn-only (7.8 m) was greater than that in the control (6.7 m) but not different from that for the thin-only (7.4 m).

Canopy Cover

After treatment, the thin-only and thin-burn had significantly lower CC than the control and burn-only and the thin-burn treatment had significantly lower CC than thinning alone (Figure 2c). The control and burn-only retained high and similar CC (70 and 65%, respectively) after treatment in 2003 and nearly double the cover (36%) that remained in the thin-burn (Figure 2c).

Multidimensional Stand Structure

Before treatments were applied in 2001, there were no differences among treatments in tree diameter distributions (MRPP, n = 30, A = −0.04, P = 0.7164). However, in 2005, differences among treatments were significant (MRPP, n = 3, A = 0.25, P = 0.0123), with diameter distributions in the thin-only and thin-burn treatments differing significantly from those in the control and burn-only (MRPP, n = 30, all A > 0.05, all P < 0.001).

The NMS ordination of diameter distributions before and after treatment provided a three-dimensional solution with a stress of 15.2 and an instability of 0.00049. All treatment units clearly clustered together before treatment, but by 2005 plots in the thin-only and thin-burn treatments significantly separated from pretreatment, control, and burn-only plots on axis 1 (Figure 3). Several strong correlations emerged, suggesting that thinning treatments significantly reduced TR ha^{-1}and BA ha^{-1} while increasing QMD and percent ponderosa pine/other composition. Correlations against axis 2 suggest that there were preexisting differences among treatment units related to aspect and slope (HLI) and proportion of ponderosa pine/other trees (joint plot vectors) (Figure 3).

Growth Increment

Basal Area

Basal area increment varied significantly (P < 0.05) among treatments for all size classes ≤50 cm dbh (Figure 4). Average BAI ranged from about 5% year^{-1} for the smaller diameter classes to about 2% year^{-1} for the larger classes in the thin-only and thin-burn treatments (Figure 4). In contrast, average annual BAI in the control and burn-only ranged from only about 2% year^{-1} in the smaller classes to about 1% year^{-1} in the larger classes.

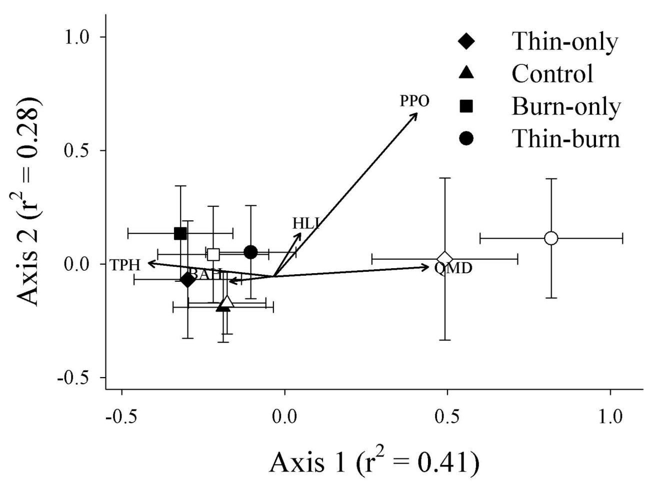

Figure 3. Ordination of structural attributes with NMS, by treatment, before treatment (solid symbols) and after treatment (open symbols), where TPH is trees ha^{-1}, BAH is basal area ha^{-1}, QMD is quadratic mean diameter, HLC is height to live crown, PPO is percentage of ponderosa pine/other, and HLI is heat load index. Symbols represent treatment centroids with 95% confidence intervals based on plot means (n = 30).

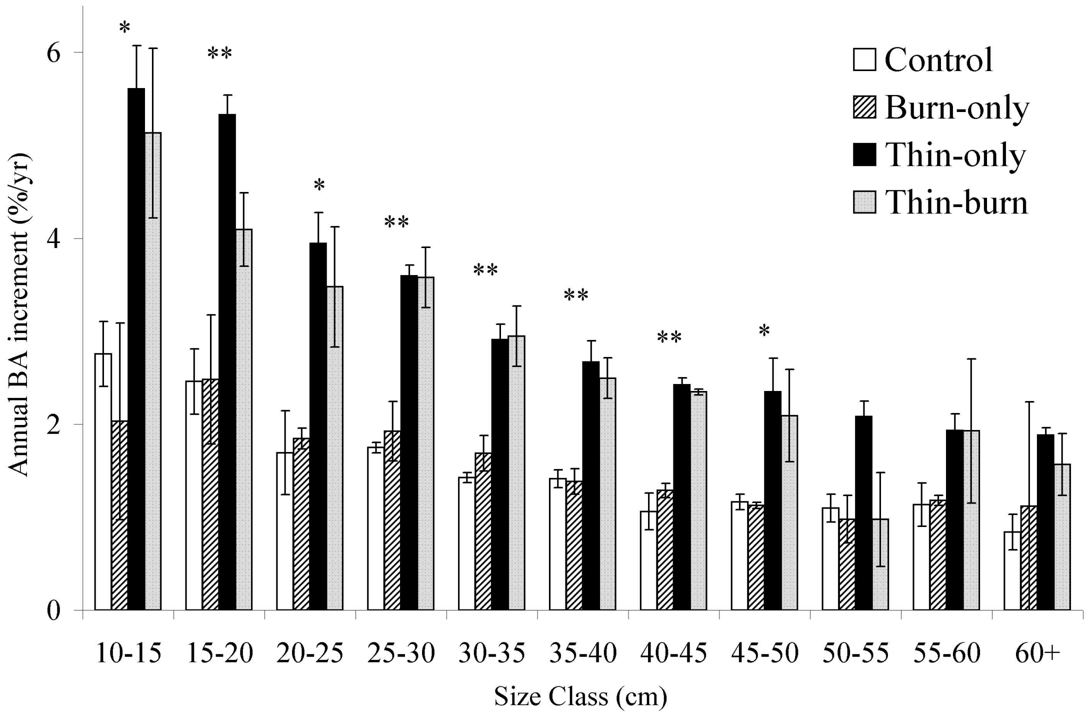

Figure 4. Average annual BAI for leave trees standardized to pretreatment basal area by treatment and initial 5-cm diameter class. Significant differences among treatments within diameter classes are indicated by *($0.01 < P < 0.05$) or **($P < 0.01$). Whiskers are 1 SE ($n = 3$).

Height

Tree height growth showed little response to treatment. Only trees in the 45–50 cm diameter class in the thin-burn treatment showed a significant increase in average annual HI over the response period (Figure 5). Annual HIs were quite consistent across diameter classes and among treatments, with most increments averaging approximately 0.3–0.4 m year^{-1} (Figure 5).

Crown Fire Potential

The posttreatment TI was higher in the two burning-related treatments compared with the control (Table 2). In contrast, the TI in the thin-only was estimated to be 7 km h^{-1}, which was lower than that for all other treatments, including the control. Estimated CI was highest in the two thinning-related treatments, and both were greater than the control and burn-only, which were similar (Table 2).

Table 2. Posttreatment TI and CI, by treatment, at 90th percentile weather conditions

	Control	Burn-only	Thin-only	Thin-burn
Torching index (km h^{-1})	32	145	7	145
Crowning index (km h^{-1})	64	67	84	110

Values >145 km h^{-1} were rounded to 145, which approximates the upper end of the cumulative wind velocity distribution at our site. Data presented were generated in a meta-analysis of treatment effects on fire hazard for six western sites in the national FFS network (Stephens et al. 2009).

Discussion

Structural Characteristics

Treatment prescriptions in our study focused on reducing density, modifying forest structure, changing species composition, and reintroducing fire. These changes have been documented in this and related studies at our site to influence numerous ecosystem properties and processes, including CC, HLC, QMD, diameter distributions, ponderosa pine composition, tree growth, and resiliency to fire (all in this study); shade-intolerant tree regeneration (Dodson et al. 2007); understory productivity and diversity (Gundale et al. 2006, Metlen and Fiedler 2006); nutrient cycling (Gundale et al. 2005); decomposition of high C:N substrates (Gundale et al. 2005); bark gleaners' nesting and foraging behavior (Woolf 2003); and bark beetle/predator dynamics (D.L. Six and K.R. Skov, unpublished data, University of Montana-Missoula, Feb. 22, 2009).

Meyer (1934) described ponderosa pine forests in the Inland Northwest as relatively open, many-aged, and nearly pure, key features of historically sustainable ponderosa pine forests that translate to restored forests as well. Fuel reduction treatments are designed to reduce fuel loadings and associated crown fire potential via density reduction. These density reductions may or may not be adequate to provide suitable sites (i.e., light and moisture) for regeneration of shade-intolerant pines (see Moghaddas et al. 2008). Although creating hospitable conditions for regeneration may not be an objective of hazard reduction projects, it was a key consideration in the broader forest restoration prescriptions used in our study. The posttreatment BA densities in the thin-only and thin-burn treatments in this study fall within the recommended density levels needed to regenerate ponderosa pine in western Montana (Fiedler et al. 1988), whereas the control and burn-only do not.

QMD, which is the preferred means for expressing and comparing average stand diameter (Curtis and Marshall 2000), is insensitive to proportional changes in stand diameter distributions and relatively insensitive to modest asymmetrical ones. Thus, increased QMD in the thin-only and thin-burn treatments in our study suggest fundamental changes in the underlying diameter distributions and significant progress toward large-tree dominated structures, one of the primary objectives of treatment. Youngblood et al. (2006) also found increased QMD after thin-only and thin-burn treatments in eastern Oregon, and Stephens and Moghaddas (2005) reported that QMD increased in the thin-burn in a study of fuel treatments in California, but not in the burn-only or thin-only. However, the thin-burn was the only treatment in their study that reduced BA by more than 30%. Taken together, these results suggest that substantial reductions in density are required to increase QMD, yet significant reductions in density may not increase QMD, depending on the underlying diameter distribution. For example, a 50% BA reduction removed proportionally across a normal diameter distribution would have no effect on QMD yet would significantly reduce hazard. Thus, QMD may not be particularly useful for assessing the effectiveness or intensity of fuel reduction treatments, but it does provide a unique measure of stand change relative to restoration objectives.

Simulations by van Wagtendonk (1996) of thinning and burning treatments in ponderosa pine forests suggested that CCs ranging from approximately 20 to 50% are appropriate for fuelbreak purposes. Hollenstein et al. (2001) selected a 40% CC level for simulating long-term sustainable production of biomass from uneven-aged ponderosa pine stands in the Rocky Mountains and Southwest. This CC level was selected as appropriate for regenerating and growing ponderosa pine in uneven-aged structures, with a concomitantly low fire hazard. Waltz et al. (2003) reported that alternative restoration treatments implemented in a southwestern ponderosa pine forest resulted in CCs that averaged 35%. Interpreting canopy effects in our study suggests that only the 44 and 36% CC levels resulting from the thin-only and thin-burn treatments are consistent with the recommendations from other analyses aimed to identify sustainable, fire-resilient ponderosa pine structures.

CC levels have special importance in the sustainability of uneven-aged ponderosa pine forests because pine germinants require some direct sunlight for adequate height development and subsequent recruitment into the main canopy. Relatively low recommended BA densities of about 8–12 m^2 ha^{-1} (Fiedler et al. 1988), which are associated with CC levels of approximately 30–45% at our site, appear necessary to ensure regeneration and adequate early growth of ponderosa pine. Mitchell and Popovich (1997) found a strong linear relationship between CC and BA up to 23 m^2 ha^{-1} in ponderosa pine stands along the Front Range in Colorado and Wyoming. We also found a strong correlation between CC and BA across treatments at our site, which provides further corroboration that desired levels of both variables were achieved in the thin-only and thin-burn treatments.

In addition to conventional measures of stand structure, we used ordination to evaluate whether the treatments we applied fundamentally changed the underlying species-specific diameter distributions. Many indexes or coefficients

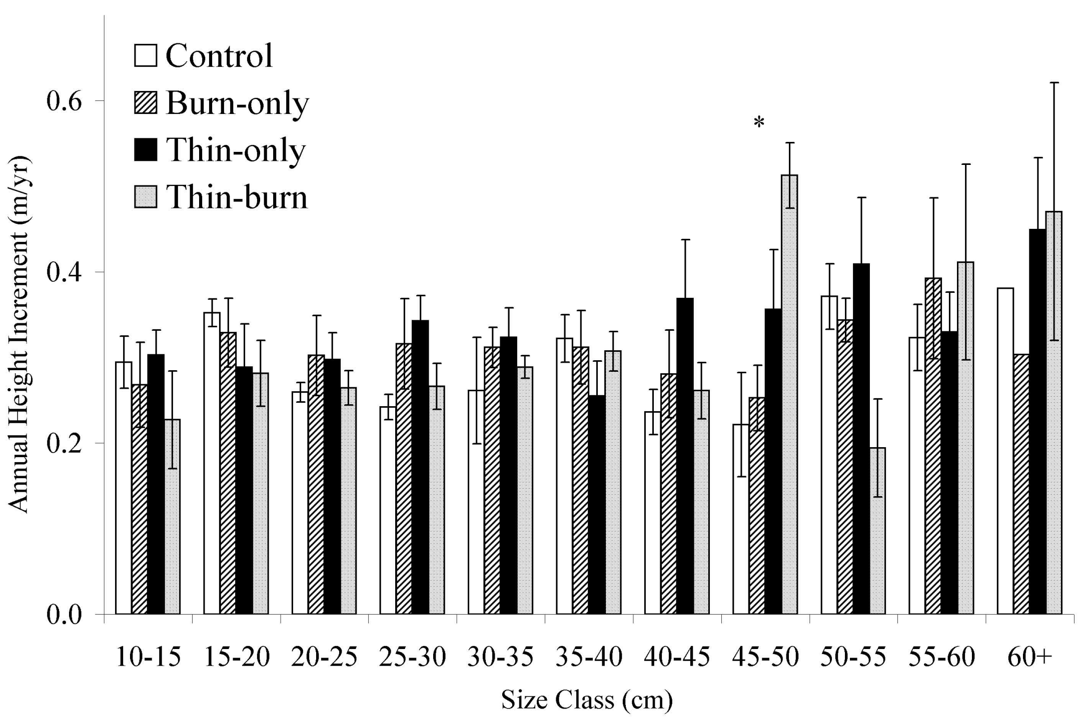

Figure 5. Annual HI for leave trees, by treatment and initial 5-cm diameter class. Significant differences among treatments within diameter classes are indicated by *(0.01 < *P* < 0.05). Whiskers are 1 SE (*n* = 3).

exist for comparing diameter class distributions (e.g., Gini, Shannon, and others), yet the use of multivariate comparisons coupled with ordination allows insights into how treatments alter stand structure. For example, Ruiz-Jaén and Aide (2005) found ordination to be a useful tool for evaluating progress or success associated with alternative restoration treatments, with diameter classes being an important measure of vegetation structure in such analyses. This technique is similar to the way community ecologists use ordination to represent plant communities, only here tree diameter classes are substituted for species and density (TR ha^{-1}) becomes the measure of abundance.

Our treatment prescriptions were designed to directly manipulate several structural variables (TR ha^{-1}, BA ha^{-1}, QMD, and species composition). Not surprising, these variables were strongly correlated with the axis that separated the two thinning-related treatments from their pretreatment correspondents and from the posttreatment control and burn-only units. Our ordination analysis also showed that although primary differences among treatment units were due to thinning, some differences in HLI and species composition existed before treatment. These latter two differences could be linked because our primary species (ponderosa pine) occurs more frequently on hot, dry sites (steep, southwest slopes) than does the relatively shade-tolerant Douglas-fir.

The NMS ordination clearly demonstrates that the restoration treatments involving thinning significantly modified stand structure: they reduced stand density (both TR ha^{-1} and BA ha^{-1}) and increased average stand diameter and proportional composition of ponderosa pine, changes that provide significant progress toward desired conditions (i.e., relatively open, large-tree dominated, primarily pine composition, suitable for regenerating shade-intolerant pine, and resistant to crown fire).

Growth Increment

Growth increment is a useful variable for evaluating restoration treatment effectiveness in terms of tree vigor, large tree development, and stand susceptibility to bark beetles. Thinning has been widely reported to increase availability of moisture and nutrients (Feeney et al. 1998, Kaye and Hart 1998, Stone et al. 1999, Skov et al. 2004), factors (especially moisture) that limit growth in dense stands. A study monitoring seasonality of thinning response near our site documented the importance of late-summer moisture availability to growth (Carl Fiedler, unpublished data, University of Montana-Missoula, Sept. 9, 2005). Radial growth ceased in the control by early July, but continued until mid to late August in a treatment thinned to nearly the same density as the thinning treatments in this study.

Numerous investigators (McDowell et al. 2003, Skov et al. 2004, Fajardo et al. 2007) have reported ponderosa pine growth responses to thinning. Increased BAI has also been observed in large old trees (Feeney et al. 1998, Stone et al. 1999, Fiedler 2000a), with increases persisting up to 25 years in one Oregon study (Latham and Tappeiner (2002). Old pines accrue even greater benefit than younger trees from restoration thinning due to relatively greater resin production response (Kolb et al. 2007), a key factor in resisting bark beetle attack. McDowell et al. (2007) found that resin flow was strongly correlated with BAI and concluded that growth rate can provide managers a simple and direct index of resin defenses against bark beetles. The strong BAI response in our thinning-related treatments thus provides a useful indicator of increased resistance to beetle attack.

Treatments that include prescribed burning show variable effects on radial growth and BAI. For example, Fiedler (2000) found similar and large positive growth responses in thin-only and thin-burn treatments relative to a control. Yet Fajardo et al. (2007) found no differences in BAI between a thin-burn and a control, despite a significant growth response in a thin-only treatment at the same reserve density. Landsberg et al. (1984) reported 16–28% reductions in BAI after burning in central Oregon. These conflicting results are understandable given the variation in intensity and seasonality of burning from study to study, as well as among-site differences in slope, aspect, fuel moisture, burn-day weather conditions, and surface fuel loading. Burning can potentially reduce growth by damaging tree roots, cambium, foliage, or buds and can potentially increase radial growth by reducing stand density and releasing nutrients (particularly nitrogen).

The lack of a treatment effect on HI in the two thinning-related treatments in this study may seem incongruous given the positive effect these treatments had on BAI. However, height growth is commonly assumed to be relatively independent of stand density across a broad range of densities (Husch et al. 2003 p. 196). Height growth occurs early in the growing season when moisture is generally available, probably explaining the lack of differences in HI in thinned and unthinned stands. Uzoh and Oliver (2006) evaluated individual tree height growth in ponderosa pine stands across the western United States and found that stand density (estimated by stand density index; Reineke 1933) ranked as only the seventh most important predictor of HI.

Few other studies have examined prescribed burning effects on HI. Consistent with our results, Busse et al. (2000) observed no effect on HI after spring burning in ponderosa pine in Oregon. However, Landsberg et al. (1984) reported modest decreases in height growth after burning in areas of moderate to high fuel consumption. The limited data available suggest caution in drawing conclusions; however, they also suggest that burning probably has negligible effects on height growth so long as damage to roots and crowns is limited.

Crown Fire Potential

Increased management activity in pine/fir forests points to the need for some kind of objective procedures or principles against which to assess prospective hazard reduction treatments. Below we evaluate our treatments against the basic fuel reduction principles proposed by Agee and Skinner (2005). These principles include reducing surface fuels, increasing HLC, decreasing crown density, and reserving big trees of fire-resistant species.

Evaluated against the fuel reduction principles, the no-treatment control achieves only the fourth principle—reserving large, fire-resistant trees. Although all large trees remain in this treatment, sensu stricto, their persistence is at great risk to wildfire given the heavy ladder fuels and dense stand matrix within which they occur (Agee 2002). They are also probably more susceptible to bark beetle attack than similar-sized trees in the thinned treatments.

The burn-only treatment reduced surface fuels and increased HLC. It also reserved big, fire-resistant trees, but they remain at considerable risk in a dense canopy little changed by the burn-only treatment (Figure 2c). Furthermore, the reduction in surface fuels is likely to be short-lived (Stephens 1998), as trees killed by the fire begin to fall.

The thin-burn treatment had little effect on surface fuel loading. Slash generated by thinning was largely offset by subsequent burning that consumed some activity fuels as well as some preexisting fuels, with resulting surface fuel loadings (7.6 Mg ha^{-1}) similar to that of the control (8.2 Mg ha^{-1}). However, this treatment increased HLC, reduced CC, and retained nearly all large trees.

The thin-only treatment illustrates a key point relative to effective hazard reduction. This treatment reduced TR ha^{-1} by more than two-thirds and BA ha^{-1} by about half, yet the torching potential increased because of the heavy slash loads left in the woods by the particular harvest system used. This undesirable result underscores the importance of selecting a harvest system that is consistent with overall treatment objectives.

Thinning treatments should specify the size and density of trees to be left given a particular diameter distribution, because although low thinning is necessary to achieve substantial hazard reduction, it may not be sufficient. For example, Fiedler et al. (2004) analyzed crown fire hazard in Montana and found that crowning potential remained high in many dense pine stands, even if the sapling/pole ladder fuels were removed. Similarly, van Wagtendonk (1996) modeled a range of thinning and burning treatments in ponderosa pine forests and found severe fire behavior occurred even with ladder fuel removal, if the associated surface fuels were not treated. Indeed, Cram et al. (2006) observed such behavior in a review of the differential effects of wildfire in treated and untreated stands in the Southwest.

Effective treatments in dense second-growth stands should 1) reduce ladder fuels and create a vertical discontinuity in fuels, 2) reduce canopy bulk density and increase distances between crowns, and 3) remove or treat the fuels generated in the thinning operation. Lack of addressing the first two components explains the high torching and crowning potential in the control; lack of addressing the second explains the ineffectiveness of the burn-only treatment in reducing crowning potential, and lack of addressing the third component explains the high torching potential in the thin-only treatment.

The heavy posttreatment surface fuels in the thin-only treatment could have been avoided had a whole-tree harvest system been used. The cut-to-length system used in this study is increasingly favored in western Montana because it leaves nutrient-rich slash in the woods, which is deemed important on low productivity sites. However, if slash is left on-site, it will need to be burned, chipped, or masticated to achieve hazard reduction objectives.

Conclusions

This study of forest structural changes associated with fuel reduction/restoration treatments is the first of its kind in the Northern Rocky Mountains. The operational scale and the replicated and randomized design used in this project are rare in studies of forest stand manipulations (Bennett and Adams 2004) and allow inferences of treatment effects based on a strong experimental framework.

Evaluation of control, burn-only, thin-only, and thin-burn treatments showed that the combined thin-burn treatment had the greatest number of desired effects compared with the control, the burn-only had the fewest, and the thin-only was intermediate. Specifically, we reduced stand density and canopy cover, while increasing average stand diameter, height-to-live crown, and basal area increment. These structural and growth effects are related to (or influence) numerous stand/ecosystem properties, including diameter distributions, species composition, large-tree development potential, overall tree vigor, potential for shade-intolerant tree regeneration, and stand resiliency to fire. We show that well-designed treatments can promote key ecosystem properties while significantly reducing crown fire potential, thereby providing managers in the region useful information and measures to guide prescription development.

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