Comparing the Effectiveness of Thinning and Prescribed Fire for Modifying Structure in Dry Coniferous Forests

Richy J. Harrod[1], Nicholas A. Povak[2], and David W. Peterson[2]

***Abstract**—Forest thinning and prescribed fires are the main practices used by managers to address concerns over ecosystem degradation and severe wildland fire potential in dry forests of the Western United States. There is some debate, however, about treatment effectiveness in meeting management objectives as well as their ecological consequences. This study assesses the effectiveness of thinning and prescribed fire treatments, alone and combined, for modifying forest structure and potential fire behavior in the Eastern Cascade Mountains of Washington State. Treatments were applied to 12 management units (~10 ha each), with each treatment combination replicated three times (including untreated controls). Thinning modified forest structure by reducing overall tree stocking and canopy fuels to ≤50 percent of pretreatment values. Furthermore, thinning greatly reduced the modeled probability of severe wildfire and reduced stand densities to below critical levels for insect outbreaks. The prescribed fire treatment, conversely, did not appreciably reduce stocking levels or canopy fuel loadings, but was effective for raising canopy height and increasing the density of standing dead trees. Prescribed fire effects were more pronounced when used in combination with thinning. While thinning was a more reliable method for altering stand structure, the spring burns conducted in the experiment were cooler and spottier than were desired and may have led to results that downplay the efficacy of fire to meet forest restoration goals.*

Introduction

Structure is an important ecological aspect of dry, coniferous forests. Dry forests throughout the Interior West have increasingly become dense, closed-canopy stands of mostly small, fire-intolerant trees as compared to the more open, fire-tolerant, large-tree dominated stands of the past (Agee 1994; Covington and Moore 1994; Everett and others 2000; Harrod and others 1999). Dense overstories with continuous ladder fuels lead to high probabilities of torching and crown fires (Peterson and others 2005; Scott 1998; Scott and Reinhardt 2001) and increased vulnerability to many insects and diseases (Hessburg and others 2005). Understory diversity, composition, and abundance have been altered due to these modified structural conditions (Covington and others 1997; Hall 1977; Smith and Arno 1999). Wildlife are also affected as many dry forest species, such as the white-headed and hairy woodpeckers lack suitable habitat (Gaines and others 2007). In general, changes in structure and composition have lead to an overall deterioration in forest ecosystem integrity and an increased probability of large, high-severity wildfires throughout the West (Dahms and Geils 1997; Patton-Mallory 1997; Stephens 1998; Weatherspoon and Skinner 1996).

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[1] Deputy Fire Management Officer, U.S. Department of Agriculture, Forest Service, Okanogan-Wenatchee National Forests, Wenatchee, WA. rharrod@fs.fed.us

[2] Biological Science Technician and Research Forester, respectively, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Wenatchee Forestry Sciences Laboratory, Wenatchee, WA.

The structure and composition of today's forests have been created by disturbance regimes that are very different from those of the past. Prior to Euro-American settlement, fire regimes characterized by high-frequency, low-severity fire promoted open structure with large trees, particularly ponderosa pine (*Pinus ponderosa*; Agee 1998; Hessburg and others 2005). Fire burned every 6 to 7 years in the Eastern Cascade Mountains (Everett and others 2000), acting as a natural thinning agent that selectively removed small trees while causing minimal overstory mortality (<20 percent of basal area; Agee 1990, 1993). Trees often grew in clumps, creating numerous canopy gaps. Canopy layering was minimal as shade-tolerant but fire intolerant species such as grand fir (*Abies grandis*) were limited by frequent fires (Harrod and others 1999; Hessburg and others 2005). Fire regimes were altered during the past century, however, by active fire suppression, land-use changes, and removal of fine fuels through heavy grazing by sheep and cattle (Agee 1994). In the absence of fire, dense forests developed, creating intense competition for light and water, greater tree mortality and increased hazards of severe wildfires. Past logging practices further altered forest structure and fire resistance by removing large, fire-resistant trees and promoting prolific regeneration of small trees (Habeck 1990). These changes are of great concern to forest managers because extensive crown fires have threatened lives and property, and fire suppression activities have proven to be costly. This paper focuses on forest restoration treatment options that modify forest structure, and their effectiveness in reducing crown fire hazard.

Forest restoration opportunities are constrained by available methods. Thinning and prescribed fire used alone or in combination are options available for modifying forest structure and reducing potential for severe wildland fire. However, there is disagreement about the appropriate balance among mechanical treatments and prescribed fire (Stephens 1998; van Wagtendonk 1996; Weatherspoon 1996) and whether or not the treatments can meet restoration objectives (Brown and others 2004). Thinning allows for control over species selection and size classes of material removed or retained. However, thinning can be problematic if the value of the wood removed does not offset treatment costs; if slash significantly increases surface fuel loads (Pollet and Omi 2002; McIver and Ottmar 2007); or if activities are limited by road access, slope steepness, or sensitive soils. Prescribed fire can be used to reduce surface and some ladder fuels and is less limited by road access, but does not allow for much control over species and size class selection and may produce secondary fire effects, such as bark beetle mortality (Ganz and others 2003; McHugh and others 2003). Prescribed fire may also kill large trees that are intended to be retained after treatment (Agee 2003). Thinning and prescribed fire may complement each other when used in combination, although empirical data are still lacking (Weatherspoon and Skinner 2002). Further, the added costs associated with completing both treatments may not be warranted if management objectives can be met with a single treatment.

The purpose of our study was to assess the effectiveness of thinning and prescribed fire alone and in combination for modifying overstory structure in dry forests with the purpose of restoring a low-severity fire regime. Data were collected from the Mission Creek Fire and Fire Surrogates site, which is part of a network of sites throughout the United States (Weatherspoon 2000), in which thinning and prescribed fire treatments were applied in factorial combinations. We asked the following research questions:

1. Can prescribed fire or thinning alone produce the structural changes necessary to restore a low severity fire regime?

2. If prescribed fire and thinning are used in combination, are the results additive or is there an additional benefit to combining treatments?
3. Which treatments reduce stand density sufficiently to reduce the risk of insect outbreaks?
4. How do treatments affect current snag inventories and future snag recruitment?

Methods

Study Area

The study was conducted in the Eastern Cascade Mountains of central Washington State within the Okanogan-Wenatchee National Forests. Forests within the study area are dominated by ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) with grand fir (*Abies grandis*) and western larch (*Larix occidentalis*) occurring at higher elevations. Plant associations include *Pseudotsuga menziesii/Calamagrostis rubescens, P. menziesii/Spirea betulifolia, P. menziesii/Carex geyeri, P. menziesii/S. betulifolia/C. rubescens, P. menziesii/S. albus, P. menziesii/ Symphoricarpos albus/C. rubescens, Pinus ponderosa/C. rubescens/Agropyron spicatum, Abies grandis/Mahonia nervosa,* and *A. grandis/S. albus/C. rubescens* (Lillybridge and others 1995).

Climate is continental due to the rain shadow produced by the Cascade Mountains. Annual precipitation averages 22 cm and occurs mostly as snow between November and April; mean January and July temperatures are –3 °C and 17 °C, respectively. Soils are stony, sandy loams (USDA 1995) and slopes vary from 30 to 40 percent. A more complete description of general site conditions will be found in Harrod and others (in progress).

Treatment Descriptions

Approximately 30 candidate stands were identified in 1999 in the Mission Creek watershed and other smaller watersheds immediately adjacent to the west. We constrained the search to eliminate units with (1) north aspects, (2) average slopes >40 percent (there are locally steeper slopes), (3) >10 percent rock or nonforest vegetation cover, and (4) known plant or animal species of concern. Twelve treatment units, each approximately 10 ha, were ultimately chosen for the study.

The treatments included: (1) thinning from below (thin only), (2) prescribed fire alone (burn only), (3) commercial thinning followed by prescribed fire (thin + burn), and (4) untreated control. Treatment combinations were assigned to the 12 study units, producing three replicates of each treatment combination. Treatment assignment was random except that four units were not considered for prescribed fire treatments due to access limitations.

The specific treatment objectives were to restore low-density dry forest stand structure, reduce ladder and surface fuels, reduce the risk of extensive bark beetle attack, and reduce the risk of high-severity fire. The overall objective of the Fire and Fire Surrogate Study was to achieve an 80 percent survival rate in codominant/dominant trees in the posttreatment stand for modeled wildfires under 80th percentile weather conditions (Weatherspoon 2000). The thinning treatment objectives on thin-only and thin + burn units were to reduce stand density and favor drought and fire resistant species (largely ponderosa pine or Douglas-fir). Target thin densities were designed to lower current stand density to the estimated upper management zone for low bark beetle risk (Cochran and others 1994), which is also the estimated historical density for this area (for example, stand density index = 263 for pine sites; Harrod and others 1999). Stands were thinned from below (largely understory trees) leaving the largest and most vigorous trees at irregular spacing. Treatments were tailored to individual forest stands, and target densities were dependent on the predominant plant association and site stockability. Thinning was accomplished with contract fallers in the winter of 2002/2003, and logs were yarded by helicopter to landings outside the study units. Unmerchantable tree tops and branches were left in the study units.

Prescribed burning was conducted on four of the six experimental units in spring 2004 and, because of lack of appropriate burning conditions, on the remaining two units in spring 2006. Ignition of units was by hand (drip torch) and helicopter with polystyrene spheres filled with potassium permanganate crystals, which are injected with ethylene glycol and dropped to the ground. Flame lengths ranged from 0.2 to 1.0 m and burns were generally patchy (20 to 50 percent area blackened) because of spring burning conditions.

Sampling Design

Preliminary reconnaissance of the treatment units was used to identify areas of continuous forest vegetation and to avoid sampling in areas dominated by nonforest vegetation. A series of six, 20x50m plots were permanently established within each unit in 2000 (prior to treatments), and plots were systematically stratified within the most abundant plant associations within each unit (Lillybridge and others 1995). Based on a preliminary analysis of adjacent forest stands we determined that six plots per treatment unit would adequately capture the within unit variability and provide an accurate estimate of vegetation characteristics.

Within each sample plot, all live and standing dead trees >7.62 cm d.b.h. were identified by species, permanently numbered and measured for diameter, total height, height to crown base (height from tree base to the intersection of the lowest live limb at the tree bole), bole scarring, and crown condition (Keen 1943; Hawksworth 1977). Saplings (height >1.37 m, diameter <7.62 cm) were also tallied. Canopy closure was measured in the center of the plot using a Lemmon Spherical Densiometer, Model-C. Slope, aspect, and elevation were also recorded for each plot.

In general, sampling occurred 1 year before and after the treatments were implemented; however, the actual years each unit was measured depended on the timing of the treatments (Harrod and others in progress). Upon reassessment of the units following treatment we noted that two plots located in burn units escaped the fire because they were located on the wrong side of the handline and had no possibility of being burned. These two plots were subsequently removed from all analyses.

Data Analysis

Data were averaged up from the plot-level to the experimental unit level for all analyses (Hurlbert 1984). Live trees and snags >7.62 cm, and saplings (≥1.37 m tall and ≤7.62 cm d.b.h.) were analyzed separately. Response variables of interest included: density (ha^{-1}) and basal area ($m^2\ ha^{-1}$), quadratic mean diameter (cm), stand density index, canopy bulk density ($kg\ m^{-3}$), canopy fuel loading ($Mg\ ha^{-1}$), and canopy base height (m).

A two-factorial analysis of variance (ANOVA) was used on the pretreatment data to determine if there were significant differences in forest structural components between treatments prior to the experiment. Factors were burn (two levels, burn or no burn) and thin (two levels, thin or no thin). Of all the response variables tested in the pretreatment analysis, only snag basal area (BA) was significantly different among treatments. Even though there were largely no significant differences in pretreatment forest structure, there was enough variability among treatment units to warrant the use of a pretreatment covariate for the analysis of treatment effects. Therefore, to determine the treatment effects on stand structure, a two-factorial analysis of covariance (ANCOVA) was used with absolute change as the dependent variable (posttreatment – pretreatment) and the respective pretreatment condition included as a covariate in the model. This analysis was chosen because it (1) accounts for pretreatment variability in structural components, and (2) accounts for the repeated measures aspect of the experiment by analyzing the absolute change of the response variables rather than the posttreatment values.

Least square means were used to compare main treatment and interaction effects on stand structure, and the Tukey-Kramer adjustment for multiple comparisons was used to control the experiment-wise error rate. An error rate of 0.1 was chosen over the more traditional 0.05 level to (1) reduce the probability of Type II errors and (2) because a 90 percent success rate is favorable for most management decisions.

Because treatments were designed to remove trees based on their size, trees were grouped into four diameter classes for some analyses to elaborate upon the effects of treatments on different size classes of trees. Diameter classes included small (7.62 to 19.9 cm d.b.h.), medium (20.0 to 39.9 cm d.b.h.), large (40 to 59.9 cm d.b.h.) and very large (>60.0 cm d.b.h.).

Stand density index is a useful measure of competition in forest stands and has been applied to many forest types around the world (Shaw 2006). Originally developed for even-aged pure stands, SDI has since been applied to uneven-aged and mixed-species forests (Shaw 2000; Woodall and others 2003; Woodall and others 2005). Stand density index for each sample plot was calculated using the summation method following Cochran and others (1994) and Shaw (2000):

[1] $$SDI = \sum(D_i/25)^a$$

Where, D_i = individual tree diameter (cm), a = 1.77 for ponderosa pine and 1.51 for Douglas-fir and all others.

A variant of Reineke's maximum size-density model was used to construct Gingrich-type stocking charts, following the methods of Cochran and others (1994), for use in forest types similar to those in the current study. Average model parameters for Douglas-fir and ponderosa pine were calculated to determine tree density and basal area at full stocking over a range of average stand diameters:

[2] $$TPH=\exp^{[a-b(\log(Dq))]*(SDIf/SDIn)}$$

Where TPH = trees per hectare, Dq = quadratic mean diameter, a = 9.70 and b = 1.64, SDIf = stand density index at full stocking for our stands (777), and SDIn = average maximum SDI for self-thinning stands (922). Basal area (BA; m2 ha-1) was then calculated for each Dq as:

[3] $$BA=TPH*0.0000785398*Dq^2$$

While SDI is reportedly robust to changes in site quality and stand age, full-stocking values have been shown to vary by region and plant association (Woodall and others 2000). The (SDIf/SDIn) in equation 2 is an adjustment factor used in the model to tailor maximum size-density models to specific forests of interest. An SDIf value of 777 was calculated by averaging the SDI values for the individual plant associations (PA) in our study area (based on Lillybridge and others 1995) and weighting them by the total number of sample plots on which each PA occurred. An SDIn of 920 was used as an average maximum density for ponderosa pine and Douglas-fir over a wide range of plant communities as summarized by Cochran and others (1994). Upper and lower management zones were calculated as 75 and 50 percent of full stocking, respectively.

Canopy fuels were modeled at each time period using the Crown Mass® software in the Fuels Management Analyst 3® (FMA) package. Canopy bulk density, canopy fuel loading, and canopy base height were calculated using pre- and posttreatment, plot-level data for each unit. Canopy bulk density is the crown mass per unit volume in a forest stand and is an estimate of available fuel in the canopy. Crown Mass® calculates canopy bulk density as the maximum of the running mean estimates for 0.3048 m canopy segments on the basis that fires will most likely spread in the denser portions of the canopy. Canopy fuel loading is the crown mass per unit area and is calculated as the cumulative foliage, 1-hr live and dead timelag canopy fuel mass. Canopy base height is defined as the vertical distance from the ground to the lowest point in the canopy where bulk density is high enough to propagate fire into the canopy (0.011 kg m^{-3}; Scott and Reinhardt 2001).

Results

Treatment Effects on Tree Density and Stocking

The thinning treatment greatly reduced stand density over the course of the experiment, particularly in the small and medium size classes. Thinning significantly reduced total live tree density by >60 percent ($P<0.0001$), with similar declines found using thin only and thin + burn treatments (fig. 1A). Thinning removed over two-thirds of the trees in the small and medium size classes, and removed some trees >40cm d.b.h. (fig. 2). Residual trees were generally vigorous, with few signs of mistletoe or other insects or diseases. Less than 2 percent of the residual trees had signs of mechanical scarring related to the thinning treatment. The percentage of Douglas-fir stems increased slightly following thinning; however, all changes in species composition were <10 percent (by density) and no significant differences were found among treatment combinations ($P>0.5847$).

The burning treatment caused minimal tree mortality, most of which was restricted to the smaller diameter classes. Evidence of bole scorching was found on over half of the trees on plots that received only a burn; however, fires burned into the crowns of only 20 percent of the trees on these plots. The burn-only treatment caused only 8 percent mortality for all size classes of trees, which was not significantly different than the 1 percent background mortality observed on control plots ($P=0.5061$; fig. 1A). Burning alone removed 20 percent of small diameter trees and its effect on larger size classes was negligible, with more than twice as many trees in the 20 to 40cm d.b.h. class remaining on burned only units as compared to the thinned areas (fig. 2). Under the thin + burn treatment, fire scorched about two-thirds of the trees and fire-related mortality was higher under this treatment as compared to burning alone (fig. 2). The burn-only treatment had no effect on species composition with burning causing <2 percent increase in Douglas-fir on average ($P>0.6020$).

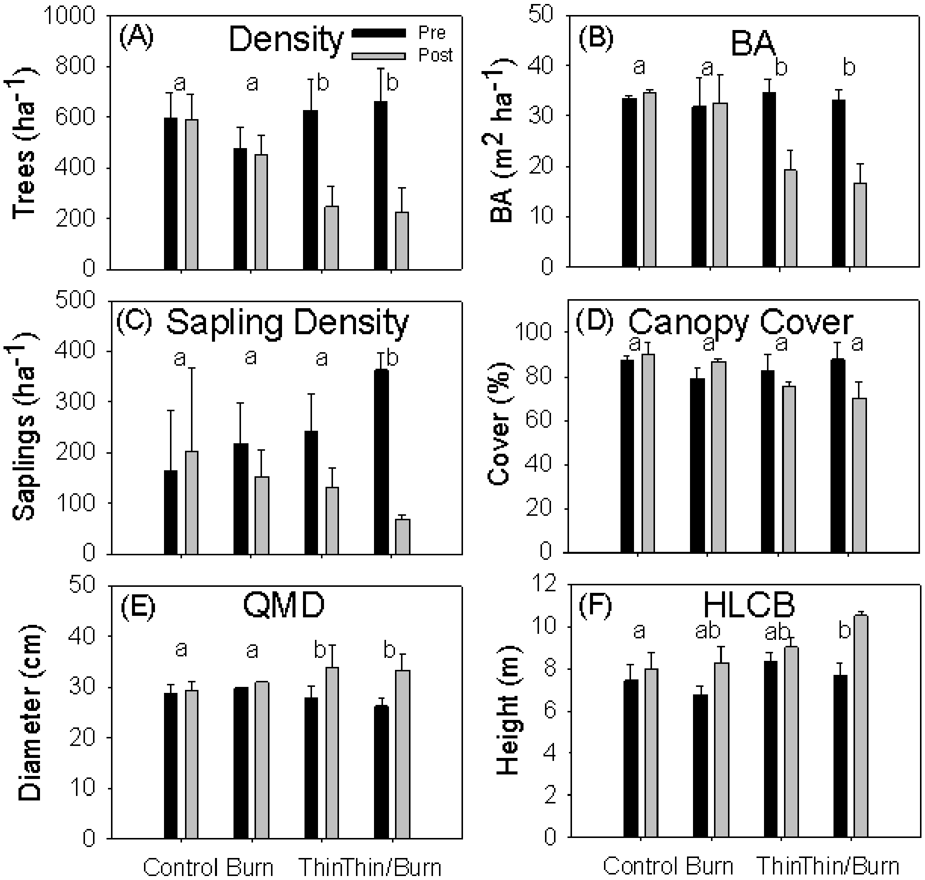

Figure 1—Changes in (A) live tree density, (B) live tree basal area, (C) sapling density, (D) canopy cover, (E) quadratic mean diameter, and (F) height to live crown base following treatments in dry-forests of central Washington. Error bars represent standard deviation. Treatments with the same letter indicate no significant differences between the absolute change in the attribute from pre- to posttreatment (P<0.1).

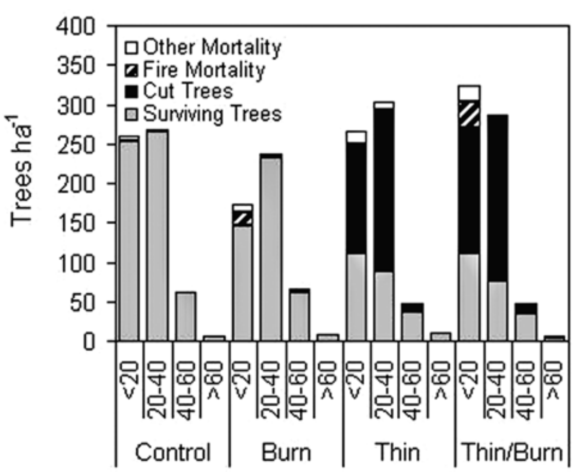

Figure 2—Causes of tree mortality by diameter class (cm) within each treatment combination. The full bars in each treatment are equal to the pretreatment diameter distribution for live trees and the bottom "surviving tree" bars are approximately equal to the posttreatment diameter distribution (actual posttreatment diameter distributions may differ due to tree recruitment into other diameter classes over the course of the experiment). The "other" mortality category includes trees that died of either unknown or natural causes not directly attributable to the experimental treatments.

All treatment combinations caused a decline in sapling densities over the course of the experiment. Thinning caused a ~45 percent decline in sapling density when used alone and >80 percent when used in combination with burning. The burn-only treatment also reduced sapling densities, but to a somewhat lesser extent (fig. 1C). The thin + burn treatment led to a drastic and significant decline in future tree recruitment compared to the control (P=0.0809), and thinning alone and burning alone had a similar yet lesser effect on reducing sapling densities.

Burning alone was not effective at reducing tree stocking, while thinning led to a marked reduction in basal area (BA) and an increase in average stand diameter. Prior to the experiment, most stands were at or near full stocking for their respective plant associations (as defined by Cochran and others 1994; see fig. 3). Basal area on burn-only units increased slightly over the course of the experiment, but was not significantly different than the trends observed on control units (P=0.9986; fig. 1B). The thin-only treatment reduced BA by almost half following treatment, which was significantly less than observed on control units (P<0.0001). The thin + burn treatment had a somewhat greater effect on reducing BA compared to the thin-only treatment; however, no significant differences were found between treatments (P=0.8754). Thinning, in general, reduced stocking to between 50 and 75 percent of full stocking, whereas burning alone led to an increase in stocking (fig. 3). Ponderosa pine dominated units responded similarly to the thin-only and thin + burn treatments and were well below 50 percent stocking following treatment. The decline in stocking levels on thin-only and thin + burn units led to a significant increase in average live tree diameter (P<0.0001; fig. 1E). Average diameter on burn-only units also increased following treatment; however, this change was not significant and mimicked control units where increases in stand diameter were a function of tree growth and suppressed tree mortality (P=1.000).

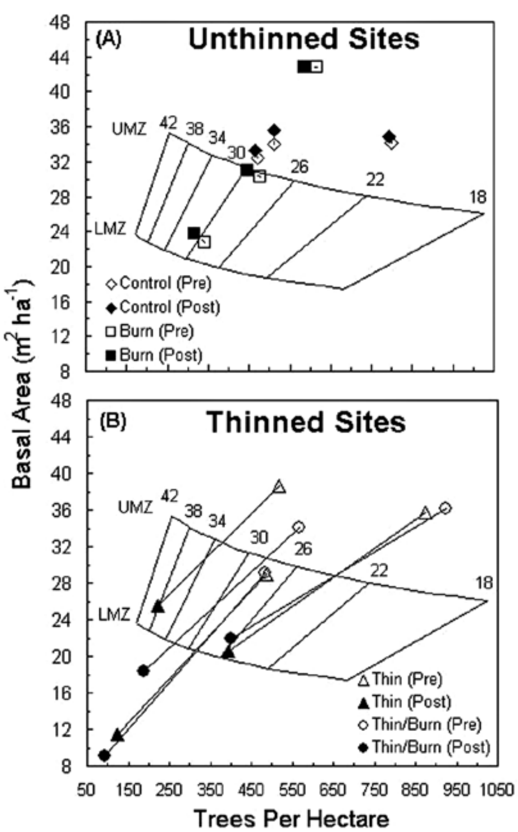

Figure 3—Pre- and posttreatment stocking for the 12 treatment sites located in central Washington. The dotted lines show the change in stocking for individual units following treatments. Upper management zone (UMZ) and lower management zone (LMZ) values are equal to 75 and 50 percent full stocking, respectively. Quadratic mean diameters (cm) are presented for each calculated stocking level.

Snag Dynamics Under Thinning and Burning Treatments

Burning and thinning treatments had dissimilar effects on snag density, and snag populations did not follow the same trends as live trees. The density of snags prior to treatment was highly variable between sites; however, no significant differences were found among treatments (P>0.3087). Pretreatment snag densities ranged from 8 to 83 ha^{-1} and averaged 47 ± 7 ha^{-1} across all units with a higher density of snags on control units and fewer snags on thin + burn units (fig. 4). About three-quarters of the snags in all treatments were <20cm d.b.h. with densities attenuating in sequentially larger size classes in a reverse-J pattern. Burning significantly increased snag densities on both burn-only and thin + burn units (P=0.0124). Increases in snag density on burn-only units were generally restricted to trees <20 cm d.b.h.; however, the thin + burn treatment created snags in all size classes (fig. 4). Thinning alone, conversely, led to a ~50 percent reduction in snag density, which was significantly different compared to the thin + burn (P=0.0286). Thinning alone removed snags in all diameter classes, with the largest reductions occurring in the <20 cm d.b.h. class.

Treatment effects on snag basal area differed somewhat from the changes observed in snag density. Pretreatment basal area of dead standing trees ranged from 0.2 to 2.9 m^2 ha^{-1} and averaged 1.6 m^2 ha^{-1} across all treatments. Thin-only units had the highest snag BA prior to the experiment, and was significantly different to the thin + burn treatment with the least amount of snag BA (2.4 and 0.8 m^2 ha^{-1}, respectively; P=0.0359). Snag BA remained relatively constant on both control and burn-only units, whereas the thin-only treatment reduced snag BA by >50 percent. Snag BA more than doubled under the thin + burn treatment, and had the most snag BA of all treatments by the end of the study. The main effect of burning was a significant increase in snag BA (P=0.0178); however, there were no significant differences found among treatments (P>0.1020).

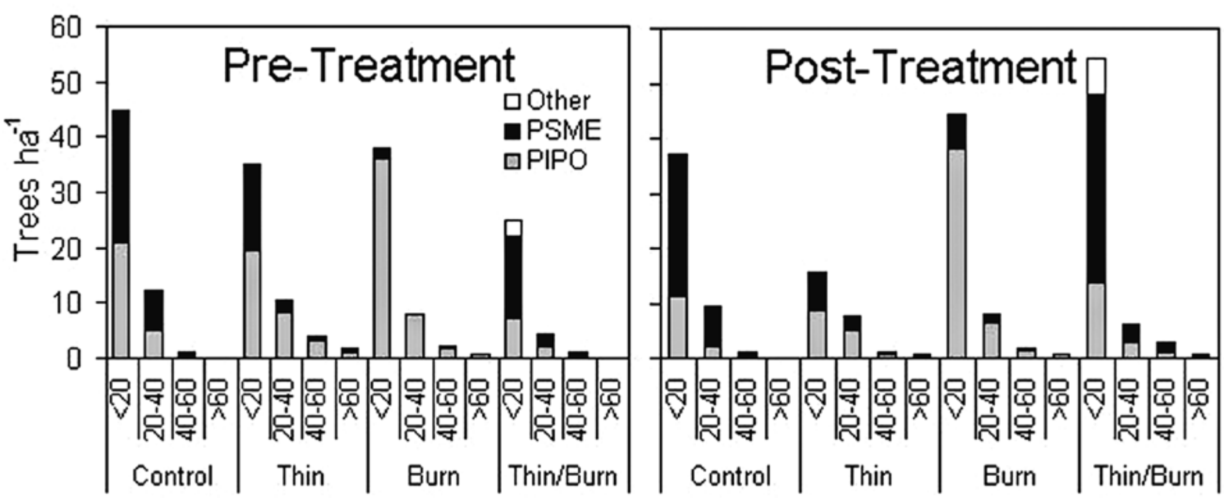

Figure 4—Diameter distribution (cm) and species composition of dead standing trees pre- and posttreatment in dry forests of central Washington. The "other" species category includes western larch and grand fir.

Changes in Canopy Structure Following Treatments

Canopy base height (CBH) increased over the course of the experiment under all treatment combinations; however, this increase was greatest under the thin + burn treatment. The burn only treatment raised CBH by ~1 m, but this was not significantly different as compared to the control (P=0.9208; fig. 1F). Thinning had a much larger effect on CBH, with the thin-only treatment and thin + burn treatment causing a ~3.5 and ~5.5 m increase in CBH, respectively. The rise in CBH on both thin-only and thin + burn treatments was significantly different compared to the control (P=0.0917, P=0.0101, respectively), and the thin + burn was significantly different compared to the burn-only (P=0.0232).

Canopy fuel loadings were greatly reduced by the thinning treatments, while burning was not effective at altering canopy structure. Canopy bulk density and canopy fuel loading remained relatively constant under the control and burn-only treatments, with values somewhat higher on control plots (fig. 5). The thin-only and thin + burn treatments both caused a significant two-fold reduction in canopy bulk density on average, compared to burn-only and control units (P=0.0006). Canopy bulk densities in both thin-only and thin + burn treatments were significantly different from burn-only and control treatments (P<0.0294). Similar trends were observed for canopy fuel loadings, with significant reductions occurring on thin-only and thin + burn units (P<0.0001). Both thin-only and thin + burn treatments led to significant declines in canopy fuel loadings as compared to the control treatment; however, the thin + burn treatment reduced canopy fuels by >6 Mg ha^{-1}, while thinning alone caused only a 3.5 Mg ha^{-1} decline. The greater reductions on thin + burn units may be due to greater pretreatment canopy fuel loading (fig. 5).

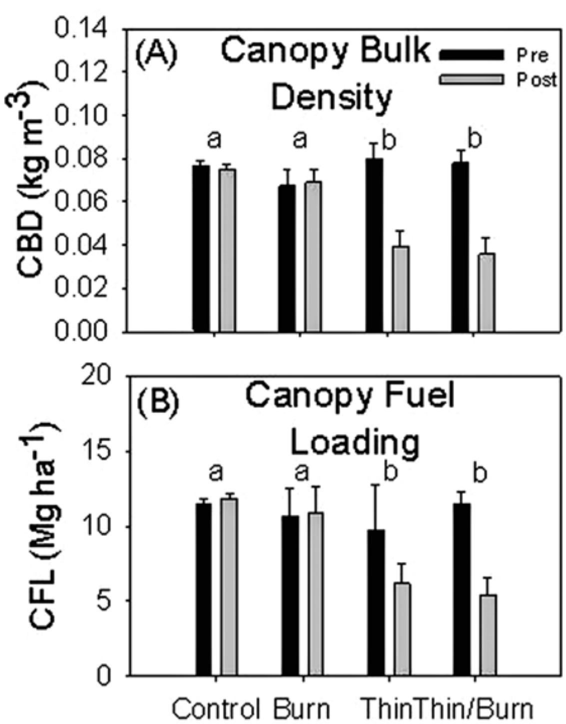

Figure 5—Changes in (A) canopy bulk density and (B) canopy fuel loading as calculated by Crown Mass®. Bars with differing letters are significantly different (P<0.1).

Canopy cover increased slightly when burning was used alone; while the reduction in canopy fuels on thin-only and thin + burn units led to a more open canopy. The minimal effect of burning alone on canopy cover was similar to the unmanaged control ($P=0.9991$, fig. 1D). However, thinning accounted for a 10 percent reduction in canopy cover on average over all thin-only and thin + burn units. This decline was significant compared to control and burn-only units ($P=0.0363$). No added benefit was found when thinning and burning were used in combination as compared to thinning alone ($P=0.9662$, fig. 1D).

Discussion

Tailoring Management Prescriptions Using Density Management Guidelines

Density management guidelines can be used to regulate forest stands to achieve a broad range of management objectives (Newton 1997). The natural range of variability (NRV) in forest density is often used to determine reference points in which to judge the ultimate success of restoration treatments. Using NRV to tailor management prescriptions is an attractive way to revert forest stands to previous structural conditions that were controlled by disturbance processes in place prior to the influence of Euro-Americans. Previous studies have identified a range of historic densities for forest types similar to our study (Avery and others 1976; Covington and Moore 1994; Harrod and others 1999; Morrow 1985). Harrod and others (1999) reconstructed stand structure in forests adjacent to our study site and found presettlement stocking varied between plant association groups (PAG) and ranged from 27 to 68 trees ha^{-1} and 10 to 22 m^2 ha^{-1}. In our study, thin-only and thin + burn units following treatment differed somewhat from historical forests, with densities and BA averaging 4.6 and 2.8 times greater than historical values, respectively. However, these values may not be directly comparable due to the relatively young age and early seral stage of development of our study forests. For instance, historical stands investigated by Harrod and others (1999) were dominated by trees nearly twice the average diameter of post-treatment stands in our study.

Insect populations are often dependent on host densities, with increasing tree densities leading to higher probabilities of insect outbreaks. Sartwell and Stevens (1975) studied mountain pine beetle (*Dendroctonus ponderosae*) outbreaks in ponderosa pine forests of the Interior Western United States and found beetle outbreaks to be appreciably increased in even-aged ponderosa pine forests with >34 m^2 ha^{-1} BA. In our study, none of the thin-only or thin + burn units exceeded the BA threshold following treatment; however, seven out of the 16 burn-only plots (44 percent) had BA >34 m^2 ha^{-1}. Because we were working primarily in mixed-conifer stands, 34 m^2 ha^{-1} is likely a conservative threshold for our study sites, and higher stocking values may be acceptable. The upper management zone (UMZ) defined by Cochran and others (1994) is the stocking level at which a substratum of small diameter trees begins to develop, making forests increasingly susceptible to insect-related mortality. After accounting for the lower maximum-stocking associated with the PAs in this study we calculated a UMZ of 583, which is similar to other UMZ values for interior ponderosa pine and Douglas-fir forest types (Day 2005; Cochran and Barrett 1999; Long and Shaw 2005).

However, Harrod and others (1999) reported a lower UMZ for stands adjacent to the Mission Creek watershed (SDI=263). These values differ because Harrod's calculations (1) were based on ponderosa pine dominated stands that had considerably lower full-stocking values compared to the Douglas-fir PAs used in the current study (Lillybridge and others 1995) and (2) used slightly different UMZ calculations that were adjusted for site productivity (Cochran and others 1994).

Role of Fire in Altering Forest Structure

Since the use of fire suppression activities 50 to 100 years ago, interior ponderosa pine and Douglas-fir forests have experienced a drastic decline in fire frequency (Cooper 1960; Covington and Moore 1994; Everett and others 2000; Fry and Stephens 2006), which has led to the development of a dense substratum of small-diameter trees and an accumulation of coarse woody debris. Prescribed fire is often reintroduced into these ecosystems as a way to restore past forest structure; however, little empirical evidence supports the use of prescribed fires alone in forest restoration (Sackett and others 1996; Thomas and Agee 1986; Youngblood and others 2006). Possible solutions for manipulating overstory structure with fire under these circumstances include using a single high-intensity prescribed fire (Fulé and others 2004) or to use repeated burnings where treatment effects are amortized over time (Miller and Urban 2000). Peterson and others (1994) found that repeated burnings at 4- to 6-year intervals reduced surface and ladder fuels and increased growth in larger residual ponderosa pine trees.

The prescribed burns used in the current study removed only the smallest diameter trees and had an overall negligible effect on forest structural components. Observations made during the burns suggest that the fire intensity was variable within and among study sites. For our study area, Agee and Lolley (2007) reported on the treatment effects on surface fuels and noted that the effect of fire was negligible over 50 to 75 percent of the study area. In one burn-only unit in particular, fire scorched <5 percent of the crowns of trees and less than a third of all trees had any signs of burning. These results suggest that a single, early season burn is ineffective at reducing tree density, but may be effective at reducing some forest floor fuels (Agee and Lolley 2007). Spring burns often cause lower overstory mortality as compared to fall burns, due to the high moisture content in surface and foliar fuels following green-up. Youngblood and others (2006) studied the effect of autumn prescribed fires on overstory structure in ponderosa pine/Douglas-fir forests of eastern Oregon; however, they found that the late-season burns had a similar null effect on overstory structural components as observed in our study.

Trees killed directly by the burn were often left standing following treatment, thereby adding to snag recruitment. Snags are an important aspect of forest structure, particularly for primary and secondary cavity nesters and insect populations (Raphael and White 1984; Harmon and others 1986; Bull and others 1997). While the prescribed burns did increase snag density in this study, most were <20 cm d.b.h.. Cavity nesting birds select trees with larger than average diameters for nesting (Raphael and White 1984) and several species require snags >25 cm d.b.h. for suitable nesting habitat (Ganey and Vojta 2004; Pilliod and others 2006; Thomas and others 1979). Therefore, the general increase in snags should be viewed cautiously in terms of wildlife habitat.

The use of prescribed fire has obvious other advantages as a management tool including reducing ground fuels, increasing nutrient availability and net primary productivity, and reintroducing a natural process back into a historically fire-prone system (Weatherspoon 1996). The spring burns conducted in the experiment were cooler and spottier than were desired and may have led to results that downplay the efficacy of fire to meet forest restoration goals. Evaluations of drier spring burns or fall burns are needed to fully understand the utility of prescribed burning to meet restoration goals (McCandliss 2002).

Reducing Fire Potential with Mechanical Thinning

Thinning alone was capable of reducing canopy fuels, canopy bulk density, and tree stocking by $\geq$50 percent. Similar results were found in fire and fire surrogate experiments in eastern California and Oregon (Stevens and Moghaddas 2005; Youngblood and others 2006). However, these results ignore the deposition of additional fine- to medium-sized surface fuels created by the thinning treatments that increase flame lengths and torching potential (Agee and Skinner 2005; Peterson and others 2005). Youngblood and others (2006) studied treatment effects on forest structure in ponderosa pine forests of eastern Oregon and found that coarse woody debris density increased when thinning was used alone as compared to when burning was used alone and in combination with thinning. These results are typical for thinning operations (Cram and others 2006; McIver and Ottmar 2007), and the increased fire hazard from the accumulation of these fuels is often a deterrent for the use of thinning alone. However, when the torching index (a measure of the windspeed required to propagate fires into the canopy) was modeled in Crown Mass® using fuel loads comparable to those present following thinning in our study areas indices averaged ~100 km hr^{-1}. This suggests that thinning alone was capable of increasing fire resiliency by reducing tree stocking and crown fuels enough to counteract the resultant accumulation of slash.

Treatment rotations for individual stands often exceed 15 to 20 years; therefore, treatments should reduce stocking levels sufficiently to cover the lag between subsequent treatments. In this study, the limited effects of burning on controlling tree stocking and canopy fuels may diminish quickly and stands in our study will most likely revert to pretreatment stand structures. The drastic effect of thinning on stocking suggests that this treatment is necessary if only a single-entry treatment is feasible and large time gaps between treatments are expected.

The use of mechanical thinning also leaves open the opportunity to combine fuels reduction treatments with other silvicultural treatments elsewhere on the landscape. For instance, group selections and other uneven-aged management practices are becoming increasingly popular in ponderosa pine forests (Youngblood 2005). Incorporating alternative silvicultural prescriptions with regular fuels reduction operations will increase heterogeneity on the landscape and benefit wildlife (Graham and others 2004), aesthetics, increase landscape heterogeneity, and also help recoup some of the costs associated with fuels reduction treatments. Uneven-aged management has proved successful at reducing wildfire severity in similar forest types (Omi and Martinson 2002; Pollet and Omi 2002).

Conclusions

Dry forests of the Western United States have undergone drastic structural changes over the past century that have contributed to an apparent threat of intense crown fire and insect outbreak potential over much of the region. Foresters need to be provided with sound, science-based treatment alternatives to effectively and responsibly manage these public lands. Results from our study suggest that thinning alone is capable of enhancing forest resiliency to fire and insect mortality by reducing overstory density and canopy fuel levels. Burning was not an effective method of controlling overstory fuel loads; however, by reducing surface and other ladder fuels (see Agee and Lolley 2007), burning may be used in conjunction with thinning to restore ecosystem structural and functional components.

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