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Mechanical mastication and prescribed burning reduce forest fuels and alter stand structure in dry coniferous forests

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ABSTRACT

Mechanical thinning is often prescribed in dry coniferous forests to reduce stand density, ladder fuels, and canopy fuels before using prescribed burning to manage surface fuels. Mechanical mastication is a tool for thinning forests where commercial thinning is not viable. We evaluated the effects of mastication-based thinning – with and without subsequent prescribed burning – on forest structure and fuels in dry coniferous forests of the Pacific Northwest, USA. We thinned stands by masticating small-diameter trees and depositing the resulting slash on the forest floor. We then used prescribed burning to reduce surface fuels in half of the masticated stands. Mastication reduced overstory tree density, tree regeneration, stand basal area, canopy bulk density, and total canopy fuels, while increasing surface woody fuel loads for most fuel size classes. Increases in 100-hour and 1000-hour sound woody surface fuels were positively correlated with pretreatment stand density and local thinning intensity. Mastication reduced 1000-hour rotten woody fuels, however. Prescribed burning following mastication reduced surface woody fuels across all size classes, often as a proportion of available fuels. Surface fuel reductions from prescribed burning generally exceeded fuel inputs from mastication, so the combined treatments reduced stand density, canopy fuels, ladder fuels, and most surface fuels relative to pretreatment conditions. Mastication increased modeled surface wildfire intensity but reduced crown fire potential. Prescribed burning after mastication reduced fuels and modeled surface wildfire intensity to pretreatment or lower levels. This study shows that mastication-based thinning followed by prescribed burning can be effective for reducing fuels and wildfire hazards and for modifying overstory stand structure in forest stands with small-diameter trees.

1. Introduction

Modifying forest structure and fuels to mitigate wildfire impacts on humans and natural resources has become an important objective in restoration-based management of dry coniferous forest management in North America (USDA Forest Service, 2012, 2022). Decades of fire exclusion, timber harvesting, livestock grazing, and insect outbreaks have produced widespread changes in overstory structure and fuels in these forests, including higher densities of small-diameter trees, loss of older and larger trees, and greater accumulations of dead forest fuels (Cooper, 1960; Covington and Moore, 1994; Hessburg et al., 2005; Jenkins et al., 2008; Hagmann et al., 2021). These changes in forest structure and fuels, coupled with regional droughts and warming summer temperatures, have contributed to dramatic increases in wildfire area burned and wildfire burn severity in recent decades despite ongoing efforts to suppress wildfires (Dennison et al., 2014; Holden et al., 2018; Parks et al., 2018; Parks and Abatzoglou, 2020). In response, there is increased interest in expanding the pace and scale of dry forest restoration and fuels reduction to reduce wildfire risks to people, communities, and natural resources while restoring and

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sustaining healthy, resilient fire-adapted forests (USDA Forest Service, 2022).

Substantial structural manipulations are often needed in modern dry coniferous forests to restore forest structure to within the natural range of variability, re-establish natural processes, reduce crown fire hazards, and facilitate the use of low intensity prescribed fire (or low severity wildfire) to reduce and manage surface fuels (Allen et al., 2002). Mechanical thinning treatments are commonly used in forest restoration to reduce overstory tree densities, promote the development and persistence of large and old trees, shift forest species composition toward greater dominance by fire- and drought-tolerant species, and restore spatial heterogeneity in forest structure (North et al., 2009; Franklin and Johnson, 2012). Mechanical thinning treatments can also be used to reduce ladder fuels (e.g., small trees and tall shrubs) and horizontal continuity of canopy fuels, thereby reducing torching and crown fire spread during wildfires and facilitating subsequent application of prescribed fire to reduce surface fuels (Agee and Skinner, 2005; North et al., 2009). Restoration objectives and prescriptions often focus on removal of small-diameter trees, saplings, and shrubs that have little or no economic value, so treatments are needed that can modify stand structure and treat ladder and surface fuels at acceptably low costs.

Mechanical mastication is an increasingly popular approach for altering forest stand structure, fuel profiles, and potential fire behavior and effects in forests that cannot support commercial thinning and in forests where prescribed burning is challenging (Battaglia et al., 2010; Jain et al., 2012). Mechanical mastication uses cutting heads mounted on carrier machines to fragment small trees and shrubs – thereby reducing ladder and canopy fuels – and deposit the resulting woody debris and litter on the forest floor (Jain et al., 2018). Some mastication equipment can also be used to grind surface fuels to alter fuel size distributions, reduce fuelbed depth, and increase fuelbed bulk density (Keane et al., 2018). Final particle sizes for masticated fuels can vary from small wood chips and shreds to large wood chunks (e.g., branch segments), depending on the parent material, cutting head, and operator time (Kreye et al., 2014; Jain et al., 2018). Particle sizes, in turn, influence fuelbed depths, bulk densities, moisture dynamics, decomposition rates, and potential fire behavior (Battaglia et al., 2010; Jain et al., 2012; Kreye et al., 2012; Keane et al., 2018). Compared to natural fuelbeds, fires in masticated fuelbeds may burn with lower flame lengths and rates of spread but also with longer residence times that can promote greater heating of soils and vegetation (Busse et al., 2005, 2010; Kreye et al., 2014; Kreye and Kobziar, 2015).

Prescribed burning may be beneficial after mastication treatments to offset increases in surface fuels and further reduce potential wildfire intensity and severity, as masticated fuels can persist for a decade or more without further treatment (Knapp et al., 2011; Keane et al., 2018; Reed et al., 2020). Prescribed burning is generally an effective tool for reducing surface and ladder fuels in dry coniferous forests, thereby reducing potential fireline intensities, rates of spread, and torching and crown fire hazards during subsequent wildfires (Stephens and Moghaddas, 2005; Schwilk et al., 2009; Vaillant et al., 2009). Reducing surface fuels with prescribed fire following mastication may also help avoid lethal heating of soils and vegetation if prescribed burns are conducted when soils are moist (Busse et al., 2010). However, fuel moisture and fuel age (time since mastication) have been shown to influence fire behavior and fuel consumption in masticated fuels (Lyon et al., 2018) and questions remain about how soon prescribed burning can be used following mastication treatments to effectively reduce surface fuels and fire hazards.

In this study, we examined the effects of mechanical mastication treatments – with and without subsequent prescribed burning – on overstory structure, forest fuels, and potential wildfire behavior in dry coniferous forests of the eastern Cascade Mountains of Washington State, USA. Our study objectives were: 1) to evaluate the effectiveness of mastication for restoring live tree density, basal area, size structure, and species composition to desired conditions; 2) to examine the effects of mastication and prescribed burning treatments on surface, ladder, and canopy fuels; and 3) to assess the effects of altered forest fuels on potential fire behavior under simulated wildfire conditions. We used observations from a management-driven field study of mastication and prescribed burning effects to address the first two objectives and fire behavior model simulations to address the third objective.

2. Methods

2.1. Study area and treatment units

We conducted this management study as part of the Hungry-Hunter Ecosystem Restoration Project on the Methow Valley Ranger District of the Okanogan-Wenatchee National Forest in the eastern Cascade Mountains of Washington State, USA (latitude: 48.07–48.16° N; longitude: 120.07–120.16° W). The project area encompassed a range of dry coniferous forest types, from forests dominated by ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) near the lower tree line to dry mixed-conifer forests dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) or lodgepole pine (*Pinus contorta* Douglas ex Loudon) on cooler and wetter sites. Common shrub species included snowbush ceanothus (*Ceanothus velutinus* Douglas ex Hook.), Oregon boxleaf (*Paxistima myrsinites* (Pursh) Raf.), and shinyleaf spirea *(Spiraea lucida* Douglas ex Greene). Common herbaceous species included pinegrass (*Calamagrostis rubescens* Buckley), heartleaf arnica (*Arnica cordifolia* Hook.), Virginia strawberry (*Fragaria* virginiana Duchesne), and lupines (*Lupinus* L.).

Most of the forests in our project area were dominated by relatively dense stands of ponderosa pine, Douglas-fir, and lodgepole pine that established following a large wildfire event in 1929. Historical mean fire return intervals ranged between 7 and 25 years in these forests (Everett et al., 2000; Wright and Agee, 2004) but fire exclusion efforts since the early 20th Century have largely excluded wildfires from these forests, allowing development of high stand densities, multi-story stand structure, high surface fuel loads, and increased risks of high severity wildfires (Hessburg et al., 2005).

The Hungry-Hunter Ecosystem Restoration Project (H-H Project) was developed through a collaborative multi-party process involving the Methow Valley Ranger District and the Eastern Washington Provincial Advisory Committee. The primary objective was to reduce wildfire hazards within and adjacent to the wildland-urban interface. Secondary objectives included restoring structure and species composition to more closely resemble historical conditions, increasing forest resilience to fire, and facilitating the future use of prescribed fire for managing forest fuels.

Within the Hungry-Hunter project area, we selected 18 experimental treatment units (about 5–6 ha each) that met pre-commercial thinning requirements and were suitable for operating mastication equipment. Operation of mastication equipment required proximity of units to existing roads to allow access, target stand spacings of at least six meters to allow equipment to move through the stand, slopes less than 35 % to minimize soil displacement, and masticated tree (or surface wood) diameters to be less than 20 cm.

2.2. Treatments

2.2.1. Mastication treatments

Mastication treatments employed a vertical shaft mastication head mounted on the boom of a tracked, self-levelling excavator (Fig. 1a). This configuration allowed the operator to reach up to nine meters in any direction, thereby reducing excavator movement and soil disturbance within treatment units. The mastication head was able to thin and masticate unmerchantable overstory trees (up to 20 cm diameter) as well as understory saplings, seedlings, and large shrubs. It was also used to break up and scatter forest floor woody debris (similar to a "lop and scatter" treatment).

The silvicultural prescription for all units called for thinning forest

Fig. 1. Photos showing a) mastication equipment used in the study, b) a treatment unit prior to mastication, and c) the same treatment unit after mastication.

stands to target densities of 190–220 trees per hectare (DBH > 10 cm) by removing small-diameter (< 20 cm) trees with mastication equipment. Mastication contracts specified that retained ("leave") trees should generally be the tallest trees with the largest crowns and straightest boles and be free of damage from insects, diseases, and physical injuries. Retaining ponderosa pines was the top priority, followed by Douglas-firs, and lodgepole pines. The prescription called for retaining all conifers with stump diameters exceeding 20 cm, however, regardless of species. Snags were to be retained if their stump diameter exceeded 20 cm and their presence did not create a safety hazard for the mastication equipment operators; all other snags were to be masticated.

The study design called for testing three different levels of mastication "effort," as defined by the particle size (length) distributions in the masticated woody fuels. The lowest effort ("coarse") treatment called for thinning trees and manipulating slash so that the resulting fuel pieces approximated a fuel size distribution in which 75 % of pieces were 60–120 cm long, 20 % were less than 60 cm long, and 5 % were greater than 120 cm long. The medium effort ("mixed") treatment called for producing a fuel size distribution in which 50 % of fuel pieces were 15–61 cm long, 25 % were less than 15 cm long, and 25 % were greater than 61 cm long. The high effort ("fine") treatment called for producing a size distribution in which 75 % of fuel pieces were less than 15 cm long, 25 % were 15–61 cm long, and 5 % were greater than 61 cm long. For all three treatments, final fuelbed depths were to be less than 45 cm. Each mastication treatment was randomly assigned to six of the 18 treatment units. We applied assigned mastication treatments to all 18 treatment units between May and July of 2007.

2.2.2. *Prescribed burning treatments*

We applied prescribed burning treatments to nine of the 18 treatment units, randomly selecting three units from each mastication intensity treatment for burning. We burned the selected units in the fall, 3–5 months following completion of the mastication treatments (October 11 to November 1, 2007). Burning was accomplished under seasonally cool and moist weather conditions, with temperatures between 4 ° and 15° C and relative humidities of 30–70 %. Strip-head firing was used primarily to ignite the fires, producing backing and flanking spread rates of less than 50 m/hour and head fire spread rates of 20–400 m/hour. Fire intensity was low, with flame lengths mostly less than one meter. Burns were patchy, but all burns blackened more than 50 % of treatment units. There were no obvious differences in observed fire behavior variables among treatments.

2.3. *Sampling procedures*

2.3.1. *Sampling grids*

Within each treatment unit, we established a sampling grid oriented to the cardinal directions, with 12 sample points placed at 40-meter intervals. Units were often irregular in shape, so we adjusted the shapes of the sampling grids to accommodate that irregularity and avoid placing sample points near unit boundaries where edge effects could significantly influence results. At each sample point, we recorded latitude, longitude, elevation, slope, and aspect prior to treatment. We measured overstory canopy cover at each sample point before and after mastication and burning treatments. We also characterized local understory shrub and herb vegetation by cover class (1 = 0–10 %, 2 = 10–40 %, 3 = 40–70 %, 4 = 70–100 %) and average height (to nearest 0.1 m).

To measure surface fuels, we established two 20-m planar intercept sampling transects at random azimuths radiating out from each sample point (Brown, 1974). Sampling transects extended from 5 to 25 m from the sampling point. We surveyed fuels before and after mastication and prescribed fire treatments by recording the number of dead woody fuel intercepts for 1-, 10-, and 100-hour fuels over 2-, 3- and 5-m segments on each transect, respectively. We also recorded the diameter and decay class of all 1000-hour fuels that intercepted the entire 20-m transect length. We measured and recorded litter and duff depths at distances of 10, 15 and 20 m and fuelbed depths (height to highest fuel particle) at distances of 14, 15 and 16 m from the sample point. At each sample point, we also recorded the fuel model (Anderson, 1982), mean shrub density and height, and mean herbaceous density and height before and after treatments.

We assessed overstory stand structure and tree regeneration at each sample point using variable radius plots. Sample point plot radii for trees varied from 3 to 15 m (median = 8 m), with the goal of sampling about 10 live overstory trees (diameter $\geq$ 10 cm) per plot prior to application of mastication treatment. Sample point plot radii for tree regeneration also varied from 3 to 15 m but were sometimes smaller than the associated tree plot radius. For each live tree in a tree plot prior to treatment, we recorded the diameter at breast height (1.37 m), heights to dead and live crown, and overall tree height; we then updated the tree status (live, dead, cut) after completion of the mastication and prescribed burning (burned units only). We counted all seedlings (trees < 1.37 m tall) and saplings (trees $\geq$ 1.37 m tall and < 10 cm diameter) within each tree regeneration plot at each survey date and estimated percentages of the total count for each tree species encountered.

Within each treatment unit, we also established four 0.1-ha (20 ×50 m) vegetation sampling plots adjacent to four randomly selected sample points within each treatment unit to assess treatment effects on overstory stand structure (and understory vegetation) in more detail and over time. We tagged all trees and snags (DBH > 10 cm) rooted within each plot and recorded the species, diameter at breast height (DBH), and height during pretreatment surveys. We recorded tree and snag status (alive, dead, or cut) before and after the mastication and prescribed fire treatments.

2.4. Data analysis

2.4.1. Data calculations and summaries

Prior to analyses, we summarized field data first to the sample point or vegetation plot level and then to the unit level. To describe overstory structure, we summarized tree survey data from the vegetation plots to obtain stand density (trees/hectare), basal area (m^2/ha), and quadratic mean tree diameters (cm) for live trees and snags at the vegetation plot and treatment unit levels for each sampling period. We also calculated unit-level and study-wide tree and snag densities by species and 5-cm diameter classes for each sampling period to characterize treatment effects on stand size distributions and species composition. We used tree data from the vegetation plots rather than the sample point plots to describe overstory structure because the vegetation plots were larger and of equal size, provided larger sample sizes, and included snags. For tree regeneration metrics, we first calculated sample point-level seedling and sapling densities from sample point plot tallies, accounting for variable sample plot sizes, and then averaged those densities to the unit level.

To assess treatment effects on overstory canopy fuels, we used the FuelCalc model (Reinhardt et al., 2006) with our overstory tree survey data to estimate changes in canopy fuel loads, canopy bulk density, and canopy base height. We combined tree survey data from the four vegetation plots in each treatment unit for each survey date to generate unit-level overstory fuel estimates before and after mastication and prescribed burning treatments.

To assess treatment effects on surface woody fuels, we calculated surface woody fuel loads from the sample point fuel transect measurements (Brown, 1974). We first calculated estimated woody fuel loads (1-hour, 10-hour, 100-hour, 1000-hour sound, and 1000-hour rotten) for individual transects and then averaged those estimates to the sample point and unit levels for each sampling period. Similarly, we averaged litter depths, duff depths, and fuelbed depths to the sample point and unit levels for each sampling period.

2.4.2. Fire behavior modeling

We modeled potential fire behavior using unit-level fuels data from pretreatment, post-mastication, and post-burn fuel surveys to assess treatment effects on flame lengths, rate of spread, fireline intensity, scorch heights, and crown fire initiation under typical summer wildfire weather and fuel moisture conditions. We simulated wildfire behavior using the Rothermel equations of surface fire spread and the Van Wagner model of crown fire initiation as implemented in the R package *firebehavioR* (Rothermel, 1972; Van Wagner, 1977; Ziegler et al., 2019). We supplied the model with unit-level mean values for litter and surface woody fuels, fuelbed depths, overstory canopy structure and fuels, and topographic slope, and set live herbaceous and live woody fuel loads to zero. We used surface area to volume ratios, moisture of extinction, and heat content from a published timber-litter fuel model (TL5, Scott and Burgan, 2005) and set the litter surface area to volume ratio to 6000 $m^2 \cdot m^{-3}$ based on published SAV values for conifer needles (Brown, 1970). For all units, we set crown foliar moisture content to 100 %, which is representative of mature conifer foliage in Pacific Northwest forests (Rothermel, 1983; Agee et al., 2002). To simulate wildfire conditions, we used fuel moisture and windspeed values for 97th percentile fire weather in northcentral Washington derived from Remote Automated Weather Station (RAWS) data (Radcliffe et al., 2024).

2.4.3. Statistical analysis

This study employed a before-after experimental design without untreated control units. Responses of interest were measured on treatment units before and after each treatment and treatment effects were assessed as differences (change) between pretreatment and posttreatment measurements. With no control units, we assumed that the observed changes in response means were caused primarily by the experimental treatments.

Following preliminary data analysis, we decided to treat the three mastication effort treatments (coarse, mixed, and fine) as a single mastication treatment. We made this decision because: 1) the same mastication equipment was used for all three mastication treatments; 2) the differences in prescribed outcomes among treatments were based on lengths of the resulting woody debris particles, while our planar intercept fuel sampling procedures (Brown, 1974) only measured woody particle diameters; and 3) random assignment of treatments to units resulted in three high stand density units all being assigned to the same mastication treatment, making it difficult to distinguish between initial stand density effects and mastication effort treatment effects.

We used descriptive and inferential statistical analyses to address three basic questions about treatment effects on forest overstory structure, forest regeneration, canopy fuels, and surface fuels: 1) Did treatments significantly alter mean responses or variability among treatment units? 2) Did treatment effects vary significantly with pretreatment stand density (overstory thinning intensity)? 3) Did treatment effects vary significantly with pretreatment fuel loadings? We addressed these questions using analysis of variance (often with heterogeneous variances), correlation analysis, and linear regression procedures as implemented in the GLM, CORR, and MIXED procedures in the SAS/STAT statistical software package (version 15.3, SAS Institute).

To assess mastication and prescribed burning treatment effects on overall response means and variability, we first fit a simple analysis of variance (ANOVA) model in PROC GLM with a classification variable for the sampling period (before or after treatment) and tested for homogeneity of variances among sampling periods using Levene's test on the absolute values of the model residuals. We then used an ANOVA procedure – with heterogeneous variances, if needed – to test for significant changes in response means.

We used correlations, scatter plots, and linear regression analyses to assess the influences of pretreatment variability in stand density and fuel loadings on fuel responses to mastication and prescribed burning treatments. For each combination of treatment and fuel response variable, we first generated Pearson correlation coefficients and scatter plots to assess possible associations between unit-level treatment effects and pretreatment covariates. For mastication treatment effects, we then used linear regression analysis with pretreatment stand density (a surrogate for overstory thinning intensity) and pretreatment fuels as predictors to assess their individual and interactive effects on unit-level fuel responses. For prescribed burning treatment effects, we used linear regression analysis with pretreatment fuel loads as the only predictor to assess burning effects on unit-level fuel responses.

3. Results

3.1. Mastication and prescribed burning effects on overstory structure, canopy fuels, and regeneration

Mastication-based thinning treatments significantly modified mean overstory stand structure across treatment units. Mastication treatments reduced mean live tree densities from 598 to 310 trees per hectare ($p < 0.0001$), reduced mean live tree basal area from 18.2 to 14.2 m^2/ha ($p < 0.0001$) and increased mean live tree quadratic mean diameter (QMD) from 20.7 to 24.0 cm ($p < 0.0001$, Fig. 2). Mastication treatments also reduced mean snag densities from 34 to 13 snags per hectare ($p < 0.0001$) and reduced mean snag basal area from 1.5 to 0.8 m^2/ha ($p < 0.0001$) while increasing mean snag QMD slightly, from 24.1 to

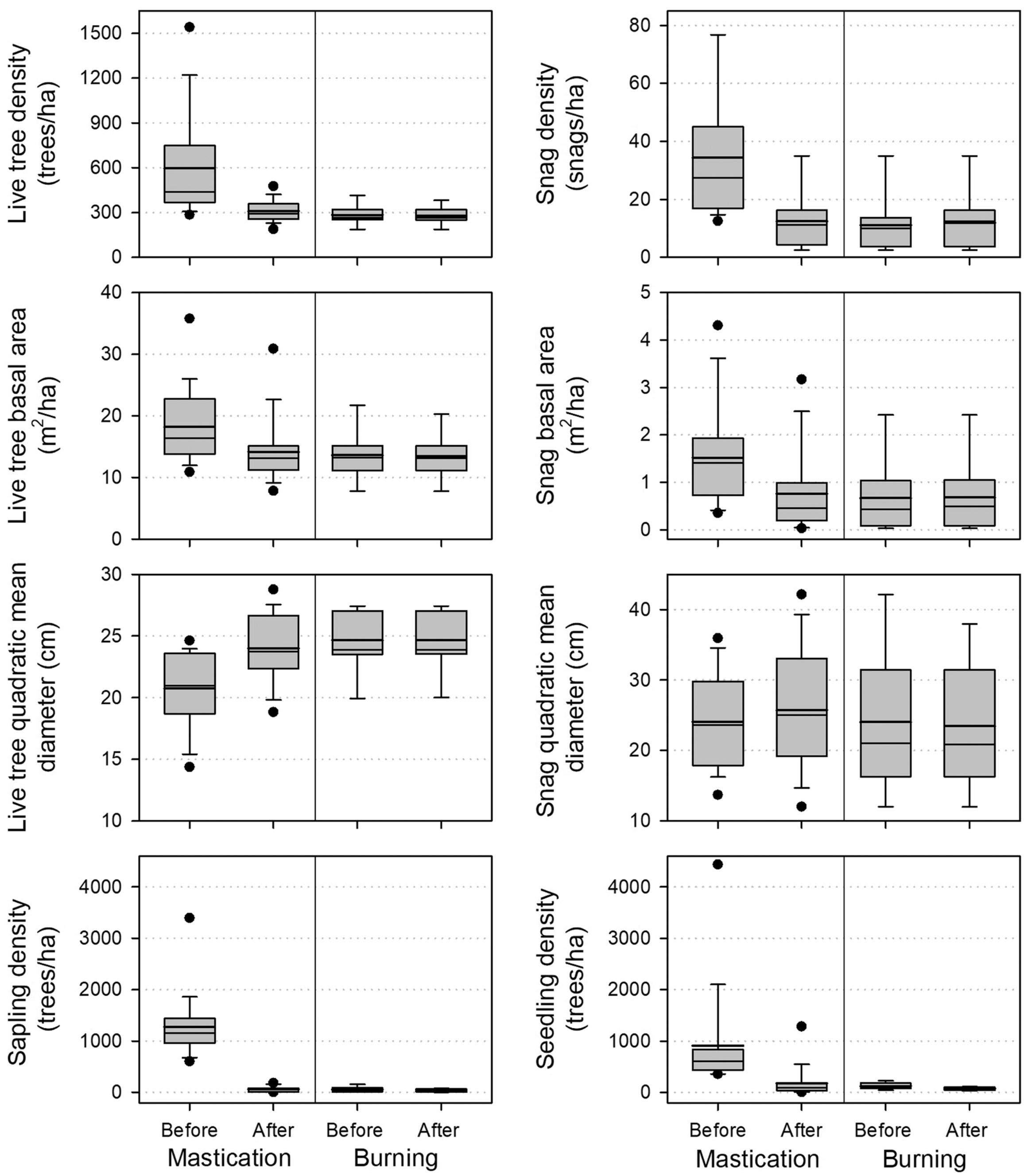

Fig. 2. Box plots show changes in overstory stand structure and regeneration density (mean and variability) in response to mastication treatments (18 units) and prescribed burning treatments (9 units).

25.7 cm ($p = 0.52$). Mastication treatments reduced mean overstory canopy cover from 67 % to 48 % ($p < 0.0001$). Finally, mastication treatments reduced mean sapling densities by about 95 %, from 1276 to 58 saplings per hectare ($p < 0.0001$), and reduced mean seedling densities by about 80 %, from 908 to 175 seedlings per hectare ($p = 0.0002$, Fig. 2).

Mastication-induced changes in overstory structure (i.e., treatment intensity) varied considerably among treatment units, with effects often correlated with pretreatment conditions. Reductions in live tree density, live tree basal area, and overstory canopy cover were greater in units with high pretreatment live tree densities than in those with lower pretreatment densities (Fig. 3). Increases in live tree QMD were higher (and less variable) in units with high pretreatment live tree densities than in units with lower pretreatment densities (Fig. 3). Reductions in sapling and seedling densities were negatively correlated with (proportional to) pretreatment sapling and seedling densities (saplings: $r = -0.997$, $p < 0.0001$; seedlings: $r = -0.92$, $p < 0.0001$). Reductions in snag density were negatively correlated with pretreatment snag density ($r = -0.90$, $p < 0.0001$) and reductions in snag basal area were negatively correlated with pretreatment snag basal area ($r = -0.64$, $p = 0.0045$). As a result of this variable treatment intensity, mastication treatments significantly reduced variances among treatment units for stand density ($p = 0.04$), snag density ($p = 0.02$), sapling density ($p = 0.005$), and seedling density ($p = 0.04$), but not live tree basal area ($p = 0.25$), mean live tree quadratic mean diameter ($p = 0.63$), snag basal area ($p = 0.43$), mean snag diameter ($p = 0.23$), or canopy cover ($p = 0.56$).

Consistent with the silvicultural prescription, the mastication treatments removed mostly small trees, saplings, and seedlings, with some bias toward retaining more fire-resistant ponderosa pines and Douglas-firs. Prior to mastication, forests in the study area were dominated by smaller trees, with both live trees and snags featuring reverse-J diameter distributions (Fig. 4). Mastication treatments removed about 70 % of live trees with diameters between 10 and 20 cm, including 81 % of lodgepole pines, 63 % of ponderosa pines, and 60 % of Douglas-firs in that size range (Fig. 4). Mastication treatments also reduced mean small-diameter (10–20 cm diameter) snag densities by 74 % and larger-diameter snag densities by 48 % (Fig. 4).

By reducing overstory live tree densities, mastication treatments also reduced model estimates of forest canopy fuels. Mastication treatments reduced mean canopy fuel load from 1.48 to 1.13 Mg/ha ($p = 0.06$) and mean canopy bulk density from 0.073 to 0.053 kg/m^3 ($p = 0.011$). Unit-level changes in canopy fuel load and canopy bulk density were highly correlated with pretreatment stand density ($r = -0.89$ to -0.93, $p < 0.0001$, Fig. 3). Mastication treatments produced only a small effect on estimated mean canopy base height, which increased from 2.7 to 3.0 m ($p = 0.28$), but model estimates were based only on overstory tree

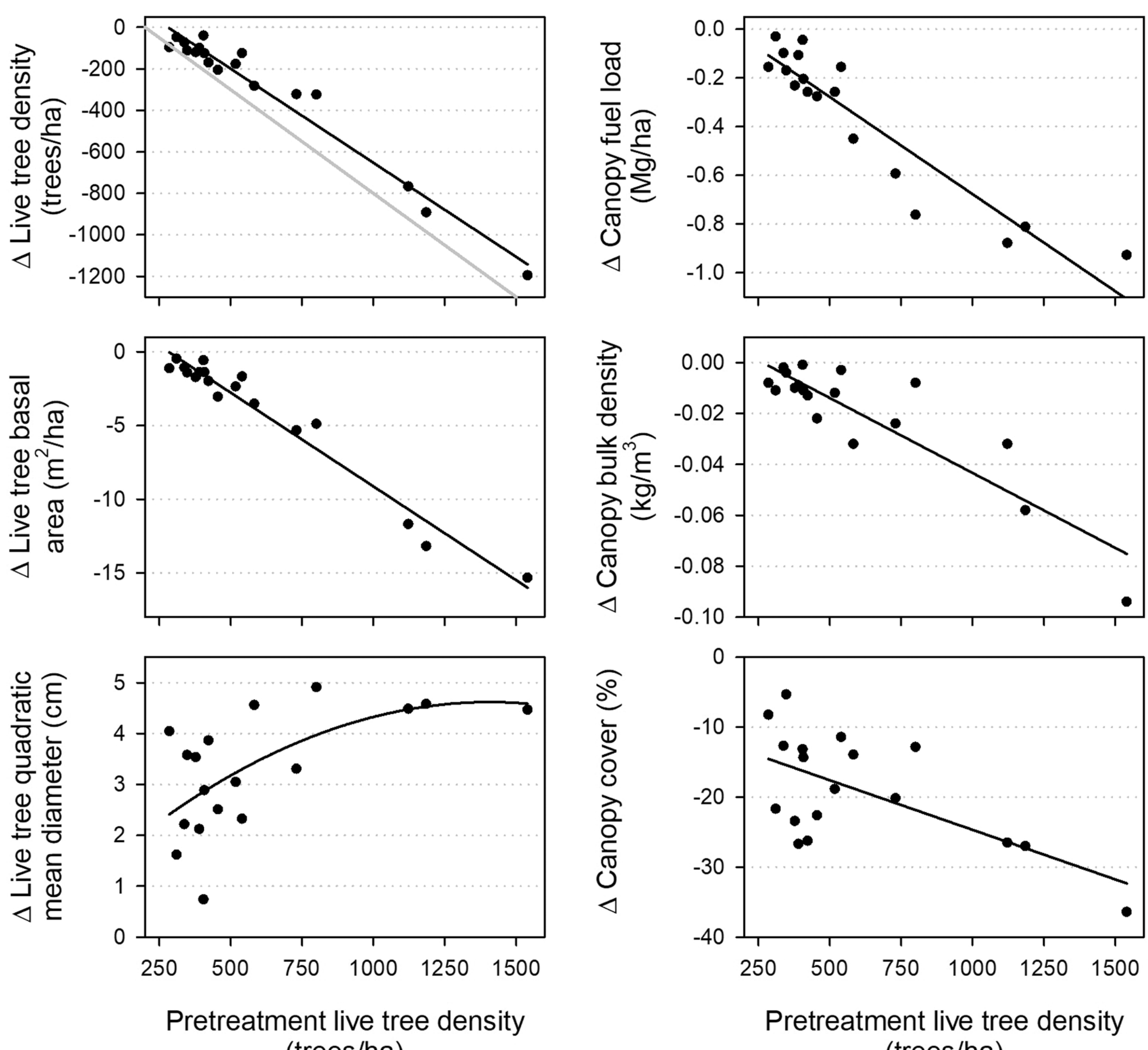

Fig. 3. Mastication effects on overstory live tree density, basal area, quadratic mean tree diameter, canopy fuels, canopy bulk density, and canopy base height varied with variability in unit-level pretreatment live tree density. For changes in live tree density (upper left pane), the solid gray line approximates the density reduction needed to reach the maximum target density of 220 trees/ha.

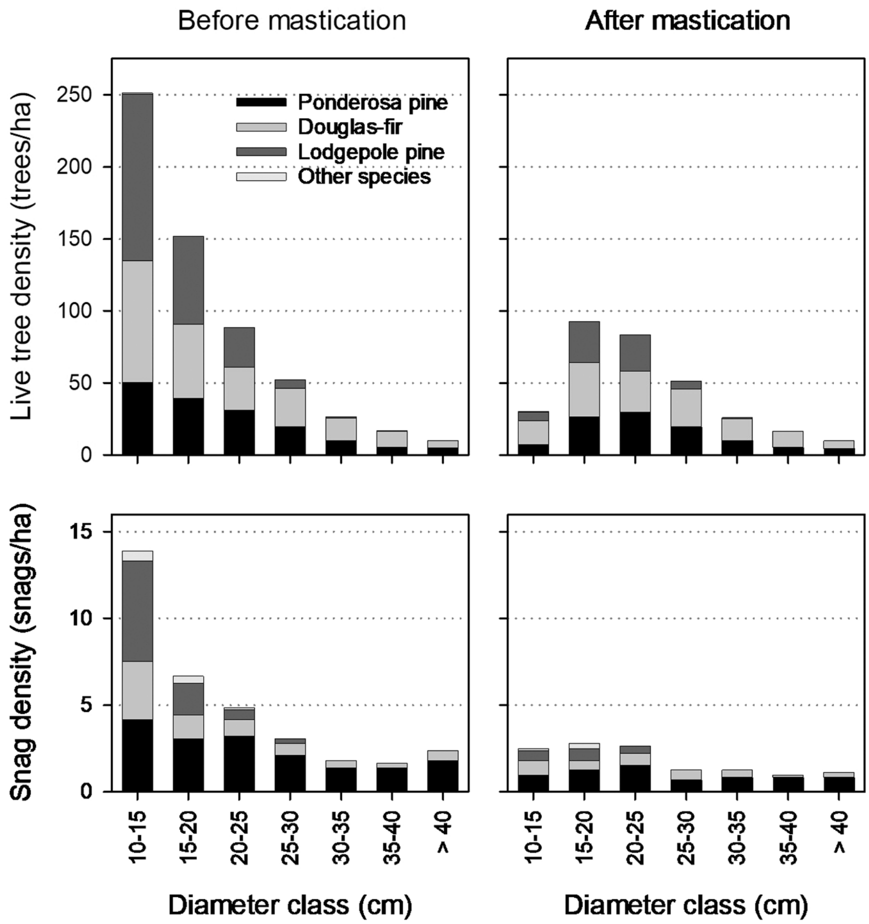

Fig. 4. Species and size distributions for overstory live trees and snags, before and after mastication treatments.

survey data and did not include contributions from seedlings, saplings, and small trees (DBH < 10 cm) that can contribute significantly to ladder fuels.

Prescribed burning treatments produced minimal impacts on overstory stand structure and canopy fuels (Fig. 2). Burning killed only three trees within our vegetation sampling plots across nine treatment units (one tree on each of three units), so effects on stand density, basal area, and mean tree diameter were minimal. Mean bole char height was 0.70 m. Crown scorch was minimal except in local patches, with 85 % of trees with crown scorch less than 10 %, so burning effects on canopy fuels were also minimal.

Prescribed burning further reduced understory tree regeneration. Across all burned units, prescribed burning reduced mean sapling densities from 56 to 38 saplings per hectare ($p = 0.34$) and reduced mean seedling densities from 120 to 73 seedlings per hectare ($p = 0.05$). Seedling and sapling density reductions varied among treatment units and were significantly correlated with pre-burn densities for saplings ($r = -0.87$, $p = 0.002$) and seedlings ($r = -0.89$, $p = 0.0013$).

3.2. Mastication and prescribed burning effects on surface fuels

Mastication treatment effects on surface fuels varied among fuel types and woody fuel size classes. Mastication treatments significantly increased mean 1000-hour sound woody fuels (4.5–7.4 Mg/ha, $p = 0.04$) and 1-hour woody fuels (0.5–1.1 Mg/ha, $p < 0.0001$), while significantly reducing mean 1000-hour rotten woody fuels (8.0–3.0 Mg/ha, $p < 0.0001$, Fig. 5). Mastication produced nonsignificant changes in mean 100-hour woody fuels (5.0–6.7 Mg/ha, $p = 0.13$) and 10-hour woody fuels (3.5–3.1 Mg/ha, $p = 0.52$, Fig. 5). Mastication treatments also significantly increased mean fuelbed depths (6.2–10.8 cm, $p < 0.0001$) but did not significantly alter mean litter depth (27–28 mm, $p = 0.70$) or duff depth (36–32 mm, $p = 0.21$, Fig. 5).

Fuel responses to mastication treatments varied considerably among units, particularly for the larger fuel diameter classes. Pretreatment stand density was positively correlated with changes in 1000-hour sound woody fuels ($r = 0.68$, $p = 0.0018$) and 100-hour woody fuels ($r = 0.90$, $p < 0.0001$, Fig. 6). Changes in 1000-hour rotten woody fuels were negatively correlated with (proportional to) pretreatment 1000-hour rotten fuel loads ($r = -0.78$, $p = 0.0001$, Fig. 7). Changes in 10-hour woody fuels were also negatively correlated with pretreatment 10-hour woody fuels ($r = -0.65$, $p = 0.0036$) but, unlike 1000-hour rotten fuels, mean 10-hour woody fuels increased on eight of the 18 treatment units. Multiple regression analysis suggested that changes in sound 10-hour woody fuels were influenced by both a positive response to pretreatment stand density ($p = 0.005$) and a negative response to pretreatment 10-hour woody fuels ($p = 0.0002$).

Prescribed burning treatments reduced mean unit-level woody fuel loads across all size classes (Fig. 5). Burning reduced mean 1000-hour sound woody fuels from 5.1 to 2.5 Mg/ha ($p = 0.006$) and reduced 1000-hour rotten fuels from 2.9 to 0.4 Mg/ha ($p = 0.0006$). Burning reduced mean 100-hour woody fuels from 4.4 to 2.8 Mg/ha ($p = 0.0065$), 10-hour woody fuels from 2.6 to 1.4 Mg/ha ($p = 0.0002$), and 1-hour woody fuels from 0.9 to 0.4 Mg/ha ($p = 0.0001$). For all size classes, unit-level changes in mean woody fuels were negatively correlated with pre-burn woody fuel loads (Fig. 8).

Prescribed burning also reduced ground fuels, total fuelbed depth, and live fuel densities (Fig. 5). Burning reduced mean litter depths from 23.5 to 9.7 mm ($p < 0.0001$), duff depths from 28.9 to 9.5 mm ($p < 0.0001$), and fuelbed depths from 97 to 41 mm ($p < 0.0001$). As with woody fuels, changes in mean litter and duff depths were highly

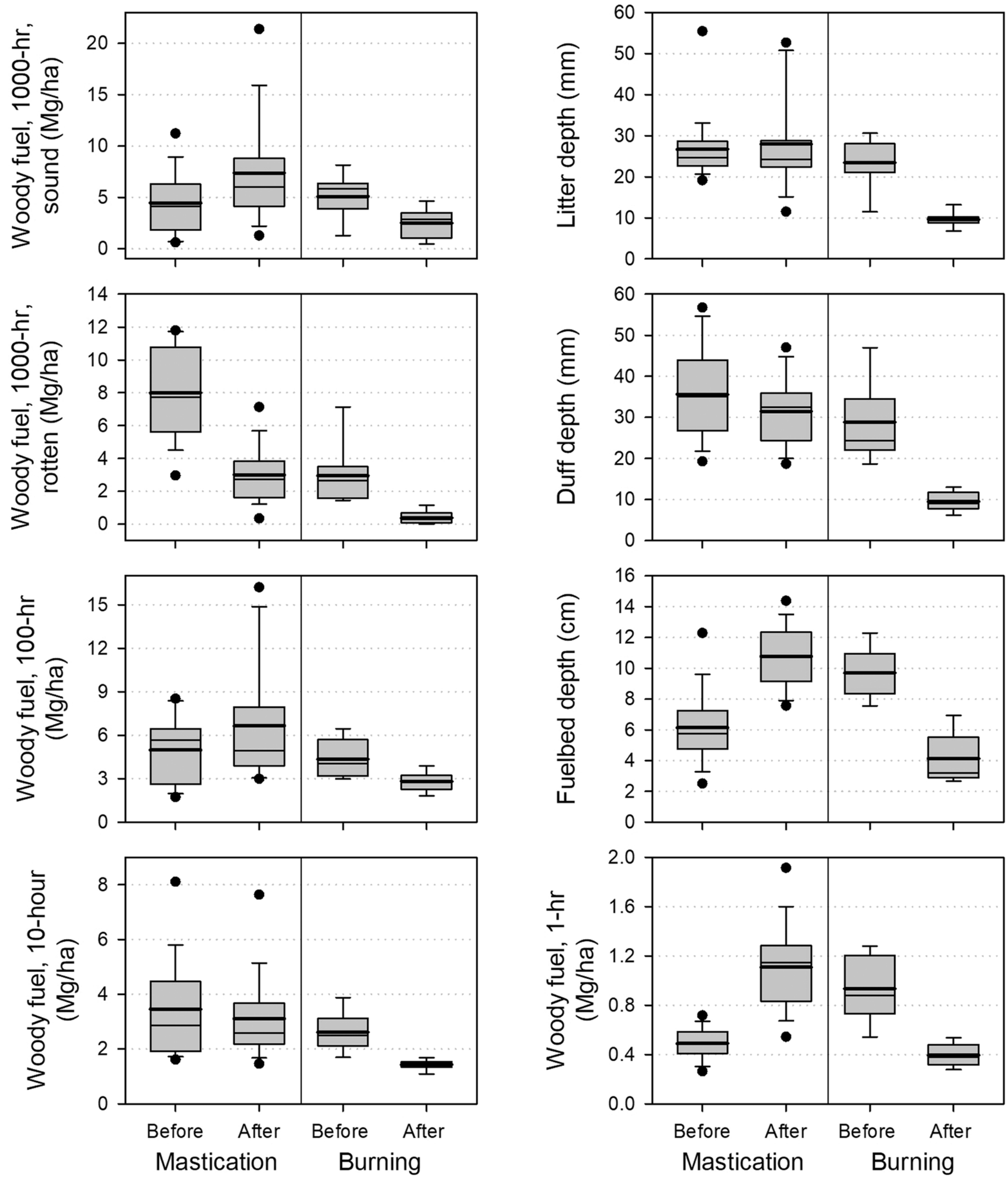

Fig. 5. Surface and ground fuels (mean and variability) before and after mastication treatments (18 units) and prescribed burning treatments (9 units).

correlated with pre-burn values (r = -0.96 and r = -0.97, $p < 0.0001$) but changes in mean fuelbed depth were not (r = -0.47, p = 0.20).

The combination of mastication and prescribed burning treatments generally reduced mean unit-level fuels relative to pretreatment levels. For the nine treatment units that received both treatments, fuel loads declined significantly for the 1000-hour rotten woody (7.5–0.4 Mg/ha, $p < 0.0001$) and 10-hour woody (2.5–1.4 Mg/ha, p = 0.0085) fuel classes. Mean fuel loads also declined for the 1000-hour sound woody (3.0–2.5 Mg/ha, p = 0.58), 100-hour woody (3.8–2.8 Mg/ha, p = 0.15), and 1-hour woody (0.45–0.39 kg/m^2, p = 0.22) fuel classes but the differences were not statistically significant. Mastication followed by burning also produced significant net reductions in mean litter depth (30.0–9.7 mm, $p < 0.0001$) and mean duff depth (29.5–9.5 mm, $p < 0.0001$) but not in mean fuelbed depth (5.7–4.1 cm, p = 0.15).

3.3. *Mastication and prescribed burning effects on potential wildfire behavior*

Fire behavior modeling showed that mastication treatments increased measures of surface fire behavior under wildfire weather and fuel moisture conditions, but reduced crown fire potential. Mastication treatments increased projected mean flame lengths (0.31–0.62 m, p = 0.0009), rate of spread (0.43–0.82 m·min^{-1}, p = 0.006), fireline intensity (44.5–102.6 kW·m^{-1}, p = 0.04), and scorch height (1.02–2.57 m, p = 0.004) by increasing surface fuel loads (Fig. 9). However, mastication treatments also increased the mean crowning index (25.0–31.7 km·hr^{-1}) by reducing canopy density.

In contrast, prescribed burning treatments reduced measures of surface fire behavior but had no direct effect on crown fire potential. Within the nine burned units, prescribed burning treatments reduced mean flame length (0.68–0.25 m, $p < 0.0001$), rate of spread (0.94–0.31, $p < 0.0001$). fireline intensity (115.6–17.2, $p < 0.0001$), and scorch height (2.78–0.49, $p < 0.0001$), but did not change the mean crowning index (Fig. 9).

The combination of mastication and prescribed burning treatments reduced mean measures of surface fire behavior and reduced crown fire potential relative to pretreatment conditions but, with high variability and only nine units receiving both treatments, the changes were not

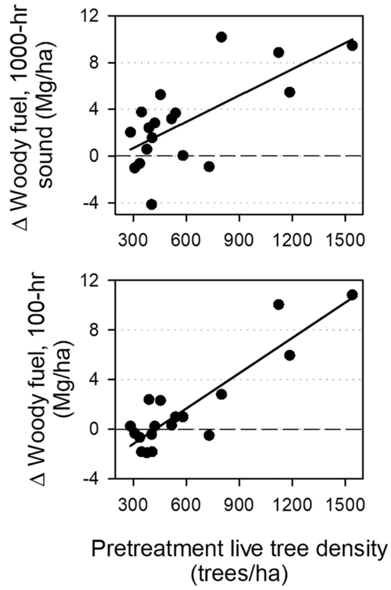

Fig. 6. Mastication treatment effects on 1000-hour sound woody fuels and 100-hour woody fuels varied with pretreatment live tree density.

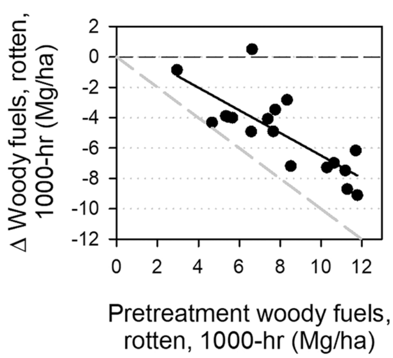

Fig. 7. Mastication treatment effects on rotten 1000-hour woody fuels varied with pretreatment rotten 1000-hour woody fuel loads. Dashed gray reference line shows the maximum possible reduction.

statistically significant. The combined treatments reduced mean flame length (0.34–0.25, $p = 0.50$), rate of spread (0.49–0.31, $p = 0.41$), fireline intensity (61.4–17.2, $p = 0.35$), and scorch height (1.25–0.49, $p = 0.36$), while increasing the mean crowning index (26.3–31.0, $p = 0.09$).

4. Discussion

4.1. Mastication and prescribed burning effects on overstory structure, canopy fuels, and regeneration

Mechanical thinning treatments are commonly used with success to modify overstory stand structure and reduce ladder and canopy fuels in fire-prone forests (Harrod et al., 2008; Schwilk et al., 2009). Like traditional low thinning methods, the track-mounted mastication equipment used in this study reduced live tree density and basal area, increased quadratic mean tree diameters, and shifted forest species composition toward greater proportions of fire-resistant ponderosa pine and Douglas-fir trees. Most of the masticated overstory trees were similar in size (10–20 cm DBH), so changes in stand density were highly correlated with changes in other metrics of overstory structure, including live tree basal area, canopy bulk density, and total canopy fuels. The narrow diameter range of trees removed also limited

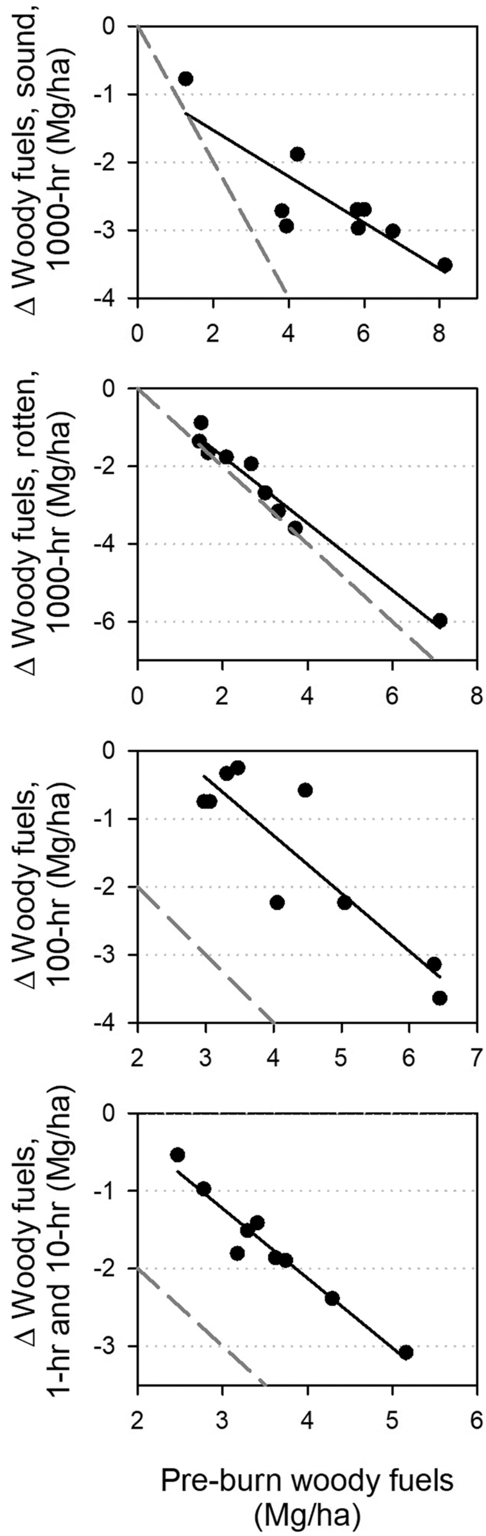

Fig. 8. Prescribed burning effects on woody fuels varied with pretreatment (post-mastication) woody fuel loads for all woody fuel size classes. Dashed gray reference lines show maximum possible reductions.

unit-level increases in quadratic mean tree diameters following thinning. However, reductions in tree density in most units are also likely to trigger growth releases in residual trees, increase longer-term growth rates, and further increase quadratic mean tree diameters over time (Cochran and Barrett, 1998; Vernon et al., 2023).

Mastication treatments did not reach stand density and basal area

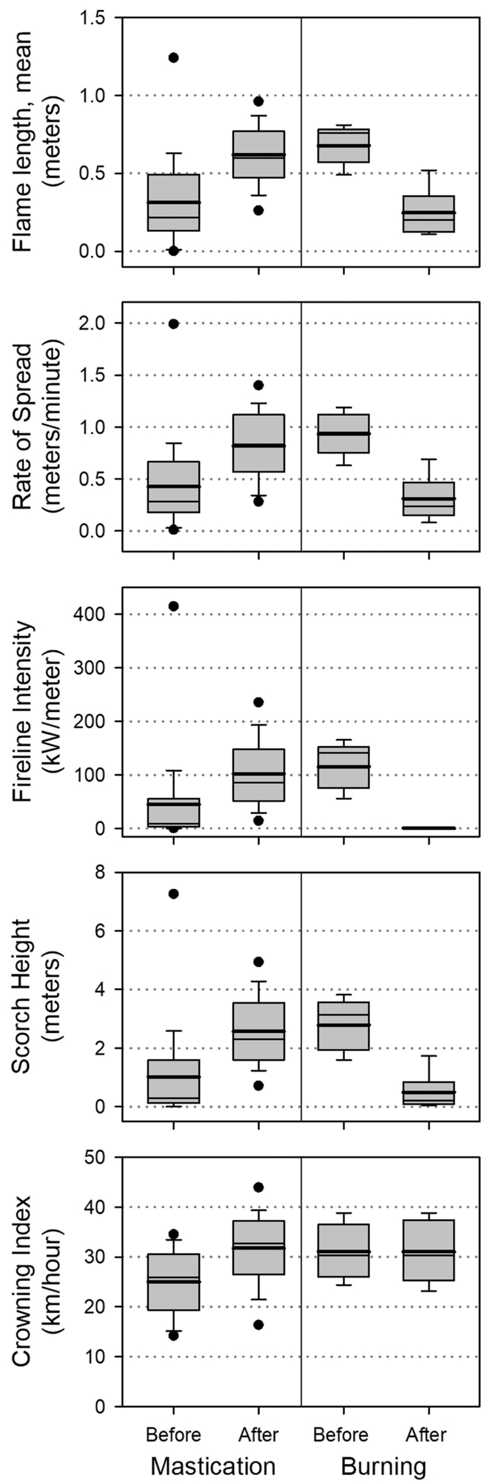

Fig. 9. Mastication and prescribed burning effects on projected wildfire behavior, including mean flame length, rate of spread, fireline intensity, scorch height, and crowning index. Box plots show changes in modelled fire behavior metrics (mean and variability) in response to mastication (18 units) and prescribed burning treatments (9 units).

targets for all units, primarily because of the upper limit on masticated tree diameters. This upper limit in the silvicultural prescription was driven partially by a desire to retain larger trees, but also reflected limitations of the mastication equipment, which became less efficient as tree heights and diameters increased. If reaching prescription targets is deemed important, traditional thinning methods could be used – before or after prescribed burning – to supplement mastication treatments and attain the desired overstory stand density or basal area. Deferring additional thinning until after prescribed burning might also allow managers to replace some surface woody debris for wildlife use.

Mastication and prescribed burning treatments combined to reduce ladder and canopy fuels, thereby reducing the likelihood of torching and crown fire initiation and spread during wildfires (Graham et al., 1999). Mastication significantly reduced canopy bulk density, reduced total canopy fuels, and raised canopy case heights. Model-estimated changes in canopy base heights were relatively small because they only considered the contributions of overstory trees. Mastication of tree seedlings and saplings (0.1 < DBH < 10 cm), as well as large shrubs, removed ladder fuels that could carry surface fires into the overstory canopy; however, their effects on canopy base height could not be modeled because we measured sapling densities within broad size classes and did not measure individual sapling diameters or heights. Prescribed burning also contributed to reducing ladder fuels and promoting fuel treatment longevity by further reducing seedling and sapling densities and delaying the re-development of tall ladder fuels (Hood et al., 2020).

Mastication treatment intensity varied spatially within and among treatment units, with important implications for restoring overstory structure and managing fuels. The thinning prescription provided a relatively narrow target stand density range for treated stands (190–220 trees/ha), but pretreatment stand density was highly variable (285–1540 trees/ha), so reductions in stand density necessarily varied considerably among stands and reductions were highly correlated with pretreatment stand density. Although smaller on a percentage basis, stand basal area reduction were also highly correlated with reductions in stand density because the masticated trees were mostly small and of similar sizes (< 20 cm DBH).

4.2. Mastication and prescribed burning effects on surface fuels and potential fire behavior

Mastication treatments created a pulse of new litter and surface woody fuels as they thinned and broke up small trees, saplings, seedlings, and large shrubs. Litter and woody fuel amounts generated by mastication treatments were positively correlated with pretreatment stand density, especially for 100-hour and 1000-hour sound woody fuels, so fuel production was positively associated with local mastication intensity. In effect, mastication treatments transferred spatial variability in pretreatment overstory stand density to spatial variability in post-treatment surface fuel loads; similarly, mastication treatments reduced crown fire potential but increased potential surface fire intensity and severity. This pulse of increased surface fuels is a cost of accomplishing overstory restoration goals and reducing canopy and ladder fuels and is commonly observed following thinning treatments of all types (Stephens et al., 2009). This study and others have shown, however, that increases in potential surface fire intensity and severity can often be offset through subsequent use of prescribed burning to reduce surface fuels (Stephens and Moghaddas, 2005; Vaillant et al., 2009).

Surprisingly, mastication treatments were associated with reductions rather than increases in 1000-hour rotten woody fuels (Fig. 5). Reductions in 1000-hour rotten woody fuels were likely the result of intentional mastication of large-diameter woody fuels by the operator combined with incidental crushing of rotten fuels as the mastication equipment moved through the treatment units. In either case, mastication probably transformed large-diameter rotten woody fuels into smaller diameter woody fuels or duff. Mastication treatments may have had similar crushing effects on rotten fuels in the smaller diameter classes (10- and 100-hour fuels), but we could not test those effects because the standard planar intercept survey methods used in this study do not assess decay states for smaller diameter fuels.

Prescribed burning in the fall reduced surface fuels significantly, consistent with other prescribed fire studies (Stephens and Moghaddas, 2005; Schwilk et al., 2009; Vaillant et al., 2009). Prescribed burning was especially effective for reducing rotten large-diameter woody fuels, small-diameter woody fuels, duff, and litter. Overall, surface fuel reductions from prescribed burning exceeded fuel inputs from mastication treatments, so the combination of mastication and prescribed burning reduced mean surface fuels and, by extension, reduced potential wildfire intensity and severity.

Mastication treatments often employ equipment that grinds or shreds shrubs and trees, creating compact surface fuelbeds that are dominated by 1-hour and 10-hour fuels with non-cylindrical shapes (Glitzenstein et al., 2006; Kane et al., 2009; Battaglia et al., 2010). These masticated fuelbeds have been shown to differ from natural and slash-based fuelbeds in terms of moisture dynamics (Kreye et al., 2012), decomposition rates (Reed et al., 2020), and fire behavior and effects (Knapp et al., 2011; Kreye et al., 2014). In contrast, the mastication equipment used in this study produced masticated fuels were more like slash fuels than mulch fuels and did not create an especially compacted fuelbed. Our mastication treatments allowed slash fuels to be burned 3–5 months after treatment, thereby minimizing the duration of elevated wildfire hazards from increased surface fuels. The masticated fuels were easily burned under the relatively cool and moist weather conditions that typify fall prescribed burns, without producing undesirable overstory tree mortality or soil heating (Harrod et al., 2008). The low levels of overstory tree scorching and mortality during our fall prescribed burns should also favor fuel treatment longevity by avoiding rapid replacement of surface litter and woody fuels from needle cast and shedding of dead branches.

4.3. Management implications

This study shows that mastication followed by prescribed burning is a viable treatment option for reducing fuels and modifying overstory structure within dense forest stands with large proportions of non-merchantable trees. This type of mastication followed by prescribed burning appears to be best suited for use in small-diameter, overstocked stands, where the retained trees are sufficiently fire resistant to survive low intensity prescribed fires. It could also be effective for reducing ladder and canopy fuels in older, multistory stands, in which prior disturbances (e.g., beetles) have reduced overstory tree density and released understory seedlings and saplings. Mastication may also be useful for modifying heavy surface woody fuels (especially rotten fuels) prior to prescribed burning in stands with prior disturbances.

Mastication treatments do have limitations for use in forest restoration and fuel reduction. Mastication treatments alone may not be able to fully meet management objectives if prescriptions require removing larger trees. Road access and moderate slopes are also required to transport equipment to the site and to allow the equipment to move safely through the forest stand, which limits the forests that can be treated. However, mastication could still be a valuable tool for treating stands near values at risk in valleys and in wildland-urban interface areas.

This study showed that these mastication-based fuel treatments are less beneficial in forests where subsequent prescribed burning is not possible or planned. Like other studies (e.g., Battaglia et al., 2010), we found that mastication alone generally increased surface fuels, creating the potential for more extreme fire behavior and effects if burned under warm and dry conditions typical of summer wildfires. Elevated surface fuels may not be a problem if fuel increases are small (e.g., masticating low densities of shrubs and small trees) or the resulting forest structure is highly fire resistant (e.g., large trees with thick bark and no ladder fuels). If elevated surface fuels would create unacceptable hazards to residual trees or other resource values, follow-up fuels management treatments like piling or chipping of surface woody fuels could be used to modify the size or arrangement of surface fuels to limit wildfire intensity and severity (Glitzenstein et al., 2006; Kreye et al., 2014).

4.4. Conclusions

This study showed that fuel reduction treatments using mastication-based thinning followed by prescribed burning can effectively modify stand structure and forest fuel profiles to reduce potential wildfire intensity and severity. Mastication treatments reduced stand densities, ladder fuels, and canopy fuels, while increasing surface fuels and projected surface fire intensity. In contrast, prescribed burning following mastication significantly reduced surface fuels and projected surface fire intensity, but had minimal effects on overstory stand structure or canopy fuels. The mastication-based fuel reduction treatments tested in this study could be effective for managing fuels and fire behavior in wildland-urban interface settings if used in conjunction with prescribed burning to reduce surface fuels. In areas where prescribed burning is not feasible, however, alternative mastication treatments (e.g., shredding or chipping) or mechanical thinning and piling may be more effective for limiting wildfire hazards.

CRediT authorship contribution statement

David Peterson: Conceptualization, Formal analysis, Data curation, Writing – original draft preparation, Funding acquisition. **Richy Harrod:** Conceptualization, Methodology, Investigation, Writing – original draft preparation, Project administration, Funding acquisition. **Erich Dodson:** Formal analysis, Writing – review and editing, Investigation. **Peter Ohlson:** Investigation, Data curation, Supervision. **Natalie Pawlikowski:** Writing – original draft preparation. **Kathryn Ireland:** Investigation, Writing – review and editing. **Roger Ottmar:** Conceptualization, Methodology, Funding acquisition.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Richy J. Harrod reports financial support was provided by Joint Fire Science Program. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Peterson, David W.; Harrod, Richy J. 2024. Hungry-Hunter mastication and prescribed fire study. Fort Collins, CO: Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2024-0069

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