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The effect of salvage logging on surface fuel loads and fuel moisture in beetle-infested lodgepole pine forests

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ABSTRACT

Widespread tree mortality from mountain pine beetle (MPB; *Dendroctonus ponderosae* Hopkins) outbreaks has prompted forest management activities to reduce crown fire hazard in the Rocky Mountain region. However, little is known about how beetle-related salvage logging and biomass utilization options affect woody surface fuel loads and fuel moisture dynamics. We compared these attributes in salvage-logged lodgepole pine (*Pinus contorta* var. *latifolia* Engelm. Ex S. Wats.) stands harvested using either biomass removal (whole-tree harvest) or biomass retention (bole only harvest) prescriptions with untreated MPB-infested stands. Both prescriptions roughly doubled 1-h and 10-h fuel loads compared to untreated forest. Biomass retention left ten times more 1000-h fuels compared to biomass removal prescription (28 vs 3 Mg ha^{-1}). Overall, the woody fuel load was more than twice as high with biomass retention compared to biomass removal (60 vs 25 Mg ha^{-1}). Fuel moisture content was lower in salvage logged units compared to untreated forest plots, but it did not differ among the biomass prescriptions. Fine (10-h) and heavy (1000-h) fuels dried to a critical ignition threshold 3–8 weeks earlier in the two prescriptions, respectively, compared to the untreated forests. Salvage logging removes canopy fuels and crown fire hazard, but we found that depending on the amount of biomass retained it can both increase surface fuel load and decrease fuel moisture compared to untreated stands. In the coming years, snag fall will transfer crown to surface fuels in untreated beetle-killed stands adding coarse surface fuel loads surpassing those in treated stands.

1. Introduction

A recent mountain pine beetle (*Dendroctonous ponderosae* Hopkins; MPB) outbreak has resulted in widespread tree mortality in lodgepole pine (*Pinus contorta* var. *latifolia* Engelm. Ex S. Wats.; LPP) forests throughout the Rocky Mountain region. In northern Colorado, the outbreak lasted for nearly a decade and caused up to 70% reduction in tree basal area and up to 90% mortality of large trees in some stands (Collins et al., 2011; Nelson et al., 2014). On forested lands under active management, managers are now faced with salvaging merchantable timber and mitigating fire hazard across Rocky Mountain forests. Despite recent studies evaluating the dynamics of fuel loads and fire potential following bark beetle outbreaks in untreated forests (e.g., Harvey et al. 2014; Lynch and Moorcroft 2008; Jenkins et al. 2008; Simard et al. 2011), little is known about how common harvest and slash prescriptions affect fuels and fire hazard. In this study, we evaluate the effects of salvage logging and two distinct post-harvest slash prescriptions (biomass removal and retention) on dead surface fuel loads and seasonal dynamics of surface fuel moisture—two important metrics for assessing forest fire hazard.

Given our understanding of post-MPB fuel dynamics (Page and Jenkins, 2007; Jenkins et al., 2008; Simard et al., 2011; Hicke et al., 2012), we anticipate that different post-harvest slash prescriptions may result in an increase or decrease in surface fuels at different times post-outbreak. Throughout much of the Rocky Mountain Region, salvage treatments in LPP forests commonly involve clear-cutting MPB affected stands and leaving varying amounts of slash. Slash prescriptions that retain biomass in harvested areas can positively affect nutrient cycling and site productivity while prescriptions that completely remove slash could result in significant nutrients losses and decreased long-term site productivity (Tinker and Knight, 2000; Rhoades et al., 2016; Giardina and Rhoades, 2001).

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Several studies have compared fuels dynamics of salvage logged stands after disturbance (i.e., fire, blowdown, beetle infestation) to untreated stands (McIver and Ottmar, 2007; Donato et al., 2006; McGinnis et al., 2010; Collins et al., 2012; Griffin et al., 2013). For example, Collins et al. (2012) found that salvage logging in post-MPB stands in northern Colorado increased fuel loads by 3-fold compared to untreated stands. A similar study in northwestern Wyoming concluded that all size categories of fuels doubled following harvest, while canopy fuel load and bulk density decreased, subsequently causing increased surface fire potential and reductions in regenerating trees (Griffin et al., 2013). Of the studies investigating salvage treatments in post-MPB stands, there has been little research that investigates differences based on whether slash is removed or retained post-harvest. Interest in utilization of woody biomass has grown with increased concern about energy costs, fossil fuel emissions and the threat of catastrophic wildfires (Evans and Finkral, 2009).

Fuel moisture content (FMC) is affected by salvage logging activities. Canopy removal alters incoming solar radiation, wind speed, temperature and relative humidity and dries surface fuels (Glitzenstein et al., 2006; Uhl and Kauffman, 1990; Holdsworth and Uhl, 1997; Brown, 1975). If salvage activities both increase surface fuel loads (e.g., Griffin et al. 2013) and decrease fuel moisture, potential fuel consumption and rate of fire spread could increase, potentially causing subsequent increases in fire intensity and severity depending on how fuels are arranged on the landscape (Fahnestock, 1960). The increased potential for drying of surface fuels due to increased solar exposure may negate the mitigation potential of some forest harvest practices (Estes et al., 2012). If managers are using salvage logging as a way to reduce fire severity and intensity, understanding the effects of changes in stand structure, including increased surface fuels, on FMC is essential in determining the effectiveness of slash prescriptions. Few studies have directly measured the effect of fuels reduction treatments on FMC. In Matthews (2013) review of fuel moisture research, previous studies have found FMC in thinned stands to be lower because of increased exposure to solar radiation. In contrast, a northern California study in ponderosa pine (*Pinus ponderosa* Douglas ex C. Lawson)-mixed conifer stands, found only small, insignificant, differences in FMC between thinned and unthinned treatments (Estes et al., 2012).

This study compares fuel loads and moisture after salvage logging with two distinct levels of biomass utilization – biomass retention and removal - and untreated MPB infested stands. We also quantify microclimatic factors influence on summer fuel moisture content. Specifically, this study addresses the following questions: (1) How do surface fuel loads differ among two distinct levels of biomass utilization and untreated stands? (2) How does fuel moisture vary throughout the summer between logged and untreated stands and what are the factors affecting these differences (wind, temperature, relative humidity, litter/duff temperature, vapor pressure deficit and precipitation)? For question 1, we predict a significant increase in fuel loads in both slash prescriptions, with the greatest increase in fuel loads to occur in the slash retention treatment. In the biomass removal slash prescription, where whole trees are extracted, 1-h and10-h fuel classes are expected to increase as a result of treatment, while the greatest increase in 1000-h fuels is expected to occur in the biomass retention prescription. For question 2, if FMC is affected by removing the overstory of forest, differences between slash prescriptions will be negligible, yet FMC in both treatments will likely be significantly less than untreated MPB infested LPP stands because they will be more susceptible to changes in weather variables, resulting in more immediate and prolonged decreases in FMC.

2. Methods

2.1. Study area

This study was conducted in the Colorado State Forest (COSF), southeast of Walden, Colorado in the Medicine Bow Range of the Rocky Mountains. Elevations in the plots range from 2690 to 2880 m. The climate in the COSF is temperate and continental with long, cold winters and short, cool summers. Annual precipitation averages 745 mm, with about 50% falling from May to October (2004–2015; Rawah, SNOTEL Site, NRCS, 2016). Approximately 21,000 ha of the 28,667 ha of the COSF are forested, with LPP occupying approximately 60 percent of the mixed species stands. Other tree species present include Englemann spruce (*Picea engelmannii* Parry ex Engelm.), subalpine fir (*Abies lasiocarpa* Nutt.), aspen (*Populus tremuloides* Michx.) and limber pine (*Pinus flexilis* James.).

The MPB outbreak was first observed in the COSF in 2001 and reached epidemic levels by 2005 (R. Gross, personal communication). Bark-beetle related salvage logging began at COSF and elsewhere in northern Colorado around 2005 and continues to present (2017). Throughout the winter of 2014–2015, approximately 70 ha of affected stands were harvested, with subsequent biomass removal and retention slash prescriptions applied. The beetle-killed trees in the unharvested stands were without needles, which generally fall within 3–5 years after the trees die (Hicke et al., 2012).

2.2. Study design

Data were collected during the summer of 2015 following the harvests completed in the winter of 2014–2015. We randomly selected the locations of thirty, 900 m^2 plots (30 $\times$ 30 m) to investigate differences between harvested (two slash prescriptions) and unharvested stands (Gotelli and Ellison, 2004). Plots were divided into ten block replicates that were selected to minimize differences in pre-harvest forest structure, tree species composition and site topographic condition, and plots within each block were located within 400 m from one another (Quinn and Keough, 2002). Topographic conditions among blocks and treatments were similar, differing by less than 190 m elevation, 20° aspect and 10% slope. Plots were located in each of three stand conditions: (1) unharvested, (2) clear cut with whole-tree harvest (biomass removal slash prescription), and 3) clear-cut with lop-and-scatter (biomass retention slash prescription). Whole-tree harvest salvage treatment extracts the entire tree from the harvested area, including most or all of the non-merchantable material, leaving much less slash on the site. The lop-and-scatter salvage treatment method only removes merchantable wood, while the remaining slash is scattered throughout the harvested area.

2.3. Fuel loads

We estimated surface fuel loads (Mg ha^{-1}) in each of the 30 plots using ten, 20-m planar intercept transects per plot (Brown 1974). Woody particles in the 1-h (<0.63 cm) and 10-h (0.63–2.54 cm) fuel moisture classes were tallied between 0 and 3 m of the 20 m transect; particles in the 100-h fuel class (2.54–7.62 cm) were tallied between 0 and 10 m of the 20-m transect; and particles in the 1000-h fuel moisture class (>7.62 cm) were measured along the full 20- m transect for diameter (cm) and decay class. Logs were classified into one of five decay classes, which ranged from sound (round in cross section, with bark, branches and twigs present) to rotten (elliptical in cross section and partially buried in the forest floor) (Maser et al., 1979). We defined litter as fresh (undecomposed) and partially decomposed organic forest debris measured as a depth (cm) from the forest floor, to the duff (Battaglia et al., 2010). If duff was absent, we measured from top of litter to mineral soil. We defined duff as decomposed, unrecognizable organic matter and measured as a depth (cm) from bottom of litter to mineral soil (Jenkins et al., 2008). We measured litter and duff depths at 1, 2 and 3 m along the 20 m transect. To calculate litter and duff fuel loads, depth was averaged per plot and multiplied by the bulk density for lodgepole pine and scaled up to Mg ha^{-1} (bulk density of litter = 73.2 kg m^{-3}, bulk density of duff = 95.2 kg m^{-3}; Battaglia et al., 2010).

2.4. Fuel moisture content and microclimate

At the beginning of the sampling season, we established three FMC stations in each plot, totaling 90 FMC stations, to capture variation within plots. To simulate fuel moisture representative of salvage harvests in LPP forests, the wood samples used for each fuel moisture class were taken from a single slash pile of trees with bark and green needles that were harvested during the winter of 2014/2015, and were collected when snow was melting in May of 2015. Fuel particles were placed in the assigned plots one week prior to the first sampling. Each FMC station included all four woody fuel moisture classes (1-, 10-, 100- and 1000-h). The time lag in each of the fuel moisture classes refers to the number of hours it takes for fuel moisture to reach 63% of the difference between the initial moisture content and the equilibrium atmospheric moisture content under stable conditions (Pyne et al., 1996). Fuel particles (sticks) from 1-h and 10-h fuels classes were strung together in groups of five and ten respectively, and were weighed together, allowing for a more representative method of measurement using a high precision scale (0.1 g). The 100-h and 1000-h fuels were cut into 60-cm lengths and fitted with a fencing staple at one end allowing the fuel particles to be weighed with a hanging scale.

We measured fuel moisture by first weighing the fuels on site and then drying the fuels in ovens at 70 °C to a stable mass (Matthews 2013; Keane, 2015). We calculated fuel moisture as follows:

$$\text{Fuel Moisture Content} = \frac{\text{Weight of fuel particle in the field} - \text{Dry weight of fuel particle}}{\text{Dry weight of fuel particle}} x100$$

Each fuel particle in every fuel moisture station was measured in the same order, every 7–10 days, for 16 weeks. All fuel particles in each fuel moisture station were removed from the field in mid-October when FMC began to increase because of increased precipitation and decreased temperature. All fuel particles were transported to the University of Wyoming where they were placed in convectional drying ovens and their weights measured every other day until constant weights were reached (Keane, 2015). We also weighed and collected litter/duff samples at each station during each weekly measurement cycle to estimate FMC in those compartments. Samples were collected with a trowel and measured for wetweight. These samples were then placed in a drying oven at 70 °C for 72 h, or to a constant weight (Keane, 2015).

In order to estimate variation caused by differences in microclimate between the harvested and untreated areas and its effect on FMC, we strategically placed five weather stations within unharvested plots and five within treated plots. Quarter-hourly meteorological data were collected using open-source Arduino-based weather stations (Arduino, 2016). Sensors included air temperature, relative humidity, precipitation, litter/duff temperature and wind speed. We manually downloaded weather station data weekly to ensure that the stations were in proper working order.

Table 1
Mean ± standard error (n = 10/treatment) and [range] of surface fuels loads (Mg ha^{-1}) in untreated and harvested plots. Surface fuel loads were measured along ten planar transects per plot. The *biomass retention* harvest prescription removes merchantable boles only. The *biomass removal* harvest prescription removes boles, limbs and tops. Different letters indicate row-wise significant differences (α = 0.05).

Surface fuel type	Untreated	Biomass retention	Biomass removal
1-h fuels	0.7 ± 0.1 *a* [0.4, 1.4]	1.8 ± 0.3 *b* [0.8, 3.4]	1.3 ± 0.2 *b* [0.6, 2.3]
10-h fuels	2.9 ± 0.5 *a* [0.7, 6.4]	8.6 ± 1.4 *b* [3.9, 16.3]	5.8 ± 0.7 *c* [1, 9]
100-h fuels	6.0 ± 1.1 *a* [1.6, 12.8]	14.7 ± 1.5 *b* [6.8, 19.9]	8.7 ± 1.7 *a* [0.6, 18.6]
1000-h fuels – sound	5.3 ± 1.2 *a* [0.4, 11.3]	28.5 ± 3.4 *b* [16.1, 46]	2.9 ± 0.9 *a* [0.3, 9.3]
1000-h fuels – rotten	7.4 ± 2.2 *a* [0.9, 24.1]	6.0 ± 1.3 *a* [0, 10.8]	5.9 ± 1.1 *a* [0.1, 12.2]
Total woody fuels	22.4 ± 2.7 *a* [14.4, 40.6]	59.7 ± 6.4 *b* [29.9, 87.7]	24.7 ± 3 *a* [4.9, 34]
Litter	15.9 ± 1 *a* [10.4, 19.7]	17.1 ± 2 *a* [8.3, 29.7]	18.6 ± 2.1 *a* [7.1, 32.2]
Duff	26.6 ± 2.5 *a* [10.5, 42.3]	27.4 ± 3.1 *a* [17.1, 41.7]	26.8 ± 2.5 *a* [11.4, 40.9]
Total surface fuels	64.9 ± 5 *a* [39.5, 102.5]	104.2 ± 9.9 *b* [64.2, 152.9]	70.1 ± 6.9 *a* [23.4, 107.1]

2.5. Analyses

Program R was used for statistical analysis (R Development Core, 2015). All regression models were assessed for goodness of fit by visually inspecting the residuals vs fitted values on fixed and random effects (Zuur et al., 2009). In all statistical tests, *alpha* was set at 0.05. To compare differences in surface fuel loads among each of the three treatments, we used a linear mixed effect model (Zuur et al., 2009; Bates et al., 2015) with treatment as the fixed effect and block as a random effect. If treatments were found to be significant, post hoc multiple comparison Tukey's HSD test were conducted to detect individual treatment effects (Hothorn et al., 2008). For comparing differences in each FMC class among each of the treatments, the three fuel moisture stations in each plot were averaged by plot and compared by treatment using a repeated measures mixed effect model (Zuur et al., 2009; Bates et al., 2015; Pinheiro and Bates, 2000) with treatment and date of sampling as the fixed effects and block as the random effect. A random intercept of each plot was nested in the random effect to account for repeated measures. If treatments were found to be significant, post hoc multiple comparison Tukey's HSD test were conducted to detect individual treatment effects (Hothorn et al., 2008).

We used the moisture of extinction to determine how differences in FMC may affect the likelihood of wildfire ignition and spread. A fuel particle with a FMC that is higher than the moisture of extinction is unlikely to ignite and spread with the assumption that no wind or slope are present (Keane, 2015; Rothermel, 1972). In establishing the Standard Fire Behavior Fuel Models, Scott and Burgan (2005) use 25% moisture of extinction in similar fuel loads to those found in this study. To compare differences in the number of days it took for FMC to decrease below the moisture of extinction and the number of days each treatment was below the moisture of extinction, we used a linear mixed effect model (Zuur et al. 2009; Bates et al. 2015) with treatment as the fixed effect and block as the random effect.

Precipitation measurements from each weather station were paired with the fuel particles found in the corresponding plots for each data collection event. We used linear regression to assess the effect of precipitation, transformed with a second order

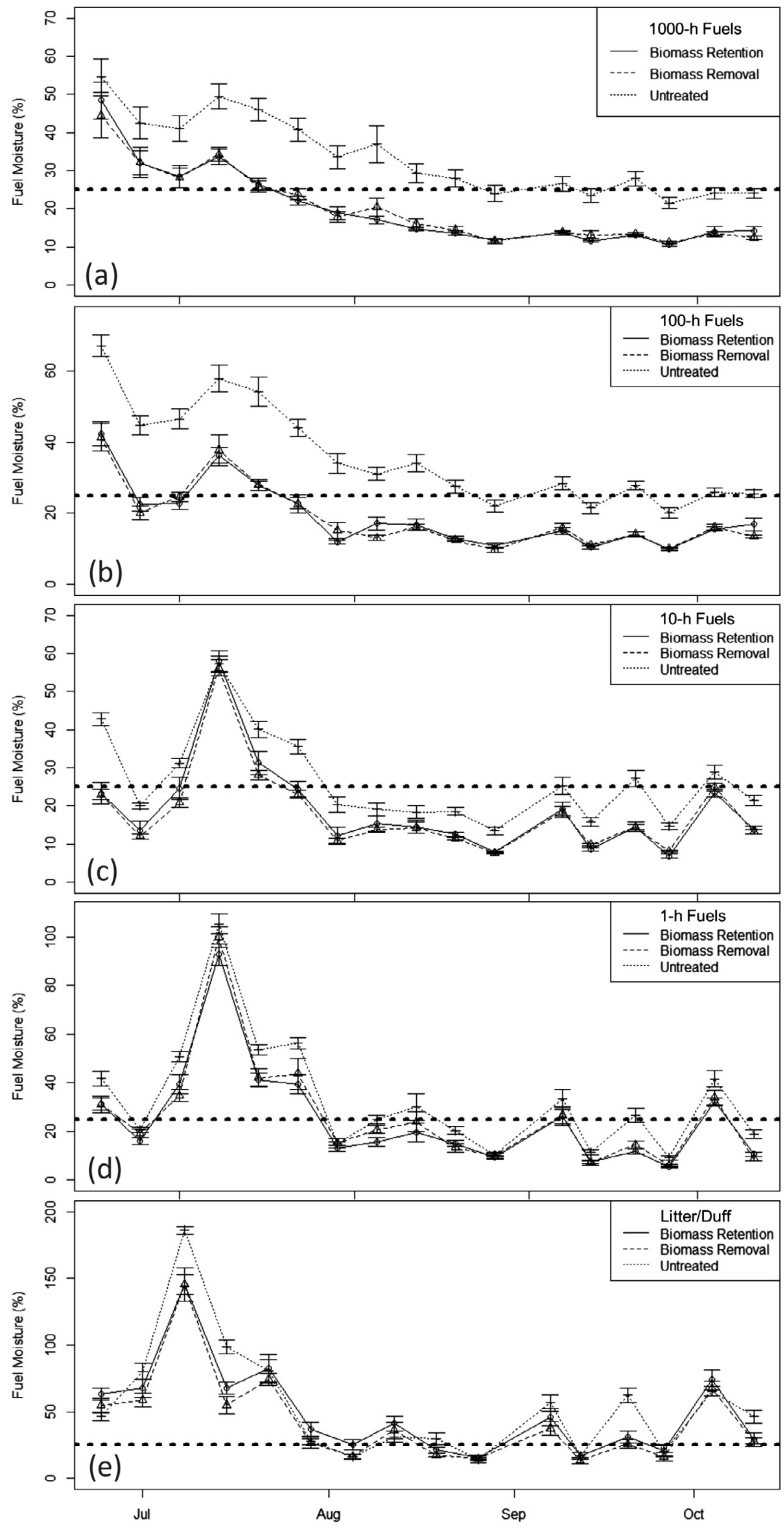

Fig. 1. Variation in 1000-h (a), 100-h (b), 10-h (c), 1-h (d) and litter/duff (e) fuel moisture in untreated and both biomass retention and removal post-harvest slash precriptions. Error bars represent one standard error from the mean (n = 10 measurements/treatment at each sampling event). The horizontal dotted line indicates the moisture of extinction (25%).

polynomial, on FMC in each treatment. Daily minimum, median, and maximum values were computed for each weather variable, aggregated by treatment, and plotted through the 2015 growing season with ±1 standard error using a *locally weighted smoothing (LOESS)* function. Weather variables include temperature, relative humidity, litter/duff temperature, VPD and wind. Daily vapor pressure deficit (VPD) values were estimated to delineate differences in the amount of evaporation occurring in each treatment. We estimated VPD using the Monteith and Unsworth (1990) equation.

3. Results

3.1. Surface fuel loads

Both slash prescriptions exhibited increases in fuel loads compared to unharvested plots. Mean total surface fuel loads ranged from 64.9 Mg ha^{-1} in unharvested plots to 104.2 Mg ha^{-1} in the biomass retention plots, which had 33–38% higher fuel loads than both biomass removal and unharvested plots (Table 1). In all but the 1000-h rotten fuel class, biomass retention resulted in significantly larger fuel loads than both biomass removal and unharvested plots (Table 1). The dry mass of the smaller fuel classes was greater in both the slash prescriptions than in untreated plots. One-hr and 10-h fuel classes were 64% greater in the biomass retention plots, and 46% greater in biomass removal, than in untreated plots. The 100-h fuel class was 40% and 60% greater than biomass removal and unharvested plots, respectively (Table 1).

Sound 1000-h fuels averaged 5.3 Mg ha^{-1} in untreated stands (Table 1). The biomass retention plots had five times more sound 1000-h fuels and the biomass removal plots had about half the sound 1000-h fuels of unharvested plots (Table 1). The 1000-h rotten fuels include residual fuels on the ground prior to harvesting

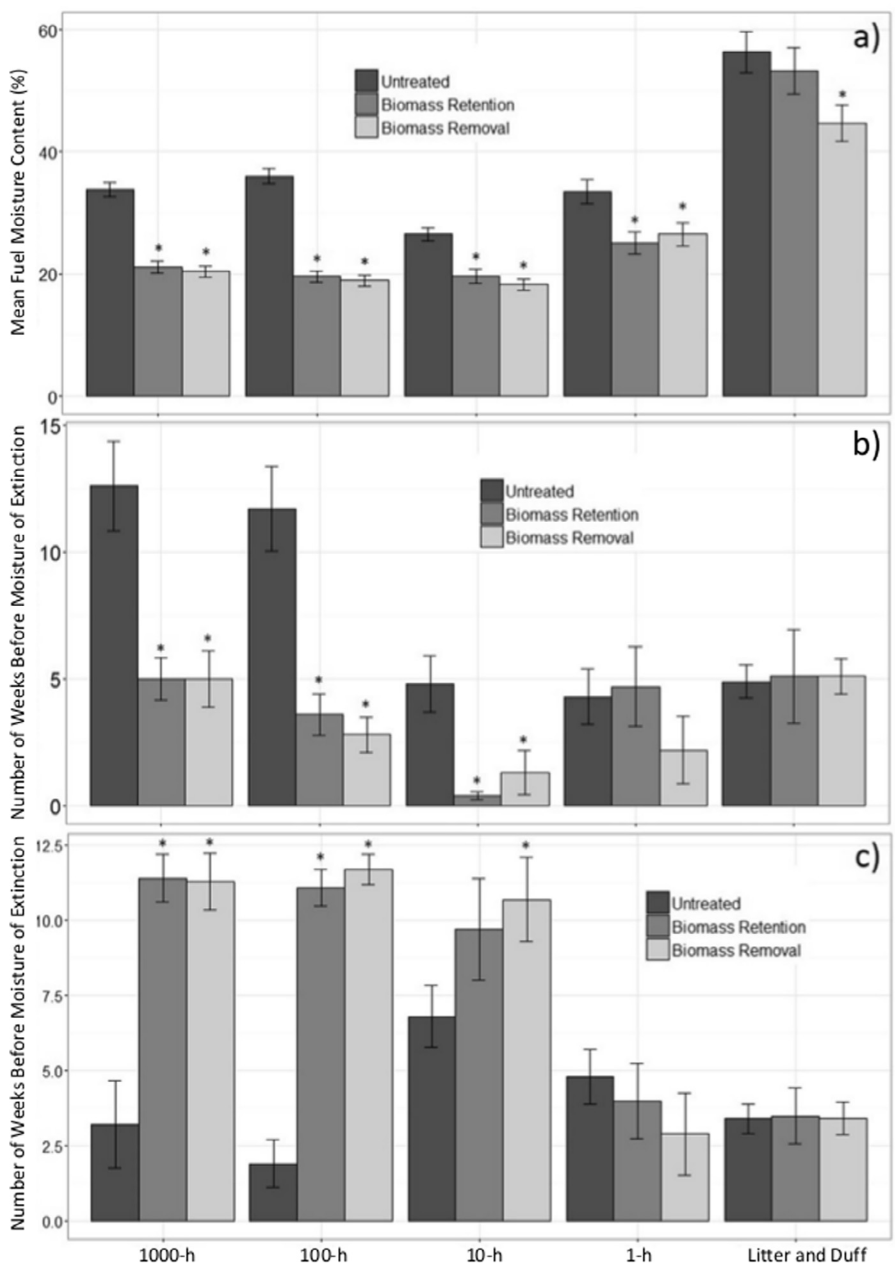

Fig. 2. Mean and standard error by treatment type (untreated, biomass retention and biomass removal) of (a) fuel moisture throughout the fire season, (b) the number of weeks until each fuel class became drier than the moisture of extinction and (c) the number of weeks throughout the fire season that each fuel class was drier than the moisture of extinction. All fuels classes were calculated with a 25% moisture of extinction.

and were not affected by the treatment since there was not sufficient time for significant decomposition to occur. Litter and duff comprised up to 65% of the total surface fuels in unharvested and biomass removal plots, and nearly 50% in the biomass retention plots, and did not differ significantly among the three treatments (Table 1).

3.2. Fuel moisture and weather

Fuel moisture of all woody fuel classes, excluding litter and duff, was higher in unharvested plots than in both slash prescriptions throughout the 16-week sampling period (Fig. 1). Litter/duff FMC was less than unharvested plots only in the biomass removal prescription (Fig. 2a). In both slash prescriptions, all fuel classes, except 1-h fuels and litter/duff, decreased below the moisture of extinction at least 2 times faster than in untreated stands (Fig. 2b). During the 16-week sampling period, 1000-h and 100-h fuels in untreated stands had a FMC that was less than the moisture of extinction for only 30 percent of the sampling period (Fig. 2c). In contrast, in both post-harvest slash prescriptions, the 1000-h and 100-h fuel classes had FMC values less than the moisture of extinction for 70 percent of the sampling period (Fig. 2c). Of the smaller fuel classes (1-h and 10-h) and litter/duff, only 10-h fuels in the biomass removal prescription had FMC values less than the moisture of extinction for a longer portion of the sampling period (Fig. 2c).

Overall, microclimate differences between treated and untreated plots were small. Minimum, median, and maximum daily values for air temperature, relative humidity, VPD, and precipitation were not different (Fig. 3). However, median and maximum litter/duff temperature and wind speed exhibited significant differences between treated and untreated plots. On average, maximum litter/duff temperature was 4.4 °C lower in unharvested plots than harvested plots and maximum wind speed was, on average, 55% higher in harvested plots than in unharvested plots.

Although the amount of precipitation (mm) did not differ between treated and untreated plots (Fig. 3), the effect of 1 mm of precipitation had on FMC on each fuel class was always greater in unharvested plots (Fig. 4). When precipitation was zero (y-intercept), FMC in unharvested plots was double that of both slash prescriptions in the 100- and 1000-h fuel moisture classes (Fig. 4). Of all the fuel classes in each of the three treatments, the effect of precipitation on FMC was greatest in 1-h fuels and the smallest in

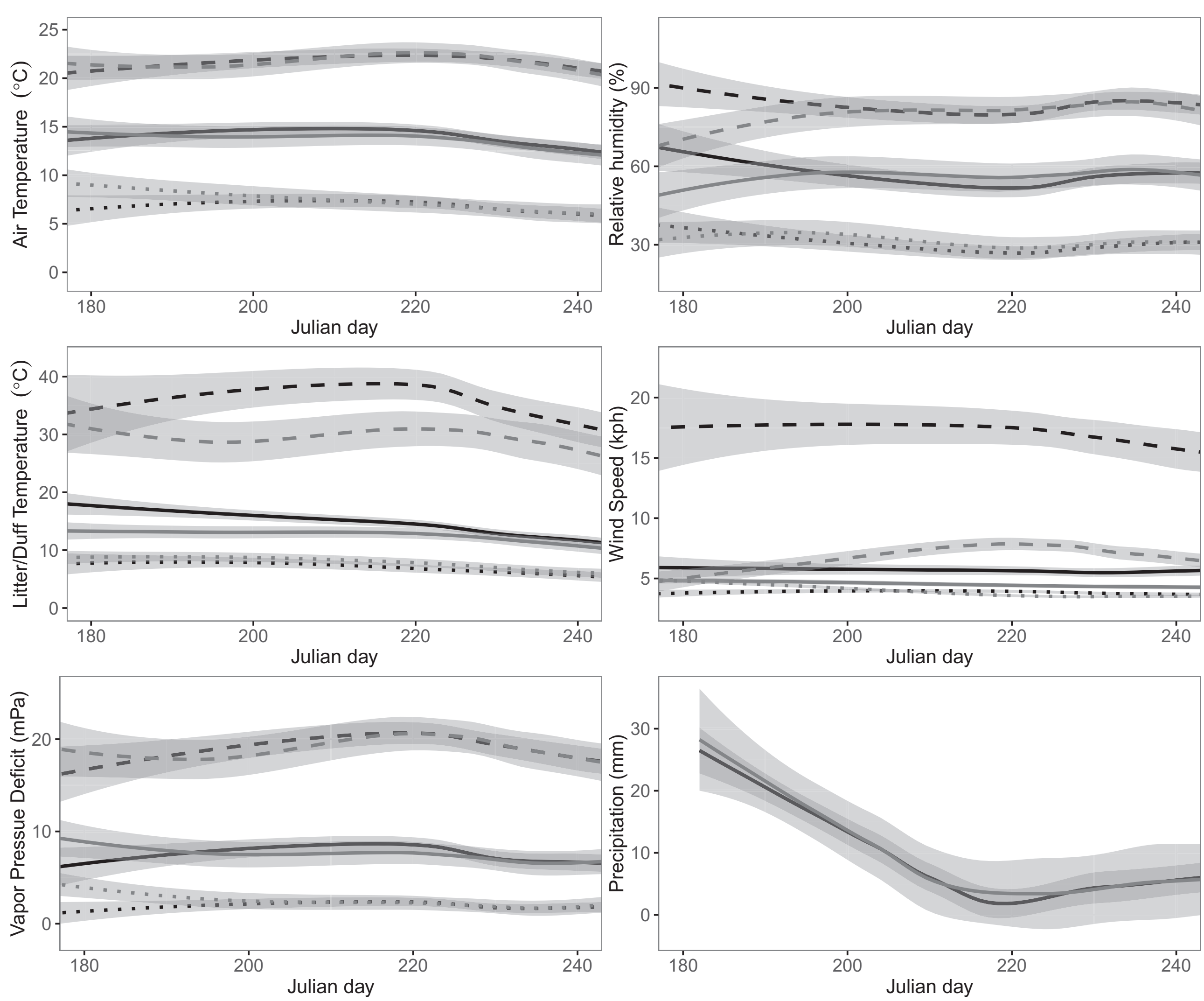

Fig. 3. Daily minimum (dotted line), median (solid line), and maximum (dashed line) weather conditions (±standard error) in treated (clear cut; black line) and untreated (grey line) plots in lodgepole pine forest located in the Colorado State Forest. Measurements were collected every 15 min from June 15th until October 10th, aggregated by treatment and plotted through the 2015 growing season with ±1 standard error.

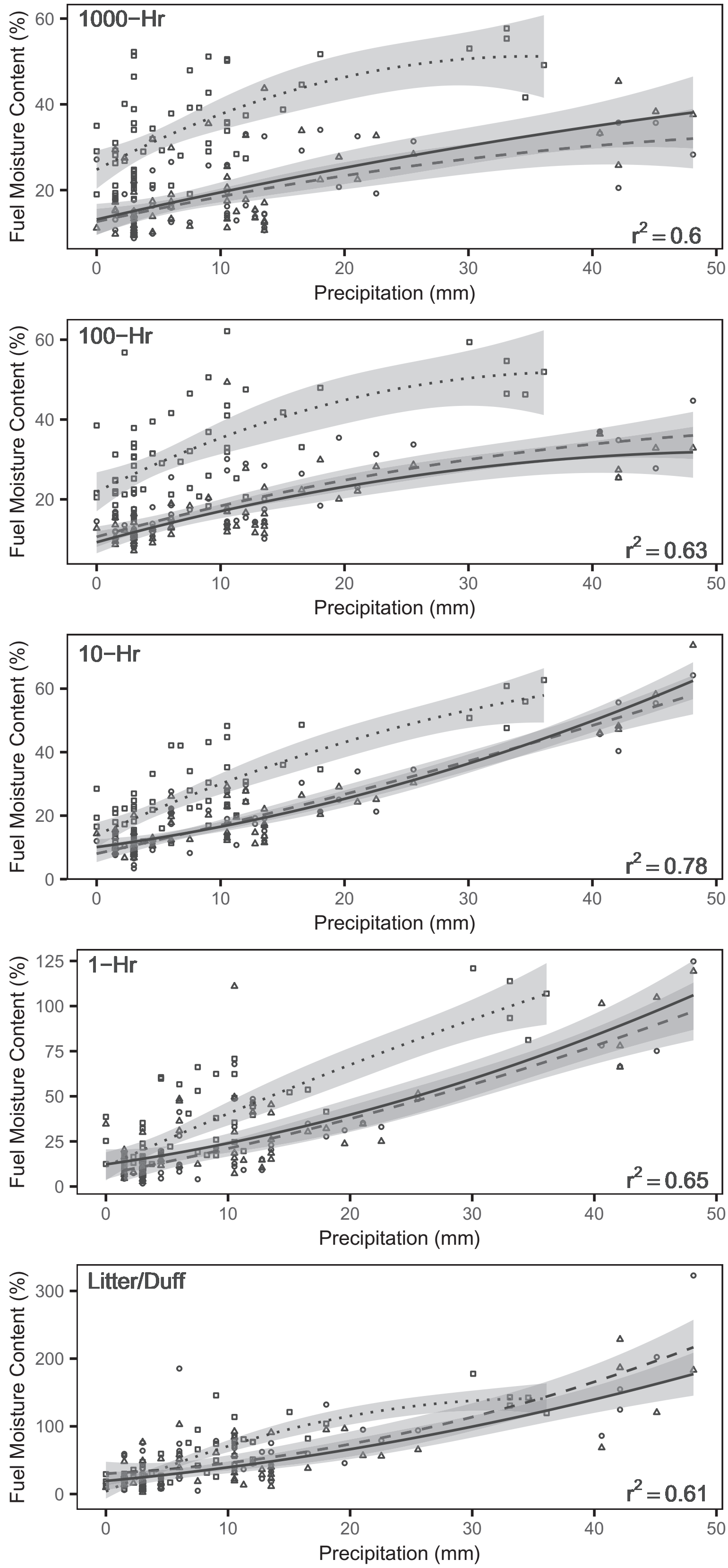

Fig. 4. Comparison of the effect of precipitation on each fuel class's fuel moisture content in untreated (dotted line and squares), biomass removal (dashed line and circles) and biomass retention (solid line and triangles) using linear regression (±1 standard error). Precipitation and fuel moisture content were measured during the same sampling event every 7–10 days throughout the sampling period (16 weeks).

1000-h fuels (Fig. 4). The litter and duff exhibited the least difference in the effect of precipitation across treatments.

4. Discussion

4.1. Effects of biomass utilization treatments on surface fuels loads

We found that total woody fuel loads, consisting primarily of 100- and 1000-h fuels, were far greater in biomass retention plots compared to both untreated and biomass removal plots (Table 1). Our findings also revealed that fine fuels in both post-harvest slash prescriptions were elevated compared to untreated plots. Other studies have found similar trends in which increases in fine fuels in treated stands were associated with heavily thinned stands (Griffin et al., 2013; Jenkins et al., 2008). In our study, the increase in fine fuels in the biomass retention plots is a direct result of felling trees, extracting the boles and leaving fine fuels. However, the increase within biomass removal prescription is likely from bole and crown breakage during harvesting. Projections of stand recovery after salvage logging at COSF and elsewhere in northern Colorado indicate that decomposition of fine fuel and reduced litter inputs may reduce the fine fuels generated by logging in about two decades (Collins et al. 2012). Moreover, removing the overstory in treated stands eliminates the possibility of crown fire but the increases in both fine fuels and 1000-h fuels may increase surface fire spread and intensity (Griffin et al., 2013).

Surface fuel loads will continue to increase in untreated MPB-infested LPP stands over the next 10–30 years as beetle-killed trees fall (Hicke et al., 2012; Collins et al., 2012). Such increases in 1000-h surface fuels may increase potential wildfire intensity, severity, extent and duration through prolonged smoldering and receptors of fire brands that promote spotting and crowning in adjacent stands (Hyde et al., 2011; Koo et al., 2010). Fuels reduction and salvage harvests are being implemented, in part, to make forests more resistant to potential high-severity fire.

4.2. Effects of biomass utilization treatments on fuel moisture content and microclimate

This study demonstrated that FMC differences between unharvested and harvested stands were significant (Fig. 2a). Notably, fuel particles in the large fuel classes (100-h, 1000-h) were found to have a FMC below the moisture of extinction earlier and for a longer portion of the sampling period in both slash prescriptions (Fig. 2b), indicating that these fuels may have a higher ignition probability and fire spread rate earlier in the fire season and that they are more susceptible to combustion and faster rates of fire spread for a longer portion of the sampling period (Keane, 2015). Our findings support earlier studies that also suggest that changes in vegetation structure, including removal of overstory, often result in changes in FMC through the fire season (Matthews, 2013; Viney, 1991; Simard, 1968; Fahnestock, 1960).

Harvesting is known to expose sites to surface microclimatic conditions that increase drying of fuels (Uhl and Kauffman, 1990; Holdsworth and Uhl, 1997; Swift et al., 1993). Ray et al. (2005) measured FMC and microclimate in mature regrowth and logged stands and found that increased canopy height and leaf area index slowed drying of fuels after rain compared to logged stands. In our study, although ambient air temperature and relative humidity did not differ between unharvested and harvested plots, litter/duff temperature and wind speed were significantly greater in harvested plots (Fig. 3). Several studies have also found an increase in litter/duff temperature in harvested forest that was attributed to canopy removal (Griffin et al. 2013; Stoffel et al., 2010; Londo et al. 1999; Carlson and Groot, 1997; Swift et al., 1993).

5. Management implications

Harvest treatments aimed at reducing crown fuels often increase surface fuel load and decrease fuel moisture (Collins et al., 2012; Fahnestock, 1960). Of the two most common post-harvest slash prescriptions, salvage logging with biomass retention increased surface fuel loads compared to harvesting followed by biomass removal (Table 1). Both slash prescriptions lowered fuel moisture content and resulted in an earlier and longer period of dry fuels compared to unharvested plots. Because wind speed and litter/duff temperature were higher in treated stands due to less wind resistance and increased insolation as a result of canopy removal (Fig. 3), precipitation increased FMC in untreated stands more than in both biomass prescriptions (Fig. 4).

These results contribute to a growing understanding of post-disturbance salvage harvest and biomass retention through different slash prescriptions. Based on these surface fuel loads and FMC, surface fire hazard appears to be greater in treated stands than untreated stands (Fahnestock and Dieterich, 1962); however, this relationship may change once untreated stands begin to experience widespread snag fall and fuels in treated stands decay. Making inferences as to exactly how these increases in fuel loads will affect wildfire are difficult due to uncertainties such as the continuity of fuels across the landscape. Future studies will be necessary to evaluate whether fuel treatments with slash retention or removal may provide more long-term benefits relative to when snags begin to fall in adjacent untreated forest stands.

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