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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 × 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