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Salvage harvest effects on advance tree regeneration, soil nitrogen, and fuels following mountain pine beetle outbreak in lodgepole pine

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ABSTRACT

The extent and severity of recent native bark beetle (Dendroctonae) outbreaks in western North America have created a pressing need for forest managers to understand potential consequences of post-disturbance management. For example, post-outbreak timber harvest (i.e., salvage harvest) could alter future forest development, productivity and susceptibility to subsequent disturbance. To assess the potential for such consequences, we measured first-year effects of post-outbreak timber harvest on tree regeneration, soil nitrogen (N) availability and fuels by using a paired and replicated before–after-control-impact (BACI) experimental design with eight pairs of 0.25-ha plots in beetle-killed lodgepole pine (*Pinus contorta* var. *latifolia*) in Greater Yellowstone (Wyoming, USA). Post-outbreak timber harvest reduced total (live + dead) lodgepole pine basal area by 90%. Total sapling density (advance regeneration) declined by about 50% following harvest, with tall (30–140 cm) saplings declining most, but mean post-harvest sapling density still exceeded 1600 stems ha^{-1}. Relative species density was unaffected and remained dominated by lodgepole pine. Soil temperature at the litter–soil interface was warmer during summer in harvested stands, and soil NO_3^- concentration increased with harvest relative to untreated plots. Soil NH_4^+ concentration and resin bag N accumulation increased through time in all beetle-killed plots and were not affected by harvest. Following harvest, dead woody surface fuels in all size categories doubled, and canopy fuel load and canopy bulk density both were reduced; dead fuel depth, duff depth, and canopy base height did not differ between untreated and harvested plots. Harvest did reduce canopy fuels, but the natural progression of needle shedding after beetle-kill accounted for 25–40% of this total canopy fuel reduction. Salvage harvest seems unlikely to alter post-outbreak successional trajectories in these lodgepole pine forests. However, the altered fuel complex (immediate increase in dead woody surface fuels and expected long-term reduction in large-diameter fuels) in harvested plots could cause subsequent fire behavior and effects to differ between harvested and untreated stands.

1. Introduction

Recent outbreaks of native bark beetles (Dendroctonae) have affected millions of hectares in western North America and killed up to 70–90% of large trees in some areas (Raffa et al., 2008). Because of their extent and severity, the outbreaks have created a pressing need for forest managers to understand how post-disturbance management may affect these ecosystems. Salvage harvest (the removal of disturbance-killed trees) is often conducted to recover economically valuable timber, reduce perceived risk of subsequent disturbance, and/or enhance recovery of disturbed areas (Dale et al., 2001; Beschta et al., 2004; McIver and Ottmar, 2007). Across all land ownerships in the western US, over 3.5 million ha of forests affected by beetle outbreak have been identified for potential treatment (USFS, 2011). Although salvage harvest has been the focus of research following fire (e.g. Donato et al., 2006; Greene et al., 2006) and, to a lesser extent, windstorms (e.g. del Rio, 2006; Peterson and Leach, 2008b; Fraver et al., 2011), few studies consider salvage harvest in beetle-killed forests (but see Collins et al., 2010, 2011, 2012). Knowledge of whether salvage harvest changes future forest development, potential productivity, and susceptibility to subsequent disturbance is sparse but needed to guide post-outbreak forest management (e.g., D'Amato et al., 2011). To assess the potential for such consequences, we evaluated first-year ecological effects of salvage harvest on tree regeneration, soil nitrogen availability and fuels in lodgepole pine (*Pinus contorta* var. *latifolia*) forests recently attacked by the mountain pine beetle (*Dendroctonus ponderosae*).

Bark beetles are phloem-feeding specialists native to temperate and boreal coniferous forests (Bentz et al., 2009), and the effects of

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bark beetle outbreaks on stand structure have been well documented (e.g. Romme et al., 1986; Axelson et al., 2009). In lodgepole pine forests, successful mountain pine beetle attack is usually limited to canopy and large sub-canopy trees (Safranyik and Carroll, 2006). Thus, stand-level beetle-caused tree mortality is incomplete, and the disturbance is also gradual because tree mortality occurs over several years. Snags remain standing for years or decades (Lewis and Hartley, 2005). The forest floor and duff layer remain intact during an outbreak, although dead needles are gradually added to the litter layer as canopy trees die. A flush of understory vegetation is often observed, likely in response to increased light, water and soil nutrients (Griffin et al., 2011). However, sapling densities are largely unchanged and sufficient for stand replacement (Rocca and Romme, 2009; Vyse et al., 2009; Diskin et al., 2011; Kayes and Tinker, 2012). Release of these understory survivors is often a major mechanism of regeneration (Veblen et al., 1991; Boggs et al., 2008; Nigh et al., 2008).

Salvage timber harvest operations cut and remove the merchantable disturbance-killed trees (and some live trees as well, depending on prescription), thus reducing the density and basal area of standing-dead trees. Harvested trees are generally large, and post-logging slash can be treated in various ways (e.g., removed, scattered, or cut and piled). Salvage harvest could unintentionally reduce live sapling density and understory vegetation by physical damage and mortality, soil disturbance, or altered microsite conditions (Blouin et al., 2005; Bulmer and Simpson, 2005; Kamaluddin et al., 2005). For example, post-fire salvage harvest has reduced conifer seedling density (Martinez-Sanchez et al., 1999; Donato et al., 2006; Greene et al., 2006) and total vegetative cover (Stuart et al., 1993; Purdon et al., 2004; McIver and Ottmar, 2007). However, salvage operations following beetle outbreaks might also enhance establishment of post-outbreak tree seedlings in areas where soil disturbance exposes mineral soil (Collins et al., 2010).

Nitrogen (N) often limits productivity of lodgepole pine forests and can be a sensitive indicator of disturbance (Fahey et al., 1985), but the effect of post-outbreak salvage harvest on N availability is difficult to predict. During the first few years of a bark-beetle outbreak, soil temperature decreases because increased litter provides added insulation (Griffin et al., 2011; Simard et al., 2011); soil moisture also increases as trees die and evapotranspiration declines. However, salvage harvest can increase soil temperature (Smethurst and Nambiar, 1990; Fontaine et al., 2010), and logging machinery can compact forest soils, reducing porosity and water-holding capacity (Blouin et al., 2008). Thus, post-outbreak salvage harvest could lead to warmer, drier soils, which might reduce N availability, but data are inconclusive. Some studies report short-lived increases in N mineralization rates following compaction (Kranabetter et al., 2006) and others report no effect (e.g. Goodman and Hungate, 2006) or reductions in soil inorganic N pool sizes (Blouin et al., 2005; Choi et al., 2005; Kamaluddin et al., 2005). Inputs of litter and fine wood may further increase following salvage logging (Smethurst and Nambiar, 1990; Goodman and Hungate, 2006), and this material may serve as a temporary N sink if it remains on the forest floor (Remsburg and Turner, 2006). Thus, evidence for how post-outbreak salvage might affect soils and N cycling is inconclusive, and alternative expectations are plausible.

Reducing the likelihood and/or severity of subsequent fire is among the objectives of post-outbreak salvage logging in the western US (USFS, 2011), but the effectiveness of such treatments has not been evaluated. Bark beetle outbreaks initially (i.e., 1–4 years) change fuel abundance and distribution in lodgepole pine by thinning canopies and enhancing understory plant growth (Page and Jenkins, 2007b; Jenkins et al., 2008; Simard et al., 2011). Shortly after beetle attack, reduced canopy fuel moisture and altered foliar chemistry may increase fire hazard (Jolly et al., 2012; Page et al., 2012), but the concurrent reduction in canopy fuels through needle fall may mitigate this effect (Simard et al., 2011; Schroeder and Mooney, 2012). Salvage harvest removes the large standing snags but may increase the quantity of dead surface fuels (Collins et al., 2012), as with post-fire salvage logging (Donato et al., 2006; McIver and Ottmar, 2007; McGinnis et al., 2010). However, the effects of salvage harvest may differ following fire and beetle outbreak because their disturbance legacies are very different; fires directly remove canopy and surface fuels and directly affect understory vegetation, whereas bark beetles do not consume canopy biomass or surface fuels and do not directly affect the forest understory.

In this study, we asked how post-outbreak salvage harvest in beetle-killed lodgepole pine affected tree regeneration potential, soil N availability, and fuels during the first year following harvest. We expected sapling density (and thus tree regeneration potential) to be reduced following harvest. For soils and N availability, expectations were less clear, as canopy opening would increase soil temperatures but added litter would insulate soils and reduce soil temperature. Soil N pools and N availability might increase, decrease or remain unchanged. Finally, we expected canopy fuels and live surface fuels to be reduced, but dead surface fuels to increase.

2. Materials and methods

2.1. Study region and experimental design

Study sites were located in a 4-km^2 area of the Green River Lakes region on the Bridger–Teton National Forest in northeastern Wyoming, USA (Fig. 1). The forests established following a fire in 1849 and were dominated by lodgepole pine, with minor components of subalpine fir (*Abies lasiocarpa* Hook.), Engelmann spruce (*Picea engelmannii* Parry), and whitebark pine (*Pinus albicaulis* Engelmann). Stands were approximately 160 years old at the time of this study and had not been harvested previously (M.A. Dasher, personal communication). Mean temperature for the nearest weather station (Cora, Wyoming) is 14.2 °C in July and −10.2 °C in January, with annual precipitation averaging 302 mm per year, mostly as snow (WRCC, 2012). Soils are nutrient poor and derived from andesitic substrates. Mountain pine beetle activity in the area peaked in 2005, but affected forests included a mix of unattacked live trees and beetle-killed trees in the red and gray stages of canopy decline when initially sampled in 2007. A tree's foliage turns red within a year (red stage) after successful beetle attack, and the needles are shed from the canopy within 1–3 years (by the gray stage). Because trees are attacked over several years and not all trees are killed, the infested stands included live and dead trees in varying stages of post-attack condition (Table 1). Stands were all in the gray stage when sampled in 2010, post-treatment.

We used a paired and replicated before-after-control-impact (BACI) experimental design (Underwood, 1994) consisting of eight pairs of 50-m × 50-m plots located in beetle-killed forests. In each pair, one plot was designated for salvage harvest (Bend in the River timber sale), and a similar plot <400 m away was unmanaged (untreated plots). The timber sale was developed in response to the mountain pine beetle epidemic and the perceived need to remove dead and infested trees to improve stand diversity and reduce fuel loading (M.A. Dasher, personal communication). Timing of salvage operations was not under investigator control, and harvest was delayed somewhat because of market forces. A commercial operator conducted the salvage harvest in summer 2009 using a feller–buncher, with lop-and-scatter slash treatments in all harvested plots. The harvest prescription was to remove dead and dying (beetle-infested) lodgepole pine and stipulated that young growth (advance regeneration) should be protected throughout the harvest;