Forest Ecology and Management 336 (2015) 11–20

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Species composition influences management outcomes following mountain pine beetle in lodgepole pine-dominated forests

K.A. Pelz [a,*], C.C. Rhoades [b], R.M. Hubbard [b], M.A. Battaglia [b], F.W. Smith [a]

[a] Department of Forest & Rangeland Stewardship, Colorado State University, United States
[b] U.S.D.A. Forest Service, Rocky Mountain Research Station, Fort Collins, CO, United States

ARTICLE INFO

Article history:
Received 6 June 2014
Received in revised form 3 September 2014
Accepted 9 September 2014
Available online 29 October 2014

Keywords:
Bark beetles
Mountain pine beetle
Fuel management
Lodgepole pine
Subalpine fir
Rocky mountains

ABSTRACT

Mountain pine beetle outbreaks have killed lodgepole pine on more than one million hectares of Colorado and southern Wyoming forest during the last decade and have prompted harvest operations throughout the region. In northern Colorado, lodgepole pine commonly occurs in mixed stands with subalpine fir, Engelmann spruce, and aspen. Variation in tree species composition will influence structure, fuel profiles and fire hazard as forests recover from bark beetle outbreaks, and this diversity has implications for design and implementation of fuel reduction treatments. We used stand inventory data to predict forest structure and fuel loads starting after needle fall through one century after bark beetle infestation for three lodgepole pine-dominated forest types (pine, pine with aspen, pine with fir and spruce), and compared simulated effects of no-action and fuel reduction treatments (thinning, broadcast burning). In pine stands mixed with significant density of fir and spruce, the high canopy bulk density and low canopy base height increases passive and active crown fire hazards compared to stands with few shade tolerant trees. In contrast, stands of pine mixed with aspen had lower canopy bulk density and active crown fire hazard. All three forest types had high snag and coarse woody debris loads. Thinning and broadcast burning reduced canopy fuels in all forest types for several decades, but had the largest effect in forests with abundant fir. Burning temporarily reduced fine woody fuel, and caused a longer-term reduction in coarse wood and duff. Overall, these simulations indicate that management aimed at reducing canopy fuels in beetle-killed lodgepole pine forests should prioritize stands with high densities of overstory and understory fir and spruce. Forest growth following treatment requires frequent stand manipulation (as often as every 20 years) to maintain reduced fuel loads, and since such treatments are expensive and likely not analogous to natural disturbances these activities are most appropriate where resource and infrastructure protection and human safety concerns are high.

1. Introduction

Mountain pine beetle (MPB; *Dendroctonus ponderosae* Hopkins) has killed trees on over one million hectares of lodgepole pine-dominated (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm. ex S. Wats.) forests in Colorado and southern Wyoming since the late 1990s (U.S.D.A. Forest Service, 2010). The severity of tree mortality elevated concerns about crown fire hazard (U.S.D.A. Forest Service, 2011; Hicke et al., 2012; Page et al., 2013). Low foliar moisture content increases flammability of fine fuels during the 'red needle phase' (Jolly et al., 2012; Page et al., 2012), though this contributor to crown fire hazard is thought to decline with needle fall, typically 3–5 years after beetle infestation (Simard et al., 2011; Page et al., 2013). The fire hazard implications of the 'red stage' have been widely discussed, but we focus on forest fuels after needles have fallen (the 'grey-stage' of post-beetle development) since most forests affected by the recent outbreak are in this condition. The abundance of snags and subsequent accumulation of coarse woody debris generated by overstory mortality represent a longer-term fire hazard (Gray, 2013; Page et al., 2013). Loss of the relatively uniform lodgepole pine overstory (even age, single strata) has also been shown to increase dominance of shade-tolerant conifers in some stands and create more vertically continuous fuel profiles, increasing crown fire hazard starting 1–2 decades after beetle infestation (e.g., Lynch et al., 2006; Page and Jenkins, 2007a,b; Collins et al., 2012; Hicke et al., 2012; Pelz and Smith, 2012; Gray, 2013; Page et al., 2013). These longer-term contributors to fire hazard have prompted planning of fuels reduction treatments on nearly 100,000 hectares throughout Colorado and

* Corresponding author.
E-mail address: kristen.pelz@colostate.edu (K.A. Pelz).

http://dx.doi.org/10.1016/j.foreco.2014.09.034
0378-1127/

southern Wyoming (U.S.D.A. Forest Service, 2011; Colorado State Forest Service, unpublished data).

Post-outbreak changes in forest structure and fuel profiles depend on the size and species composition of the remaining live trees in addition to MPB-caused mortality severity and killed tree biomass. Non-host tree species are unaffected and small diameter lodgepole are less susceptible to MPB attack (Cole and Amman, 1969; Klutsch et al., 2009; Diskin et al., 2011). Even the nearly pure lodgepole stands selected for post-outbreak treatments are well stocked with live pine and non-host advance regeneration (Collins et al., 2012). Lodgepole pine-dominated forests of the Southern Rockies are commonly mixed with Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.) or quaking aspen (*Populus tremuloides* Michx.) (Peet, 1981; Diskin et al., 2011; Kayes and Tinker, 2012). Where present, these co-occurring species will play an important role in future forest conditions.

Fire hazard will likely vary with species composition in beetle-killed lodgepole pine forests (Klutsch et al., 2011; Hicke et al., 2012; Pelz and Smith, 2012). Lodgepole forests mixed with subalpine fir or Engelmann spruce typically have lower canopy base height (CBH) and higher canopy bulk density (CBD) than pure lodgepole stands (Muir, 1993; Scott and Reinhardt, 2001; Gray, 2013). Vertical continuity of branches and foliage from the forest floor to the overstory canopy create ladder fuels that permit surface fires to burn into the canopy and become active crown fires (Alexander et al., 2004). In these mixed pine, fir and spruce stands, the combination of ladder, canopy and coarse fuels, from the release of understory conifers and windthrow of beetle-killed overstory, may lead to torching and high intensity surface fires with long residence time and increased potential for spotting (Hvenegaard, 2012; Albini et al., 2012; Page et al., 2013). In contrast, crown fire probability is expected to be lower where pine is mixed with abundant aspen due to the high CBH and greater foliage moisture of this forest type compared to pure lodgepole (Turner and Romme, 1994; Cumming, 2000). Simulated fire in lodgepole forests recently attacked by MPB showed crown fire was unlikely in stands with aspen, but much more likely when fir and spruce were present (Klutsch et al., 2011).

Clearcut harvests are the most widely applied prescription in beetle-affected lodgepole pine forests, but we need to evaluate potential alternatives for future management. We need to know how varying amounts of spruce, fir, and aspen affect fuels reduction treatment effectiveness, and how treatments complement or conflict with other management objectives. For example, the increase in coarse wood and fir and spruce abundance will enhance Canada lynx (*Lynx canadensis*) habitat following MPB (Chan-McLeod, 2006), and protection of forest structure beneficial to lynx will conflict with fuel reduction priorities. Here we simulated forest structure and fuel dynamics in three lodgepole-dominated forest types common to the Southern Rockies and examined changes following two potential fuel reduction treatments (thinning, broadcast burning) during the century after bark beetle infestation. In the absence of replicated thinning and prescribed burning trials, these simulations provide a first approximation to help assess the consequences of these treatments on forest structures and fuel profiles in multiple forest types.

2. Methods

2.1. Study area and data collection

We used stand inventory and fuels data collected in uncut stands within four bark beetle management areas in northern Colorado (105°51′ to 106°38′W and 39°53′ to 40°36′N; Collins et al., 2012) to initiate simulations of post-bark beetle stand development and to inform treatment comparisons. Significant beetle activity began in this area between 1998 and 2002 (U.S.D.A. Forest Service, 2010), peaked around 2008, and killed 60–92% of total basal area (Collins et al., 2011; Chapman et al., 2012; Meddens and Hicke, 2014). Forest and fuels were inventoried in 2008 after the majority of pine needles had fallen. Diameter, species, and condition (live or dead) were recorded along 100 × 5 m belt transects for trees ⩾2.5 cm diameter at breast height (1.37 m high, dbh). We tallied regeneration (trees <2.5 cm dbh and ⩾0.15 m tall) by species in two, 3.6-m radius plots per transect. Surface fuel loads were measured along two, 15-m transects (Brown et al., 1982) per belt transect. Fuels ⩾7.62 cm in diameter (coarse woody debris, CWD) were classified as rotten or sound, and litter and duff depths were measured at three points along each fuel transect (see Collins et al., 2012, for more details).

We partitioned the inventoried stands into: (1) lodgepole pine (LP) (⩾90% of pre-outbreak basal area in lodgepole and <1% basal are in aspen or spruce/fir, with fir-dominated regeneration); (2) lodgepole pine with aspen (LP-AS) (5–30% of pre-outbreak basal area in aspen, <1% basal area in spruce and fir, with aspen-dominated regeneration) and, (3) lodgepole pine with subalpine fir and Engelmann spruce (LP-SF) (10–30% of pre-outbreak basal area in spruce and fir, <5% of basal area in aspen, with fir-dominated regeneration) (Table 1).

2.2. Simulations of forest and fuel dynamics

We used the Central Rockies variant of the Forest Vegetation Simulator (FVS) (Dixon, 2002, 2008) and its Fire and Fuels Extension (FFE) (Rebain, 2012) to project forest and fuel changes for 100 years after mountain pine beetle outbreak. FVS is a density-dependent growth and yield model that projects forest structure and fuels based on initial forest and fuel data and site index. Self-thinning began when stands reached 60% relative density. Regional maximum heights, basal areas, and densities were used to adjust the model's default levels of aspen growth (Shepperd, 1990; Shepperd, unpublished data; Smith et al., 2011). We used Regeneration Imputation Extractor (REPUTE) to add seedling cohorts based on inventory data from beetle-affected forests in Colorado and southern Wyoming (Vandendriesche, 2010).

FFE-FVS generates surface fuel loads and canopy characteristics based on initial fuels measurements and simulated stand development. It accounts for litter and woody fuel inputs, and biomass decomposition through time (Reinhardt and Crookston, 2003; Rebain, 2012). Canopy bulk density (CBD; kg dry foliage + branch [<6 mm diameter] biomass m^{-3}) is estimated by averaging within 0.3 m-thick horizontal layers (Scott and Reinhardt, 2001). Needles and branches from live trees are included in this calculation. Stand CBD is defined as the maximum value of a 4.5 m-running mean from the 0.3-m layers. Stand canopy base height (CBH) is the height at which stand CBD first exceeds 0.01 kg m^{-3}.

2.3. Treatment design and effectiveness criteria

Simulated fuel reduction treatments were scheduled to coincide with formation of dense ladder fuel strata, commencing 10 years after the outbreak (Gray, 2013; Page et al., 2013). At this time in all forest types, about half of the dead pine snags had fallen and half were still standing. A thin-from-below treatment was designed to reduce canopy fuels in the short and long term. This treatment removed 95% of subalpine fir and Engelmann spruce trees <15.2 cm dbh and immediately eliminated canopy biomass from the ladder fuel stratum. It also aimed to delay subsequent development of ladder fuels by removing small fir and spruce trees and to promote lodgepole pine and aspen. Resulting biomass from