Forest Ecology and Management 303 (2013) 160–174

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

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

Evaluating post-outbreak management effects on future fuel profiles and stand structure in bark beetle-impacted forests of Greater Yellowstone

Daniel C. Donato [a,*], Martin Simard [b], William H. Romme [c], Brian J. Harvey [a], Monica G. Turner [a]

[a] Zoology Department, University of Wisconsin, Madison, WI 53706, USA
[b] Department of Geography and Centre for Northern Studies, Université Laval, Pavillon Abitibi Price, 2405 de la Terrasse, Québec City, Québec, Canada G1V 0A6
[c] Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO 80523, USA

ARTICLE INFO

Article history:
Received 11 December 2012
Received in revised form 15 April 2013
Accepted 16 April 2013
Available online 15 May 2013

Keywords:
Carbon
Dendroctonus
Douglas-fir
Forest Vegetation Simulator
Lodgepole pine
Salvage

ABSTRACT

Large-scale bark beetle (Curculionidae: Scolytinae) outbreaks across western North America have prompted widespread concerns over changes to forest wildfire potentials. Management actions following outbreaks often include the harvest of beetle-killed trees and subsequent fuel treatments to mitigate expected changes to fuel profiles, but few data exist to inform these actions. In both lodgepole pine (*Pinus contorta* var. *latifolia*) and Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) forests of the Greater Yellowstone Ecosystem, Wyoming, USA, we used the Forest Vegetation Simulator to evaluate how fuel profiles, stand structure, and biomass carbon storage are influenced by various post-outbreak fuel treatments (removal of beetle-killed trees ['salvage'] followed by either no treatment, prescribed burning, pile-and-burn, or whole-tree-removal). The model was initialized with field data from five unmanaged gray-stage stands in each forest type and projected over 50 years of post-treatment time. Across all treatment methods, the strongest projected effects relative to unharvested stands were reductions in coarse woody surface fuels (after 10–20 yr), fewer well-decayed standing snags (after 40 yr), and reduced biomass carbon storage (throughout all 50 years). The reduction in coarse woody surface fuels suggests reduced heat release and resistance to control in future fires. Projected effects on fine fuels, both in the canopy and surface layers, were surprisingly minor or short-lived; natural fall and decay of fine material in unharvested stands led to the convergence of most fuel variables between treated and untreated stands within about a decade, especially in Douglas-fir forests. Most follow-up treatment methods – whether unmerchantable tree parts were left in place, burned, piled, or removed entirely – had similar impacts on most aspects of fuel and stand structure in both lodgepole pine and Douglas-fir forests. However, the prescribed burning treatment was distinct and generally had the strongest effects, owing to greater consumption of forest floor mass and mortality of small trees, which had persistent influences on both the canopy and surface fuel layers. Treatment effectiveness in reducing fuels was mirrored by reductions in biomass carbon storage and recruitment of well-decayed snags, illustrating common trade-offs involved in fuel treatments. Harvest of beetle-killed trees and subsequent treatments altered the fuel profile and structure of outbreak-impacted stands, but overall effects were similar among treatments, suggesting flexibility in management options in post-outbreak forests.

1. Introduction

Bark beetles (Curculionidae: Scolytinae) are major native disturbance agents in most temperate coniferous forests, often impacting more land area than wildfire (Raffa et al., 2008). Epidemic eruptions of bark beetles occur periodically and result in up to 80% mortality of trees over scales of 10^3–10^6 hectares (Meddens et al., 2012). These outbreaks can result in significant changes to the structure, function, and composition of forest ecosystems (Romme et al., 1986; Veblen et al., 1991; Hicke et al., 2012a), the signature of which may be apparent for decades to centuries (Collins et al., 2011). Affected stands are often a focal concern for land and resource management, but thus far, scarce information exists on the effects of post-outbreak management interventions on future stand development.

One of the key concerns to arise from the recent bark beetle outbreaks across western North America (>10 million hectares since the late 1990s) is their potential influence on future wildfires

* Corresponding author. Present address: Washington State Department of Natural Resources, P.O. Box 47016, Olympia, WA 98504, USA. Tel.: +1 608 265 8001.
E-mail address: ddonato@wisc.edu (D.C. Donato).

0378-1127/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.foreco.2013.04.022

(Jenkins et al., 2008; Hicke et al., 2012b). The associated pulse of tree mortality is known to significantly alter fuel profiles (arrangement, quantity, and composition of biomass) across several forest types in western North America (Page and Jenkins, 2007a; DeRose and Long, 2009; Klutsch et al., 2011; Simard et al., 2011; Hoffman et al., 2012; Schoennagel et al., 2012; Donato et al., 2013). Primary impacts center on the deterioration and falling of beetle-killed trees, thinning of canopy biomass, subsequent surface fuel accumulations, and eventual growth of understory trees into the midstory (ladder fuels). Each of these changes is expected to influence the intensity and propagation of fire within and between the canopy and surface fuel layers (Hicke et al., 2012b) – albeit to varying degrees depending on forest type, being less evident in structurally variable systems in which outbreak effects have low 'signal-to-noise' relative to background variability (Donato et al., 2013). Empirical studies of fires burning through beetle-affected landscapes have reported equivocal results on outbreak effects on fire severity (the effects of fire to the ecosystem) (Bebi et al., 2003; Lynch et al., 2006; Kulakowski and Veblen, 2007; Bond et al., 2009; Kulakowski and Jarvis, 2011), which may also vary among ecosystems.

Management objectives in beetle-affected forests often include mitigating these alterations to fuel profiles and stand structure (e.g., Collins et al., 2012). In addition to recouping economic timber value, harvest of beetle-killed trees (i.e., 'salvage') may be prescribed to reduce the amount of dead material in the forest canopy (to reduce crown fire spread potential) and to decrease the surface accumulation of woody fuels from natural snag-fall over time (to reduce surface fire intensity and resistance to control). The extent of recent beetle outbreaks has led to broadening application of these treatments, but to date, few data are available to inform post-outbreak management actions (see Lewis, 2009; Collins et al., 2011, 2012; Griffin et al., 2013) – especially compared to that for post-wildfire and post-windstorm settings (e.g., Rumbaitis-del Rio, 2006; McIver and Ottmar, 2007; Peterson and Leach, 2008; McGinnis et al., 2010; Buma and Wessman, 2011; Fraver et al., 2011; Donato et al., in press). So far, studies have evaluated operations in which both beetle-killed trees and residual green trees are removed, including most of the regeneration layer (e.g., Collins et al., 2011, 2012). Although such operations are common in parts of the western US, they are similar to, and informed by the many studies of, traditional clearcut timber harvest (e.g., Snell and Brown, 1980; Weatherspoon and Skinner, 1995). Treatment prescriptions vary widely among regions, and less is known regarding other regionally common prescriptions that remove beetle-killed trees but retain much or all of the surviving trees for a future multi-cohort stand or as seed trees. Rather than initiating a new stand, such treatments perpetuate an existing stand that may take different pathways depending, in part, on post-outbreak management.

Of particular uncertainty is how different post-harvest fuel treatments in beetle-affected stands, such as prescribed burning and mechanical removal, affect fuel profile dynamics and other characteristics of stand structure over the ensuing decades. Variations in treatment of post-harvest slash (the unmerchantable components of felled trees including branches and tree tops) are an important determinant of future fire potentials after harvest of live trees (Weatherspoon and Skinner, 1995; Graham et al., 2004; Agee and Skinner, 2005; Stephens et al., 2009), but such variation has scarcely been evaluated for dead-tree felling in post-outbreak forests. In addition, there is broadening interest in how various wildland fuel treatments, and post-disturbance harvests specifically, influence other ecosystem features such as wildlife habitat (Fontaine and Kennedy, 2012) and carbon sequestration (Bradford et al., 2012; Powers et al., 2013). Informed ecosystem management will require balancing these multiple objectives rather than focusing solely on fuels, making it essential to simultaneously evaluate how post-outbreak management affects other land-use objectives (Bradford and D'Amato, 2012).

In this study we evaluated the short- and long-term (0–50-year) effects of common post-outbreak management treatments on fuel profiles and stand structures in two major forest types of the Greater Yellowstone Ecosystem (GYE). Using a forest growth and yield model, the Forest Vegetation Simulator (FVS; Dixon, 2002), we simulated the effects of removal of beetle-killed trees followed by various fuel treatments in both lodgepole pine (*Pinus contorta* var. *latifolia*) and interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) forests affected by the mountain pine beetle (*Dendroctonus ponderosae*) and Douglas-fir beetle (*D. pseudotsugae*), respectively. We previously reported on how responses to beetle epidemics differ between these forest types, with the drier Douglas-fir type exhibiting lower and more variable post-outbreak fuel loads relative to lodgepole pine (Simard et al., 2011; Donato et al., 2013). Further, although there is considerable variability within each forest type, most studies in lodgepole pine report that abundant advance and new regeneration eventually develops into ladder fuel (vertical continuity) after outbreaks (Simard et al., 2011; Pelz and Smith, 2012), whereas much sparser regeneration in Douglas-fir stands can result in far slower re-development of vertical fuel continuity (Donato et al., 2013). In this study we asked: a) how different post-harvest fuel treatments compare in terms of fuel profile and stand structure development, and b) how these comparisons potentially differ by forest type. Responses of interest included canopy fuel metrics, surface fuel loads, snag and live-tree dynamics, and carbon storage in live and dead tree biomass. Understanding relationships among dynamics of fuel profiles and other aspects of stand structure can inform prescriptions and tradeoffs involved in post-outbreak management.

2. Methods

2.1. Study area

The Greater Yellowstone Ecosystem is an 80,000-km^2 portion of the Rocky Mountains spanning parts of Wyoming, Montana, and Idaho, USA (approximate center: latitude/longitude 44°12′N, 110°21′W). Two of the most common vegetation types in the region are subalpine forests dominated by lodgepole pine and mid-elevation forests dominated by interior Douglas-fir. Lodgepole pine forests occupy infertile volcanic (rhyolitic) soils across the Yellowstone Plateau, while Douglas-fir forests occupy moderately fertile (non-rhyolitic, sedimentary) soils on adjacent sloping terrain. The climate of the GYE is continental with cold, snowy winters and warm, dry summers. Mean July high temperatures are 21 °C on the plateau and 24 °C at mid-elevations, and mean January lows are ∼−15 °C across the region; mean annual precipitation ranges from 600 to 1100 mm on the plateau and 350–650 mm at mid-elevations (www.prismclimate.org). Study sites were at elevations of 2000–2600 m on a full range of aspects, and slopes ranged from nearly flat to 30° (mean 17°).

Lodgepole pine and Douglas-fir account for about two-thirds of the forested area of Greater Yellowstone and occur in either pure or mixed stands, along with associates Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and whitebark pine (*Pinus albicaulis*) on moist/high-elevation sites, or limber pine (*Pinus flexilis*) and Rocky Mountain juniper (*Juniperus scopulorum*) on dry/low-elevation sites. Lodgepole pine forests are characterized by a stand-replacing crown fire regime with intervals of ∼150–300 years and often contain an even-aged overstory pine cohort (Romme and Despain, 1989). Douglas-fir forests sustain a mixed-severity fire regime with surface and crown fires at intervals of ∼20–200 years, and are often multi-aged (Barrett, 1994; Baker,