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Forest-landscape structure mediates effects of a spruce bark beetle (*Dendroctonus rufipennis*) outbreak on subsequent likelihood of burning in Alaskan boreal forest

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ABSTRACT

Characterizing how variation in forest landscape structure shapes patterns of natural disturbances and mediates interactions between multiple disturbances is critical for anticipating ecological consequences of climate change in high-latitude forest ecosystems. During the 1990s, a massive spruce bark beetle (*Dendroctonus rufipennis*) outbreak took place in boreal spruce forest on the Kenai Peninsula, Alaska allowing us to ask (1) *How did the extent and duration of bark beetle outbreak differ between a homogenous landscape dominated by white spruce* (*Picea glauca*), *and a landscape in which white spruce and black spruce* (*Picea mariana*) *were intermixed?* (2) *How has the occurrence and duration of bark beetle outbreak influenced the likelihood of subsequent burning in these two landscapes?* Forest landscape structure had a substantial effect on disturbance patterns and interactions between disturbances in this study. The spruce bark beetle outbreak was smaller in extent and duration where white spruce, the beetle's primary host tree, was intermixed with more beetle-resistant black spruce. However, likelihood of subsequent burning increased where outbreak did occur. Surface fuel loads increased substantially in this landscape following the outbreak, potentially increasing the flammability of white spruce where they once served as fire breaks. In contrast, the outbreak was larger and lasted longer in the landscape with homogeneous stands of white spruce, but was not related to likelihood of subsequent burning, which is consistent with the fire history. Our results suggest that bark beetle outbreaks may have different effects on subsequent patterns of burning than in other systems, such as the Rocky Mountains. These results could inform more effective and targeted management strategies to ameliorate fire risk in beetle-killed stands of Alaska and may help us anticipate the dynamics and consequences of future boreal bark beetle outbreaks as climate warms at high latitudes.

1. Introduction

Evaluating how variation in forest-landscape structure shapes natural disturbance patterns and mediates interactions between multiple disturbances is critical for understanding ecological consequences of climate change (Turner, 2010; Johnstone et al., 2011). Warming and drying are causing pronounced increases in the frequency, size, and severity of natural disturbances (Millar and Stephenson, 2015; Trumbore et al., 2015). In western North America, annual area burned by wildfire is now nearly 6.5 times the 1970–1986 average (Westerling et al., 2006), and bark beetle outbreaks have become substantially more prevalent in recent decades (Bentz et al., 2010). Concern persists that bark-beetle-driven tree mortality could further increase the risk of subsequent fire frequency, size, and severity (Hicke et al., 2012), a concept known as linked disturbance interactions (Simard et al., 2011). However, landscape structure may mediate climate-change effects on disturbances (Turner and Romme, 1994; Duffy et al., 2007). Variation in tree-species distributions across landscapes can influence patterns of burning (Schoennagel et al., 2004; Kelly et al., 2013) and determines forest vulnerability to bark beetle outbreak (Hart et al., 2015a; Temperli et al., 2015). Accounting for the role of forest-landscape structure could yield powerful insights into changing disturbance regimes in the 21st century and the nature and

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magnitude of their interactions. This could help us anticipate when and where forests may be vulnerable to bark beetle outbreaks and whether such outbreaks may influence subsequent patterns of burning.

Few places on Earth are experiencing as rapid climate change as the Alaskan boreal forest, warming at twice the rate of the global average during the 20th century (Wolken et al., 2011). Annual area burned in boreal Canada and Alaska is expected to increase 74–118% by 2100 (Balshi et al., 2008; Flannigan et al., 2005). In white spruce (*Picea glauca*) stands of the western Kenai Peninsula in south-central Alaska, recent climate warming also led to a massive spruce bark beetle (SBB) (*Dendroctonus rufipennis*) outbreak that extended over almost 1.2 million ha during the 1990s (Berg et al., 2006). An estimated 30 million trees were killed per year between 1990 and 1996, when the outbreak peaked (Werner et al., 2006). The distribution of tree species varied markedly in SBB-affected landscapes. This variation may have mediated outbreak dynamics (Seidl et al., 2015; Temperli et al., 2015) and subsequent ecological consequences. White spruce, the beetle's primary host tree in Alaska, dominated the southern portion of the outbreak extent, forming homogenous stands of susceptible mature forest (Berg and Anderson, 2006). In the northern portion of the outbreak, white spruce trees were intermixed with black spruce (*Picea mariana*) (DeVolder, 1999), which are not vulnerable to SBB (Werner et al., 2006).

The Kenai Peninsula is one of the most densely populated areas in Alaska, and following the outbreak, there has been substantial concern about increases in the subsequent risk of wildfire. A number of wildfires have burned on the Kenai Peininsula since the outbreak. Warming trends suggest that future outbreaks and increased interaction with fire may occur in Alaska (ACIA, 2005; Berg et al., 2006; Raffa et al., 2008; Sherriff et al., 2011; Werner and Holsten, 1985; Werner et al., 2006). However, it remains poorly resolved when and where Alaskan boreal forests may be vulnerable to future outbreaks and whether future outbreaks could influence subsequent patterns of burning.

In montane to subalpine Rocky-Mountain conifer forests, bark beetle outbreaks can alter fire behavior (Hicke et al., 2012) and compromise fire-fighter safety (Jenkins et al., 2012). For example, active crown fire potential may increase 1–4 years post outbreak, before declining, as needles are shed from beetle-killed trees (Hicke et al., 2012). However, outbreaks appear to have modest or little effect on post-outbreak fuel profiles (Simard et al., 2011; Donato et al., 2013; Schoennagel et al., 2012; Harvey et al., 2014a), wildfire probability (Kulakowski et al., 2003; Lynch et al., 2006; Kulakowski and Veblen, 2007; Kulakowski and Jarvis, 2011), area burned (Hart et al., 2015b), and fire severity (Bigler et al., 2005; Harvey et al., 2013, 2014b; Andrus et al., 2015). On the Kenai Peninsula, surface-fuel loads of nearly all size classes increased following the outbreak. Duff and moss depth, an indicator of fuel moisture, also decreased (Schulz, 1995, 2003). This suggests that post-outbreak changes in forest structure may differ between boreal and Rocky-Mountain forests in ways that could lead to divergent consequences for subsequent patterns of burning.

The SBB outbreak on the Kenai Peninsula offers a tremendous opportunity to evaluate linked disturbance interactions in the boreal forest and the mediating role of forest-landscape structure. In this paper, we ask: (1) *How did the extent and duration of the 1990s SBB outbreak differ between a homogenous landscape dominated by white spruce and a landscape in which white spruce and black spruce were intermixed?* (2) *How has the occurrence and duration of SBB outbreak influenced the likelihood of subsequent burning in these two landscapes, as compared to other factors?* We hypothesized that the SBB outbreak was not as spatially extensive and of shorter duration in the north where white spruce and black spruce were intermixed. Conversely, we expected the outbreak to be substantially more extensive in the south where white spruce dominated. Despite different outbreak extents and durations, we hypothesized that increased surface fuels would lead to higher probabilities of subsequent burning in both regions.

2. Materials and methods

2.1. Study area

The Kenai Peninsula of south-central Alaska sits south of Anchorage (Fig. 1) and is an ecological transition zone. West of the Kenai Mountains, much of the peninsula is a relatively flat, topographically homogenous plain that lies at the southwestern extent of the physical and ecological conditions characterizing Alaskan boreal forest (Morton et al., 2006). This is where the majority of the SBB outbreak occurred in the 1990s (Fig. 2). On the western Kenai Peninsula, mean annual precipitation varies from 369 mm in the north to 650 mm in the south (1971–2000) (Western Regional Climate Center, 2012). Average annual temperature is approximately 1 °C. The Kenai Peninsula is also one of the most densely populated areas of Alaska, and people increase numbers of ignitions and decrease area burned by suppressing fires in proximity to roads (Calef et al., 2008). To try to minimize confounding influences of people, we limited our analyses of bark-beetle effects on fire to include only forested areas more than 20 km away from the nearest major road. Tree-species composition varies markedly. Interior stands on the Kenai Peninsula are comprised of white spruce with some resin birch (*Betula neoalaskana*) in the south. Black spruce trees dominate the north of the peninsula, with a transition zone in the middle, where black spruce and white spruce are intermixed (Berg and Anderson, 2006). Landscape structure of black spruce and white spruce strongly influence the fire regime. Black-spruce stands are highly flammable with a historical fire return interval of 60–80 years (DeVolder, 1999). White spruce forests have burned much less frequently (fire return intervals of 400–600 years) (Berg et al., 2006). Thus, we stratified our study area by tree species distributions and identified two separate study regions; one north of Tustumena Lake (97,000 ha), where black spruce and white spruce are intermixed, and one south of the lake (133,500 ha), dominated by white spruce (Fig. 1) (Berg et al., 2006).

2.2. Approach and data

To determine how forest-landscape structure mediated SBB outbreak extent and duration and to evaluate effects of SBB outbreak on the likelihood of subsequent burning, we assembled gridded geo-spatial datasets of fire perimeters (2001–2014), occurrence/duration of SBB outbreak (1989–2000), previous fire history (1946–2000), mean decadal (2001–2010) fire-season potential aridity (2001–2009), and information on forest structure (Table 1). All data were resampled using nearest neighbor to ~1 km^2 resolution (chosen because it was the resolution of our coarsest dataset; climate). This yielded 1276 pixels and 1890 pixels in the northern and southern study regions, respectively, that served as observations in analyses.

Fire perimeters between 2001 and 2014 and previous fire history were derived from Alaska Fire Service's Fire History Database (Alaska Fire Service, 2014). Perimeter maps are developed using field and aerial surveys and satellite imagery (Kasischke et al., 2002) The database includes all fires >405 ha since 1946 and all fires >40.5 ha since 1988 (Calef et al., 2015). SBB outbreak and duration between 1989 and 2000 were measured in our study regions using aerial detection surveys from The U.S. Forest Service and Alaska Department of Natural Resource's Alaska Forest Health