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Spatiotemporal dynamics of recent mountain pine beetle and western spruce budworm outbreaks across the Pacific Northwest Region, USA

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ABSTRACT

Across the western US, the two most prevalent native forest insect pests are mountain pine beetle (MPB; *Dendroctonus ponderosae*; a bark beetle) and western spruce budworm (WSB; *Choristoneura freemani*; a defoliator). MPB outbreaks have received more forest management attention than WSB outbreaks, but studies to date have not compared their cumulative mortality impacts in an integrated, regional framework. The objectives of this study are to: (1) map tree mortality associated with MPB and WSB outbreaks by integrating forest health aerial detection surveys (ADS; 1970–2012), Landsat time series (1984–2012), and multi-date forest inventory data; (2) compare the timing, extent, and cumulative impacts of recent MPB and WSB outbreaks across forested ecoregions of the US Pacific Northwest Region (PNW; Oregon and Washington). Our Landsat-based insect atlas facilitates comparisons across space, time, and insect agents that have not been possible to date, complementing existing ADS maps in three important ways. The new maps (1) capture variation of insect impacts within ADS polygons at a finer spatial resolution (30 m), substantially reducing estimated insect extent; (2) provide consistent estimates of change for multiple agents, particularly long-duration changes; (3) quantify change in terms of field-measured tree mortality (dead basal area). Despite high variation across the study region, spatiotemporal patterns are evident in both the aerial survey- and Landsat-based maps of insect activity. MPB outbreaks occurred in two phases – first during the 1970s and 1980s in eastern and central Oregon and then more synchronously during the 2000s throughout dry interior conifer forests of the PNW. Reflecting differences in habitat susceptibility and epidemiology, WSB outbreaks exhibited early activity in northern Washington and an apparent spread from the eastern to central PNW during the 1980s, returning to northern Washington during the 1990s and 2000s. At ecoregional and regional scales, WSB outbreaks have exceeded MPB outbreaks in extent as well as total tree mortality, suggesting that ongoing studies should account for both bark beetles and defoliators. Given projected increases of insect and fire activity in western forests, the accurate assessment and monitoring of these disturbances will be crucial for sustainable ecosystem management.

1. Introduction

Insects are important forest disturbance agents, influencing ecosystem structure, function, and dynamics from local to global scales. Across western North America, native forest insects affect more area annually than wildfire (e.g., Williams and Birdsey, 2003; Littell et al., 2009; Hicke et al., 2013), and, like wildfire, insects have received increasing research and public attention. In addition to their direct effects on forest mortality and succession, insects also influence fuel structure, setting the stage for potential interactions with fire, anthropogenic climate change, and forest management (e.g., McKenzie et al., 2004; Littell et al., 2010; Simard et al., 2011). Different insects vary substantially in their distribution and effects, however, and it is important to contrast the tree mortality impacts of different insect types.

In western North America, the two most prevalent native insects classified as forest pests are mountain pine beetle (MPB; *Dendroctonus ponderosae* Hopkins [Coleoptera: Scolytidae]; a bark beetle) and western spruce budworm (WSB; *Choristoneura freemani* Razowski [Lepidoptera: Tortricidae]; a defoliator) (Williams and Birdsey, 2003). Both insects exhibit cyclic outbreaks associated with endogenous and exogenous factors, including insect population dynamics, host tree vigor and distribution, and climatic

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variability (Sanders et al., 1985; Swetnam and Betancourt, 1998; Raffa et al., 2008; Bentz et al., 2010). Under sustained outbreak conditions, both insects can cause pervasive tree mortality and associated changes in forest structure and composition, although the mechanisms and rates differ (Swetnam and Lynch, 1993; Raffa et al., 2008; Meigs et al., 2011). MPB adults mass attack the stems of pine trees (*Pinus spp*., particularly mature lodgepole pine [*P. contorta* Douglas ex Louden]) to feed on cambium and lay eggs (Goheen and Willhite, 2006; Raffa et al., 2008), inducing variable but relatively rapid tree mortality across large areas (e.g., regional-scale outbreaks in British Columbia and US Rocky Mountains [Meddens et al., 2012]). In contrast, WSB larvae typically consume the current year's foliage of host trees (especially understory true firs [*Abies spp*.], spruces [*Picea spp*.], and Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco]) (Sanders et al., 1985; Goheen and Willhite, 2006; Meigs et al., 2011). Despite these subtler impacts, multiple years of WSB defoliation can result in tree mortality, often in conjunction with secondary bark beetles (Hummel and Agee, 2003; Goheen and Willhite, 2006; Vogelmann et al., 2009). In the US Pacific Northwest Region (PNW; defined here as the states of Oregon and Washington), multiple widespread outbreaks of both insects have occurred in recent decades (Williams and Birdsey, 2003), creating a strong need for a multi-decadal, retrospective analysis of their impacts.

Although numerous studies have assessed the causes and consequences of MPB and WSB from fine to coarse scales (e.g., Swetnam and Lynch, 1993; Simard et al., 2011; Preisler et al., 2012; Meddens et al., 2012), few to date have compared their cumulative impacts at a regional scale (i.e., multiple ecological units, such as ecoregions, or political units, such as states; but see Williams and Birdsey, 2003). This lack of comparison is due in part to defoliators having more gradual effects than bark beetles (e.g., Vogelmann et al., 2009; Meigs et al., 2011); it is also due to a lack of spatiotemporally explicit datasets that quantify the impacts of various agents in consistent units. In this study, we present a novel mapping framework to compare bark beetle and defoliator effects on tree mortality in consistent units, integrating spatially and temporally extensive aerial, satellite, and field data across the PNW.

Here, we suggest that a broad, regional scale (such as the PNW) is essential to elucidate potentially unprecedented changes and emergent patterns. Particularly in the context of global change, it is important to evaluate recent insect outbreaks across spatiotemporal scales that are broad enough to capture multiple outbreaks of the same insect species (e.g., Swetnam and Betancourt, 1998; Meddens et al., 2012; Flower et al., 2014). In addition, a regional framework enables the comparison of multiple insect species, forest types, and emergent impacts not apparent at finer spatiotemporal scales. Moreover, a regional framework may allow researchers and managers to assess whether particular outbreaks are driven by landscape-scale endogenous drivers (e.g., host abundance and distribution, insect population dynamics) or regional-scale exogenous drivers (e.g., climate, synchronous drought stress of host trees). There are very few datasets spanning broad spatial and temporal scales, however, and existing maps have key limitations and uncertainties (Meigs et al., 2011; Meddens and Hicke, 2014). New, regionally extensive but fine-grained maps are necessary to advance our understanding of these insect outbreak phenomena and to provide an ecological basis for emerging restoration frameworks (e.g., Haugo et al., 2015).

In the western US, the most readily available maps to assess landscape and regional insect dynamics are forest health aerial detection surveys (ADS). These surveys provide an unmatched record of insect activity and other forest disturbances and have been collected annually for decades (Williams and Birdsey, 2003). Although valuable for coarse-scale assessments, ADS data have critical uncertainties related to the spatiotemporal variability of methodology, personnel, and observation conditions (Meigs et al., 2011; Preisler et al., 2012; Meddens and Hicke, 2014). More importantly, aerial surveys delineate insect effects within inclusive polygons that contain live trees, creating the appearance of widespread, homogeneous insect activity across entire landscapes and regions, whereas actual insect impacts on tree mortality are highly variable at finer scales (Meigs et al., 2011). In contrast to this potential overestimation of insect *extent* at the regional scale, studies have shown that the ADS units of damage, at least in the case of bark beetles, are a strong underestimate of actual *impacts* at the forest stand scale (Meigs et al., 2011; Meddens and Hicke, 2014). In addition, the ADS emphasis on detecting insect activity in a given year limits the potential to quantify lasting vegetation changes that manifest over multiple years. Finally, aerial surveys characterize different insects in different units (e.g., dead trees per unit area for bark beetles; relative defoliation units for defoliation), hindering their comparison. Thus, complementary geospatial and field datasets are necessary to facilitate regional analysis and address forest management concerns.

In many ways, the Landsat satellite archive represents an ideal complementary dataset. As reviewed by Wulder et al. (2006), Meigs et al. (2011), recent studies have used a variety of remote sensing platforms to map insect disturbance, and Landsat-based approaches show considerable promise for capturing durable vegetation decline and recovery. Due to its moderate spatial resolution (30-m grain), broad temporal scope (1984-present), and consistent, seamless coverage, the Landsat TM sensor captures a variety of disturbance dynamics at forest stand, landscape, and regional scales (Cohen and Goward, 2004; Kennedy et al., 2014). Previous studies have demonstrated wide variability in Landsat spectral responses associated with insect outbreaks (e.g., Vogelmann et al., 2009; Goodwin et al., 2010; Meigs et al., 2011; Meddens et al., 2013). Although more studies have focused on MPB outbreaks (due to their generally more damaging effects; e.g., Wulder et al., 2006; Goodwin et al., 2010; Simard et al., 2011), Landsat imagery has been used to track WSB dynamics as well (Vogelmann et al., 2009; Meigs et al., 2011). Like the ADS data, however, Landsat-based estimates have important limitations. Specifically, satellite data lack any inherent attribution of specific disturbance agents, and the raw reflectance data have limited biological meaning without being linked to ground-based estimates of change (e.g., tree mortality).

Here, we build on a recent pilot study (Meigs et al., 2011), applying new approaches across a much broader area to develop a regional, Landsat-based atlas of insect activity. Our overall goal is to map and compare the effects of two native insects on tree mortality across the PNW Region from 1970 to 2012. Our specific objectives are to: (1) map tree mortality associated with MPB and WSB outbreaks by integrating aerial detection surveys, Landsat time series, and multi-date forest inventory data; (2) compare the timing, extent, and cumulative impacts of recent MPB and WSB outbreaks across the forested ecoregions of Oregon and Washington.

2. Methods

2.1. Study area

The US Pacific Northwest is a geographically diverse region with ecologically, economically, and socially important forest landscapes. Mixed-conifer forests are widespread, and their composition and structure vary across gradients of climate, topography, soil parent material, and disturbance and management history (Franklin and Dyrness, 1973; Hessburg et al., 2000). Although precipitation and temperature regimes vary substantially, a common