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Characterizing recent and projecting future potential patterns of mountain pine beetle outbreaks in the Southern Rocky Mountains

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ABSTRACT

The recent widespread mountain pine beetle (MPB) outbreak in the Southern Rocky Mountains presents an opportunity to investigate the relative influence of anthropogenic, biologic, and physical drivers that have shaped the spatiotemporal patterns of the outbreak. The aim of this study was to quantify the landscape-level drivers that explained the dynamic patterns of MPB mortality, and simulate areas with future potential MPB mortality under projected climate-change scenarios in Grand County, Colorado, USA. The outbreak patterns of MPB were characterized by analysis of a decade-long Landsat time-series stack, aided by automatic attribution of change detected by the Landsat-based Detection of Trends in Disturbance and Recovery algorithm (LandTrendr). The annual area of new MPB mortality was then related to a suite of anthropogenic, biologic, and physical predictor variables under a general linear model (GLM) framework. Data from years 2001–2005 were used to train the model and data from years 2006–2011 were retained for validation. After stepwise removal of non-significant predictors, the remaining predictors in the GLM indicated that neighborhood mortality, winter mean temperature anomaly, and residential housing density were positively associated with MPB mortality, whereas summer precipitation was negatively related. The final model had an average area under the curve (AUC) of a receiver operating characteristic plot value of 0.72 in predicting the annual area of new mortality for the independent validation years, and the mean deviation from the base maps in the MPB mortality areal estimates was around 5%. The extent of MPB mortality will likely expand under two climate-change scenarios (RCP 4.5 and 8.5) in Grand County, which implies that the impacts of MPB outbreaks on vegetation composition and structure, and ecosystem functioning are likely to increase in the future.

Introduction

As a native species, mountain pine beetle (*Dendroctonus ponderosae*; MPB) populations have existed at endemic levels and periodically have grown to epidemic levels in the pine forests of western North America for centuries (Amman, 1977; Baker & Veblen, 1990; Raffa et al., 2008). By infesting and killing older and stressed trees with larger diameters, MPB plays a critical role in shaping forest composition and structure, accelerating the movement of nutrients in biogeochemical cycles, and affecting forest productivity (Collins, Rhoades, Hubbard, & Battaglia, 2011; Edburg et al., 2012). In recent decades this historical balance has been disrupted, and the area affected by MPB has been vastly extended, exceeding the extent and impacts of outbreaks documented in the past 125 years (Raffa et al., 2008). The current MPB outbreak has impacted large expanses of lodgepole and ponderosa pine forests, reduced their ability to act as carbon sinks (Caldwell, Hawbaker, Briggs, Cigan, & Stitt, 2013; Kurz et al., 2008; Running, 2008), altered wildfire hazards (Hicke et al., 2012; Jenkins, Hebertson, Page, & Jorgensen, 2008; Parker, Clancy, & Mathiasen, 2006; Schoennagel, Veblen, Negron, & Smith, 2012), modified local surface energy balance (Boon, 2009), threatened water quality (Mikkelson et al., 2013), and changed regional climate (Maness, Kushner, & Fung, 2013).

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The population dynamics of bark beetles are governed by a variety of biotic and abiotic factors and their interactions (Raffa et al., 2008). Forest characteristics, including homogenous even-aged, high-density, and large-diameter stands, are favorable for MPB mass attack (Raffa & Berryman, 1983). Long-term drought or other events causing stress can exert either positive or negative effects on tree susceptibility to beetle attack, and the overall impact remains controversial. While the primary defense mechanism of trees will be weakened by drought stress because of reduced resin quantities (Creeden, Hicke, & Buotte, 2014; Preisler, Hicke, Ager, & Hayes, 2012; Raffa et al., 2008), beetle brood production can also be reduced since the tree's phloem thickness is attenuated (Amman & Cole, 1983). Thermal regimes, typically represented by minimum winter temperature or year-round temperature, impact beetles' developmental timing, cold-induced mortality, and the associated fungal community (Bentz et al., 2010; Preisler et al., 2012). Meanwhile, factors like elevation, direct solar radiation, and beetle mortality in adjacent areas have also been indicated as important predictors of outbreaks (Coops, Wulder, & White, 2006; Simard, Powell, Raffa, & Turner, 2012; Walter & Platt, 2013; Wulder, White, Bentz, Alvarez, & Coops, 2006). Most previous studies have focused on the effects of one or several factors. In this study, we took a comprehensive approach and considered a large set of relevant factors to improve our understanding of the spatiotemporal patterns of MPB outbreaks and investigate their drivers.

For this study, we were also concerned about the identification of forested areas with high risk for future MPB mortality. There have been a number of prior efforts to predict patterns of MPB mortality. Through an integrated seasonality and cold tolerance model, Bentz et al. (2010) suggested that rising temperatures could increase MPB population growth rates, and their range would expand along latitude and elevation gradients. Aided by an ecological niche model, Evangelista, Kumar, Stohlgren, and Young (2011) predicted that new areas of forest susceptible to MPB mortality would emerge over time but the existing area of susceptible forests to MPB mortality would also shrink, leading to an overall decrease in the amount of suitable habitat area for MPB in the future. Using a process-based model, Hicke, Logan, Powell, and Ojima (2006) found that projected warming in the western United States will result in substantial reductions in the overall area of adaptive seasonality (the synchronous emergence of adults that allows MPB to overwhelm tree defenses). Unlike population models, which can improve the mechanistic understandings of biological responses to environmental variability, but may consider a limited number of explanatory variables because of model complexity, statistical approaches are capable of incorporating a large number of explanatory variables and quantifying their relative roles. This is a crucial preliminary step before adopting and improving process-based mechanistic models.

Understanding the factors driving patterns of MPB outbreaks and predicting future outbreaks has been challenging given the types of data available that depict the spatial and temporal extents of outbreaks. The quality of response variables could affect the performance of predictive models. In general, locations of MPB mortality are collected in the field or extracted from remotely sensed imagery. Although in-situ surveys can provide accurate data, they often have restricted geographic and temporal coverage. State and federal agencies have conducted Forest Health Monitoring Aerial Detection Surveys (ADS) to identify forest disturbances since the mid-twentieth century (Man, 2010). These publicly available datasets have been used extensively in many fields, but errors introduced via observer fatigue, observer-to-observer variation, misregistration and the scale of observation (Meigs, Kennedy, & Cohen, 2011) are rarely estimated and could introduce an unknown amount of uncertainty.

Remote sensing of forest disturbances offers an alternative to the ADS data for monitoring tree mortality caused by insect outbreaks (Coops et al., 2006; White, Wulder, Brooks, Reich, & Wheate, 2004). Landsat data are especially popular for this application because they are freely available, and have multispectral data, a broad spatial extent, and temporal continuity. For these reasons, Landsat time series stacks (LTSS) have been used in large-scale efforts to detect forest disturbances (Masek et al., 2013) using the Vegetation Change Tracker algorithm (VCT; Huang et al., 2010). Remotely sensed disturbance maps produced by VCT and similar change-detection algorithms like the Landsat-based Detection of Trends in Disturbance and Recovery algorithm (LandTrendr; Kennedy, Yang, & Cohen, 2010) currently lack information about the cause of the disturbance, and that limits their utility for use in our study. Notwithstanding, several studies have demonstrated the usefulness of Landsat in capturing the patterns of MPB-caused tree mortality at various geographic scales (e.g. Masek et al., 2013; Meddens, Hicke, Vierling, & Hudak, 2013). Considering the uncertainties in the ADS data, and limitations of existing VCT and LandTrendr change-detection products, we utilized data from an automated procedure that labeled disturbance types (especially MPB mortality) detected by LandTrendr in an LTSS to generate spatially explicit annual maps of MPB occurrences over a decade-long time span (Liang, Chen, Hawbaker, Zhu, & Gong, 2014).

In this paper, we integrated remote sensing techniques and statistical models to evaluate the effects of a set of factors affecting the dynamic pattern of MPB mortality, and projected future MPB mortality in response to climate change. Our aim was to address the following questions: What drivers promote the extensive development and progressive MPB outbreak in an area situated in the Southern Rocky Mountains ecoregion? How accurately can we predict MPB disturbance with this set of response and explanatory variables? And what will future outbreak trends be?

Methods

Study area

Grand County is located in north central Colorado, covering approximately 4830 square kilometers of the Southern Rocky Mountains ecoregion (Fig. 1). The elevation ranges from 2225 m along the Colorado River to 4131 m at the summit of the Continental Divide (Grand County Department of Natural Resources, 2006). Its climate is characterized by year-round sunny days (around 244 days/year on average), with average summer temperatures of 26.6 °C, and the average rainfall of approximately 30.48 cm (Grand County Department of Natural Resources, 2006). The diversity of elevation, soil, climate, as well as strong topographic-moisture gradients leads to a variety of vegetation composition within the county, among which sagebrush shrub and steppe is the most dominant ecosystem. Lodgepole pine forests occupy a quarter of the landmass, followed by spruce-fir forests and aspen forests (Grand County Department of Natural Resources, 2006). In recent decades, MPB infestation, wildfire, and timber harvesting are recognized as the three major disturbance agents in Grand County. Wildfire occurrence has been low, but the widespread MPB outbreak affected approximately 68% of privately owned land and 70% of federally owned land (Witcosky, 2007).

Change detection analysis in detecting long-term MPB outbreaks

Maps of MPB mortality in Grand County were generated by automatic attribution of LandTrendr segmentation outputs applied to a time series of 17 Landsat images spanning 2000–2011 (path 34, row 32; Liang et al., 2014). This approach integrated a temporal