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Spatial and temporal patterns of Landsat-based detection of tree mortality caused by a mountain pine beetle outbreak in Colorado, USA

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ABSTRACT

Mountain pine beetles (*Dendroctonus ponderosae* Hopkins) have killed billions of trees in the United States and Canada in the last decades, thereby causing major alterations to forest ecosystems. Therefore, monitoring the extent and patterns of these major disturbance events are important for subsequent forest management. At 30-m spatial resolution, Landsat imagery affords the opportunity for quantifying spatial and temporal patterns of bark beetle outbreaks at plot to stand resolution. We developed a continuous measure of bark beetle-caused tree mortality using multi-temporal Landsat data (1996–2011) in the Rocky Mountains of northcentral Colorado. We report the year of detection of tree mortality, which is 1 year after attack by beetles. Two approaches were used to predict percent red stage tree mortality within a 30-m grid cell, multiple linear regression models and generalized additive models (GAM) with a nonlinear spatial term. Both models explained >75% of the variance using three Landsat spectral explanatory variables. We used the linear model to predict tree mortality across the entire study area and time series because of its simplicity, its capability for extrapolation beyond the training area, and similar performance compared with the GAM. From 1996 to 2011, cumulative tree mortality was 22% of forested areas within the Landsat scene, equivalent to 228 million mature lodgepole pine trees (range: 174–332 million trees using the 95% confidence interval of field-measured crown areas). Early in the outbreak, tree mortality was associated with expansion, whereas later in the outbreak, mortality was due to intensification (increase in mortality within areas already having beetle activity). We used three metrics (cumulative tree mortality, duration of tree mortality, and average rate of tree mortality) to investigate the temporal and spatial patterns of bark beetle-caused mortality using different grid cell resolutions within the Landsat scene. At the Landsat spatial resolution (900 m^2), we estimated that grid cells within the outbreak experienced means of 60% mortality, a duration of 3–4 years, and an average rate of mortality of 20%/year. With coarser spatial resolution, cumulative tree morality and rate of tree mortality decreased whereas duration of tree mortality increased. Our results improve the understanding of spatial and temporal patterns of tree mortality caused by bark beetle outbreaks, and provide specific information for forest managers and scientists about a severe mountain pine beetle infestation in northcentral Colorado.

1. Introduction

The mountain pine beetle (*Dendroctonus ponderosae* Hopkins) is one of the most destructive bark beetles in western North America and has killed billions of trees in the United States and Canada in the last few decades (Meddens et al., 2012). Bark beetle-caused tree mortality modifies forest successional patterns (Sibold et al., 2007), alters forest fuel arrangements (Jenkins et al., 2008; Simard et al., 2011; Hicke et al., 2012), changes water yield and peak snowpack levels (Biederman et al., 2012; Pugh and Gordon, 2012; Pugh and Small, 2012), and reduces carbon uptake by decreasing primary production of live trees (Kurz et al., 2008; Pfeifer et al., 2011) and increasing heterotrophic respiration (Edburg et al., 2011; Moore et al., 2013). Therefore, documenting spatial and temporal patterns of insect disturbances are important for understanding ecosystem impacts and formulating management strategies, e.g., mitigating tree hazards, decreasing immediate crown fire hazard, and utilizing materials from beetle-killed forests (USDA Forest Service, 2011).

Approaches to study landscape-scale patterns of beetle-caused tree mortality include aerial survey by observers in plane (USDA Forest Service, 2012), oblique aerial photography (Macfarlane

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et al., 2013), and digital remote sensing (Wulder et al., 2006a). For bark beetle outbreaks, these methods rely on a typical progression of trees following attack. In the case of mountain pine beetles, water transport in the host tree shuts down rapidly, leading to reduced carbon uptake and eventually tree death (Edburg et al., 2012). The following spring/summer the moisture content of the needles of the killed trees are reduced and the needles start to turn red (red stage). In the years following the start of the red phase, the needles drop to the ground, and when no needles remain (3–5 years) the trees are in the gray stage (Wulder et al., 2006a). In the subsequent decades the killed trees fall to the ground and the forest recovers, leading to increased productivity as well as heterotrophic respiration (Edburg et al., 2011).

Remote sensing images from satellite and aerial platforms have successfully been employed to assess extent and patterns of insect-caused tree mortality in the red stage (e.g., Franklin et al., 2003; Coops et al., 2006; White et al., 2007), and more recently the gray stage (e.g., Dennison et al., 2010; Meddens et al., 2011). High-resolution imagery (such as QuickBird and IKONOS sensors) have the capability to detect tree mortality close to the spatial resolution of an individual tree but have often limited spatial coverage, whereas medium- and coarse-resolution imagery (such as Landsat and the Moderate Resolution Imaging Spectroradiometer (MODIS)) detect tree mortality at the stand/landscape scale and have wider spatial coverage. Currently, many forest disturbance detection methods using Landsat imagery produce categorical classifications identifying regions of undisturbed forest and insect-caused mortality, and sometimes include other classes (such as herbaceous, bare soil, water, etc., Franklin et al., 2003; Wulder et al., 2005). However, few studies to date include information on the severity of the disturbance (e.g., the amount of red stage) within a grid cell. A recent study showed that Landsat data could be used for prediction of continuous tree mortality within a pixel as opposed to a categorical classification (Meigs et al., 2011), providing a more sensitive characterization of outbreak dynamics.

Temporal dynamics from bark beetle outbreaks are often described as having four stages, including endemic, incipient-epidemic, epidemic (i.e., outbreak), and post-epidemic stages (Safranyik and Carroll, 2006). However, few studies quantify the duration of tree mortality within an area larger than a stand. Bark beetle-caused tree mortality lasted approximately 6 years within two stands (two-square mile units) in the Teton National Forest and Teton National Park in northwestern Wyoming (Cole and Amman, 1980), with bark beetles attacking progressively smaller diameter trees. Past outbreaks in western Canada have lasted on average 8–9 years with a possible minimum of 4 and a maximum of 18 years (Safranyik et al., 1974). Significantly, no study to date has assessed temporal patterns of tree mortality across larger spatial extents. Doing so will provide an improved characterization of the variability of outbreak dynamics. Yearly medium-resolution satellite observations provide an opportunity to study these temporal characteristics (e.g., Meigs et al., 2011; Walter and Platt, 2013).

Spatial patterns of bark beetle outbreaks have been described from the stand level (Mitchell and Preisler, 1991; Nelson et al., 2014) to the regional level (e.g., the entire province of British Columbia, Canada (Aukema et al., 2006; Chen, 2013). Aerial surveys in the US and Canada document forest disturbance at regional to national scales (USDA Forest Service, 2012), and are used by managers and scientists to assess damage in forests. When used in quantitative ecological studies, these surveys are subject to uncertainty for three reasons. First, the unknown locations of damaged trees within recorded polygons makes assessing year-to-year dynamics difficult at stand scales. Second, the subjective nature of the surveys confers uncertainty (Meddens et al., 2012). Third, although flown in many regions annually, aerial surveys may not regularly cover national parks or wildernesses. Satellite remote sensing studies offer the opportunity for accurate and repeated mapping of tree mortality, and Landsat-resolution (30-m) imagery may be useful for studying mortality dynamics within stands. However, past studies have focused on developing and evaluating methods (e.g., Meigs et al., 2011; Wulder et al., 2006b; White et al., 2005); to date, no Landsat-based studies have quantified spatial and temporal patterns of beetle-caused tree mortality at the scale of an outbreak.

The mountain pine beetle outbreak in Colorado has gained much attention recently. Warmer conditions and anomalously dry years in 2001 and 2002 have been linked to the outbreak (Chapman et al., 2012; Creeden et al., 2014). Based on aerial survey information, mountain pine beetle-caused tree mortality in Colorado peaked in 2008 with 1.15 million ha affected (USDA Forest Service, 2009) and, although newly affected areas are decreasing, tree mortality is now occurring in the lower-elevation ponderosa pine forests on the eastern side of the Rocky Mountains near densely populated areas (USDA Forest Service, 2012). In 2010, the US Forest Service allocated approximately $30 million for mitigating impacts of the mountain pine beetle outbreak in the Rocky Mountain region.

Our objectives were (1) to develop methods to produce a continuous measure of bark-beetle caused tree mortality (a) that can be extrapolated to regions outside of the area of our reference data and over a longer period, and (b) whose predictions contain information about the severity of tree mortality within the grid cell; and (2) analyze spatial and temporal patterns of tree mortality in northcentral Colorado created by applying the continuous measure of tree mortality developed in the first objective. We developed regression models from Landsat imagery to predict percent tree mortality caused by bark beetles, taking advantage of an existing fine-resolution classification of tree mortality for model building and evaluation. We then applied the model to a Landsat scene in northcentral Colorado in 1996–2011 and quantified mortality patterns in time and space at scales from an individual 30-m grid cell to the entire Landsat scene ($\sim$10,000 ha). We report tree mortality at the year of detection rather than the year of beetle attack, which occurs 1 year earlier based on a 1-year life cycle of mountain pine beetle. This study extends our past Landsat-based research in this study area (Meddens et al., 2013) by developing a model of continuous tree mortality and by analyzing spatial and temporal patterns of tree mortality.

2. Methods

2.1. Study area

The study area is located in northcentral Colorado and in southern Wyoming (Fig. 1). The overlapping footprint of 16 years of Landsat images of Path 34/Row 32 (Worldwide Reference System 2) delineated the study area. The topography ranged from high-elevation (alpine) mountains to the plains east of the Rocky Mountains. Forests within the study area included: (a) mixed conifer forest at the higher elevations (with tree species such as Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*) and limber pine (*Pinus flexilis*)); (b) lodgepole pine (*Pinus contorta*) and occasional aspen (*Populus tremuloides*) at middle elevations; and (c) ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) at lower elevations. The average annual precipitation is 51.6 cm (1971–2000), with average annual maximum and minimum temperatures of 9.8 and −10.2 °C (Western Regional Climate Center, Frasier station, elevation 2609 m; http://www.wrcc.dri.edu; accessed 6 April 2009). The study area location was chosen because of an extensive