Remote Sensing of Environment 168 (2015) 134–145

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Detection of spruce beetle-induced tree mortality using high- and medium-resolution remotely sensed imagery

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ARTICLE INFO

Article history:
Received 24 April 2014
Received in revised form 2 June 2015
Accepted 18 June 2015
Available online 14 July 2015

Keywords:
Bark beetle
Landsat
NAIP
Aerial imagery
Support vector machine

ABSTRACT

Outbreaks of bark beetles cause widespread tree mortality, which have important consequences for wildlife, forest composition and structure, timber production, and water resources. Recent severe, extensive, and synchronous bark beetle outbreaks have motivated research into methods for surveying the location, extent, and attack stage of outbreak using remotely sensed data. In this paper, we adapt methods for classing mountain pine beetle-induced tree mortality to detect spruce beetle-induced tree mortality from single-date high-resolution imagery and multi-date moderate-resolution data. We use freely available aerial imagery from the National Agriculture Imagery Program (NAIP) to produce a tree-scale map of gray-stage spruce beetle kill across a broad spatial extent. This map was then used to train a stand-scale classification of spruce beetle outbreak from Landsat Climate Data Record (CDR) data. Gray-stage spruce beetle outbreak was characterized by higher values of the red–green index (RGI) at the tree-level. At the stand-level, gray stands were associated with high values of a Disturbance Index (DI) and low values of the Normalized Difference Vegetation Index (NDVI). Both tree- and stand-scale classifiers of spruce beetle-attributed tree mortality were highly accurate (overall accuracy and user's accuracy for gray trees/stands greater than 88%). Stand-level classification improved with post-classification correction, which removed high-frequency year-to-year variability in forest condition. Comparison of high-resolution and moderate-resolution classified imagery revealed variable amounts of tree mortality occur in areas of landscape-scale spruce beetle outbreak. Our results highlight the utility of both ecologically informed post-classification correction and coupling fine-scale and moderate-scale resolution imagery for mapping and studying spruce beetle outbreaks.

1. Introduction

During the late 20th and early 21st centuries, severe and extensive bark beetle outbreaks have caused dramatic tree mortality from Alaska to the Southwestern US (Bentz et al., 2009; Meddens, Hicke, & Ferguson, 2012). Across the western US, tree mortality and damage is currently assessed by the United States Forest Service using Aerial Detection Surveys (ADS). ADS data provides a rough estimate of bark beetle-induced tree mortality at a broad-scale (minimum mapping unit 5 ha) for select areas of National Forest land (Johnson & Wittwer, 2008). Spatiotemporal gaps in ADS data, relatively high data collection costs ($0.25/ha; Johnson & Wittwer, 2008), and only moderate agreement between ADS data and ground reference data (68% agreement with a 50 m spatial tolerance; Johnson & Ross, 2008) are among the key limitations of relying on ADS data to assess bark beetle outbreaks. These limitations in conjunction with the severity, broad spatial extent and synchrony of recent outbreaks has promoted research into methods for surveying the location, extent, and attack stage of bark beetle outbreak using remotely sensed data (Coops, Johnson, Wulder, & White, 2006; DeRose, Long, & Ramsey, 2011; Franklin, Wulder, Skakun, & Carroll, 2003; Meddens, Hicke, Vierling, & Hudak, 2013; Skakun, Wulder, & Franklin, 2003; White, Wulder, Brooks, Reich, & Wheate, 2005; Wulder, White, Bentz, Alvarez, & Coops, 2006).

Across the Southern Rocky Mountains, mountain pine beetle (*Dendroctonus ponderosae*) and the spruce beetle (*Dendroctonus rufipennis*) have caused most of the bark beetle-related damaged (Ciesla, 2013). While remote sensing of mountain pine beetle-induced tree mortality has proven successful particularly in lodgepole pine-dominated forests (Goodwin et al., 2008; White et al., 2005), remote sensing studies of spruce beetle-caused tree mortality are relatively limited and there is no consensus on the most effective detection methods (DeRose et al., 2011; Johnson, Greenfield, & Munson, 1997; Makoto, Tani, & Kamata, 2013). Further, from 2009 through 2014, the area affected by spruce beetle in Colorado grew rapidly (46,000 ha in 2009 and 196,000 ha in 2014; Ciesla, 2011; USFS, 2015). Thus there is an increased need for developing methods for remote sensing of spruce beetle-induced tree mortality, which may allow scientists and managers to better study the causes and consequences of spruce beetle outbreak.

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http://dx.doi.org/10.1016/j.rse.2015.06.015
0034-4257/

The spruce beetle is one of the most damaging forest insects in North America, where it can lead to mortality of greater than >90% of mature spruce within a stand (DeRose & Long, 2007; Hopkins, 1909). Spruce beetles predominantly feed upon Engelmann spruce (*Picea engelmannii*), white spruce (*Picea glauca*), Sitka spruce (*Picea sitchensis*), and Lutz spruce (*Picea* × *lutzii*) (Bentz et al., 2009). In the Southern Rocky Mountains (i.e. southern Wyoming to northern New Mexico), spruce beetles are found in high elevation Engelmann spruce and subalpine fir (*Abies lasiocarpa*) forests. The spruce beetle inhabits the inner bark and feeds on the tree's phloem tissues. Heavy colonization and reproduction within the inner bark interrupts the flow of water and nutrients throughout the tree and typically causes tree death. Endemic populations typically live in recently downed and weakened trees. Outbreaks occur as beetle populations grow and start attacking seemingly healthy spruce (Massey & Wygant, 1954; Schmid & Frye, 1977).

While methods for remotely sensing mountain pine beetle-induced tree mortality may inform methods for mapping spruce beetle-induced mortality, species-specific differences in the spectral signatures that accompany tree death and forest structure and composition require these methods to be adapted and tested. Several knowledge gaps exist that limit our ability to use satellite imagery to study spruce beetle-induced tree mortality. First, limited information is available about the spectral signature of spruce beetle killed trees and affected stands. Like other bark beetle-affected trees, the spectral signature of spruce beetle-killed trees is expected to change with increasing time since initial infestation (Wulder, Dymond, White, Leckie, & Carroll, 2006). Analogous to mountain pine beetle infestation, in the initial stages of spruce beetle-infestation there are no visual signs of infestation (i.e. needles remain green, “green stage”). During this initial stage of infestation, foliar moisture content declines in both mountain pine beetle and spruce beetle-affected trees (Jolly et al., 2012; Page & Jenkins, 2007). This leads to decreased reflection in near infrared (NIR) wavelengths and increased reflection in shortwave infrared (SWIR) wavelengths (Cheng, Rivard, Sánchez-Azofeifa, Feng, & Calvo-Polanco, 2010; Wulder, Dymond, et al., 2006; Wulder, White, et al., 2006). Following initial infestation, the needle color of attacked spruce beetle-attacked trees slowly fades from green to yellow-green over the course of one year (Johnson et al., 1997). This is in stark contrast to mountain pine beetle-attacked trees, which turn red one year following infestation (“red stage”; Wulder, Dymond, et al., 2006; Wulder, White, et al., 2006). About two years following attack, spruce beetle-killed trees drop their needles and twigs become exposed in the upper crown, giving the tree a reddish-gray color, (“gray stage”; Schmid & Frye, 1977). Most remote sensing studies of mountain pine beetle infestation have focused on identifying red-stage infestation, not the gray stage, limiting the transfer of methods for remotely sensing mountain pine beetle killed-trees to spruce beetle-killed trees. At the stand-scale, subalpine forests of lodgepole pine typically consist of a single tree species forming homogeneous patches of similarly aged trees across large areas (Sibold, Veblen, & González, 2006). In contrast, spruce beetle affected forests typically consist of two or more dominant tree species usually represented by multi-aged and multi-sized populations (Veblen, Hadley, Reid, & Rebertus, 1991). Thus spectral signature of spruce beetle infestation at moderate resolutions may be more diluted by an abundance of young and non-host trees.

Second, spruce beetle-induced tree mortality occurs at three distinct spatial scales: tree (square meters), forest stands (hectares), and landscapes (square kilometers) (Raffa et al., 2008). These distinct spatial scales arise from complex interactions between spruce beetle and tree host populations. Transitions among scales arise from complex tree-to-beetle, beetle-to-tree and beetle-to-beetle interactions resulting in amplifying positive feedbacks (Raffa et al., 2008). Forest stand-scale mortality may transition to a landscape-scale outbreak when a combination of factors are present: 1) abundant susceptible large host trees (Schmid & Frye, 1977), 2) high beetle population density (Raffa et al., 2008), 3) warm and dry weather (Berg, David Henry, Fastie, De Volder, & Matsuoka, 2006; DeRose & Long, 2012; Hart, Veblen, Eisenhart, Jarvis, & Kulakowski, 2014; Hebertson & Jenkins, 2008), and 4) low beetle predation (Berryman, 1982). Thus the appropriate spatial grain and extent for detecting spruce beetle kill depends on the spatiotemporal state of infestation. However, detailed information about the spatiotemporal progression spruce beetle infestation is extremely limited.

Previous efforts to detect spruce beetle-induced tree mortality have used a high (2.4 m; Makoto et al., 2013) or moderate (30 m; DeRose et al., 2011) spatial resolution. High resolution imagery (<5 m) provides spatial detail at the tree-scale, which can provide important information on tree-scale infestation patterns and severity of outbreak (e.g. mortality/survivorship of individual trees; Coops et al., 2006; Meddens, Hicke, & Vierling, 2011). However, high resolution imagery often yields more variable reflectance values within one cover type (Dennison, Brunelle, & Carter, 2010; Wulder, Dymond, et al., 2006), and rarely covers a broad area (Wulder, Dymond, et al., 2006; Wulder, White, et al., 2006). In addition, the time period of record is often short and imagery may not be regularly repeated (Jensen, 2007). In contrast, remotely sensed data collected at a moderate resolution (ca. 30 m) is typically multispectral, publically available, frequently repeated, and broad in spatial extent (Cohen & Goward, 2008). Regularly repeated imagery can be used to identifying changes in reflectance that indicate vegetation has been removed or died, which may improve classification accuracy of bark beetle infestation where the spectral signature of infestation may be diluted by uninfested host trees and non-host cover. Further post-classification correction informed by the ecological process of interest (here tree mortality) can be used to improve classification accuracy (Wulder, Dymond, et al., 2006).

Given the importance of cross-scale interactions in spruce beetle outbreak dynamics (Raffa et al., 2008), coupled high tree-scale (high resolution) and stand-scale (moderate resolution) maps of outbreak have the potential to offer important insights into the spatial and temporal patterns of spruce beetle infestation. Better understanding of the spatial and temporal patterns of spruce beetle infestation is key to understanding and predicting the transitions between different states of spruce beetle infestation. Moreover, to our knowledge, high and moderate resolution patterns of spruce beetle activity have not been compared.

To address the most critical of these knowledge gaps, we explore the use of a machine learning pixel-based classifier to detect spruce beetle-induced tree mortality from single-date high-resolution imagery and multi-date moderate-resolution data. Our objectives are (1) to adapt methods for classifying mountain pine beetle-infested trees for classifying spruce beetle-infested trees from freely available high-resolution aerial imagery; (2) to adapt methods for classifying red stage mountain pine beetle-infested stands for classifying gray stage spruce beetle-infested stands from multi-date Landsat imagery; and (3) analyze spatial and temporal patterns of spruce beetle-induced tree mortality using the high-resolution and moderate-resolution maps of spruce beetle infestation created in objectives one and two.

2. Methods

2.1. Study area

The study area was located in southwestern Colorado (Fig. 1). The area was chosen because it is the location of a landscape-scale spruce beetle outbreak, which began in the early 2000s (Lewis, Wardle, Leatherman, & Duda, 2003). Specifically, the study area is the spruce–fir zone of eastern San Juan Mountains and extends from ca. 38.1 to 37.4°N and 106.6 to 107.6°W. Elevation across the study area ranges from 2170 to 4283 m with 68% of the study area located between 3070 and 3490 m asl. The climate record (1981–2010) at Wolf Creek Pass (3243 m), which is located in the center of the study area (Fig. 1), lists total annual precipitation as 116 cm and average monthly