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Spectral evidence of early-stage spruce beetle infestation in Engelmann spruce

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ABSTRACT

Spruce beetle (*Dendroctonus rufipennis* (Kirby)) outbreaks cause widespread mortality of Engelmann spruce (*Picea engelmannii* (Parry ex Engelm)) within the subalpine forests of the western United States. Early detection of infestations could allow forest managers to mitigate outbreaks or anticipate a response to tree mortality and the potential effects on ecosystem services of interest. However, the subtle changes in the foliage of infested spruce make early detection difficult. An experiment was conducted in southern Colorado to determine important wavelengths for detecting early-stage (i.e. recently infested) spruce beetle infestation in Engelmann spruce. Spectral reflectance from non-infested and recently infested spruce needles were obtained using the ASDi Field-Spec Pro spectroradiometer. After pre-processing, random forest analysis was used to identify hyperspectral bands and aggregations of hyperspectral bands corresponding to Landsat TM bands and vegetation indices that effectively discriminated between non-infested and infested trees. Results show that the shortwave infrared region of the electromagnetic spectrum was a key area for detecting early stages of spruce beetle infestation, likely due to the effects of beetle infestation on water transport within Engelmann spruce. The strong discriminability of bands in the shortwave infrared region indicates a potential for this spectral region to be used to detect early-stage spruce beetle infestation over larger areas using multispectral satellite imagery. In a preliminary trial, we found that a time series of reflectance in Landsat TM band 7 (shortwave infrared) was strongly correlated with the progression through time of a spruce beetle outbreak in southern Wyoming. These findings suggest that multispectral indicators of early-stage spruce beetle outbreak can be developed. These indicators are needed to better understand spatiotemporal dynamics of spruce beetle outbreaks, and can be used by forest managers to detect early stages of spruce beetle infestation and to potentially mitigate some spruce mortality.

1. Introduction

The spruce beetle (*Dendroctonus rufipennis* (Kirby)) is an important mortality agent of spruce species (*Picea* spp.) throughout the western United States and Canada (Bentz et al., 2010). Within the subalpine forests of the southern Rocky Mountains, its primary host is Engelmann spruce (*Picea engelmannii* (Parry ex Engelm)) (Bebi et al., 2003; Schmid and Frye, 1972). Historically, spruce beetle infestations, along with fire, have been the most important natural disturbances shaping forest structure and function in subalpine forests, and both of these agents are anticipated to increase under a warming climate (Bentz et al., 2010; DeRose and Long, 2012; Hart et al., 2014; Veblen et al., 1991; Westerling et al., 2006). Bark beetle outbreaks have caused widespread tree mortality across the US and Canada in the last several decades, especially in Colorado (Bentz et al., 2009; Berg et al., 2006). In a Colorado outbreak lasting from 1939 to 1952, spruce beetles affected over 290,000 ha of the landscape (Anderson et al., 2010; Veblen et al., 1991), and an ongoing outbreak in Colorado has affected over 638,000 ha between 1996 and 2015 (USFS, 2016). These landscape-scale mortality events modify the size structure and

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species composition of forests, especially in terms of basal area, average tree height, and stem density (Derderian et al., 2016; Hawkins et al., 2012; Humphreys and Safranyik, 1993). Biogeochemical cycling in forests is also affected by bark beetle outbreaks, through reduction in stomatal conductance and canopy transpiration (Edburg et al., 2012; Frank et al., 2014), increases in leaf litter and coarse woody debris (Edburg et al., 2012; Meddens et al., 2012), and changes in the carbon balance of the forest (Brown et al., 2012; Edburg et al., 2012; Kurz et al., 2008).

Detection and monitoring of bark beetle outbreaks is crucial to forest management and to deciphering the ecological effects of these organisms. The effects of beetle infestations may be mitigated through various management techniques such as clearing of wind thrown trees, selective thinning, pheromone trapping, and burning (Hansen et al., 2010; Humphreys and Safranyik, 1993; Kautz et al., 2011), especially if these infestations are detected early on in the outbreak cycle (DeRose and Long, 2012; Jenkins et al., 2014). Perhaps more importantly, the relative success of forest treatments as well as the mechanisms and environmental characteristics that lead to outbreaks can be investigated through detection and monitoring of infestation stage and extent (Walter and Platt, 2013).

Aerial detection surveys are often used to assess mortality trends caused by bark beetles (USFS, 2016). Bark beetle-killed trees change in coloration as they desiccate, from green to yellow-green, and with some species to a bright red, and this color change is used as an indicator to map tree mortality. However, this visual detection is not possible in the early (i.e. green) stages of infestation, potentially too late to be helpful for effective management techniques (Franklin et al., 2003). In the case of the closely related mountain pine beetle (*Dendroctonus ponderosae* (Hopkins)), which in the Rocky Mountains infests several *Pinus* species, the foliage of infested trees changes to bright red within one year of being attacked (White et al., 2007). The foliage of spruce beetle-infested Engelmann spruce, however, remains green to yellow-green and photosynthesizing (albeit only slightly) for two or more years after the initial infestation (DeRose et al., 2011; Frank et al., 2014; Schmid, 1976). This several year window of green-stage spruce beetle attack when beetle populations are growing, but detection is difficult, may allow for spruce beetle outbreaks to reach unmanageable levels. Additionally, while aerial surveys are relatively cost-effective for the amount of forest health characteristics that they can provide, and are useful for portraying trends in insect and disease activity, the information is generally at a coarse spatial scale, and may have low positional accuracy (Hall et al., 2016; Wulder et al., 2006c).

In comparison to aerial surveys, remote sensing may allow for more extensive, consistent, and finer-resolution mapping of bark beetle damage, as well as early detection of beetle infestation. To be useful for effective and timely management planning and ecosystem response studies, however, pertinent areas of the electromagnetic spectrum for detecting early-stage spruce beetle infestations must be determined. Many studies have used remote sensing instruments to detect red-stage, and to a lesser extent, green-stage mountain pine beetle outbreaks across a broad range of its hosts, but with varying conclusions on the best waveband or vegetation index to use (Coops et al., 2006a; Franklin et al., 2003; Hall et al., 2016; Meddens and Hicke, 2014; Niemann et al., 2015; Skakun et al., 2003; White et al., 2007, 2005; Wulder et al., 2006a, 2006b). Goodwin et al. (2008) were able to identify red-stage infestation across a large study area (~1.5 million ha) in British Columbia, Canada using Landsat imagery and the normalized difference moisture index (NDMI). Coops et al. (2006a) and Hicke and Logan (2009) both used high spatial resolution QuickBird imagery to accurately map red-attack mountain pine beetle damage using the red-green index (RGI). In contrast, White et al. (2007) found that the moisture stress index (MSI) had the strongest relationship with proportion of red-attack damage using QuickBird and Hyperion imagery.

Much of the success in detecting and monitoring mountain pine beetle outbreaks in broad-scale remote sensors can be attributed to the strong red signature associated with a mountain pine beetle infestation. In contrast, the success of spruce beetle monitoring studies has been more limited. Foliar changes in infested Engelmann spruce are more subtle, and Engelmann spruce typically occurs in mixed spruce-fir stands, unlike generally mono-specific pine stands. The few existing studies on outbreak detection using multispectral remote sensing have been restricted to large-scale outbreaks, or to detecting outbreaks two years or longer into the infestation (DeRose et al., 2011; Frank et al., 2014; Hart and Veblen, 2015; Makoto et al., 2013). DeRose et al. (2011) and Hart and Veblen (2015) utilized multispectral imagery to detect gray-stage spruce beetle infestation with high accuracy using the disturbance index (DI), red-green index (RGI), blue-red index (BR), and normalized difference vegetation index (NDVI). However, spruce trees at the gray stage have already been infested for at least two years (Schmid, 1976), and have started to drop their needles, a point in the outbreak cycle which may be too late for a management response. This difficulty in detecting early-stage spruce beetle infestations suggests a need for higher-sensitivity remote sensors to identify pertinent wavebands for detecting and studying early-stage spruce beetle outbreaks.

Following a spruce beetle infestation, Engelmann spruce close their stomata, resulting in decreased canopy conductance and canopy evapotranspiration (Frank et al., 2014). These and other changes to the foliage of infested spruce may be observable in fine-scale hyperspectral data (Asner et al., 2015; Fassnacht et al., 2014), promising improved algorithms for determining the location and extent of a spruce beetle infestation. Biochemical processes in plants, such as photosynthesis, respiration, and transpiration, are inherently linked to the concentrations of the biochemicals involved in them (Curran et al., 2001). As such, changes initiated by stress, drought, or other factors result in a change in the foliar chemistry of plants. These foliar chemistry changes are often observable in hyperspectral sensors, which detect spectral reflectance in narrow wavebands of the electromagnetic spectrum (Hall et al., 2016; Kokaly and Clark, 1999). Many studies have had success using aerial and ground-based hyperspectral sensors to detect differences in spectral reflectance between leaves with varying pigments, vegetation stress, and bark beetle damage (Carter, 1994; Carter and Knapp, 2001; Delalieux et al., 2009; Fassnacht et al., 2014; Masaitis et al., 2013; Naidu et al., 2009; Santos et al., 2010; Smith et al., 2004). Näsi et al. (2015) used a hyperspectral sensor onboard an unmanned airborne vehicle to detect various stages of European spruce bark beetle (*Ips typographus*) infestation in Norway spruce (*Picea abies* (L. Karst.)). Niemann et al. (2015) and Cheng et al. (2010) both used high spectral resolution sensors to distinguish between healthy and green-stage mountain pine beetle attack, finding the near infrared and shortwave infrared regions to be the most useful. Ahern (1988) also found evidence for detection of green-stage mountain pine beetle infestation using lab spectroscopy, and a study by Carter and Knapp (2001) found significant differences in the 500–700 nm range between lab-derived spectra of healthy and nitrogen-stressed radiata pine (*Pinus radiata* (D. Don)). The success of these studies at using hyperspectral sensors to detect subtle foliar changes due to vegetation stress lends support to the use of hyperspectral data to detect green-stage spruce beetle infestation in Engelmann spruce.

It is clear that hyperspectral remote sensing, with its fine spectral and often fine spatial resolution, can provide detailed biophysical information on canopy properties such as moisture, leaf