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A framework for detecting conifer mortality across an ecoregion using high spatial resolution spaceborne imaging spectroscopy

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ABSTRACT

Between 2013 and 2015, during a time of severe drought and elevated bark beetle (*Dendroctonus spp.*) activity in California, the amount of conifer mortality in the Southern Sierra Nevada increased greatly. Remote sensing is a critical means of providing up-to-date information on the location, magnitude, and extent of mortality across a broad geographic area. We used eleven Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) flight lines, resampled to 30 by 30 m pixel size and acquired on six separate dates as part of the HyspIRI Preparatory Campaign to simulate spaceborne imaging spectroscopy. We also spectrally degraded the AVIRIS images to simulate Landsat-8 data. We tested the ability of single-date and multi-temporal remote sensing to identify red stage conifer mortality, healthy conifer, and non-conifer dominated pixels using a random forest algorithm. Accuracy was assessed with an independent validation dataset acquired via WorldView imagery in areas spatially separate from where training data were collected, as well as through comparison with aerial detection survey and canopy water loss data, with generally good agreement. We found that classifications based on imaging spectroscopy significantly outperformed broadband multispectral feature sets (with a highest overall accuracy of 85.1% obtained by imaging spectroscopy and 80.2% obtained by the simulated multispectral images). We also found that classifications based on multi-temporal imaging spectroscopy were more accurate than single-date imaging spectroscopy (the highest overall accuracy obtained for single-date imaging spectroscopy was 83.4%). Imaging spectroscopy that included interseasonal data from the end of the drought outperformed all other datasets, including interannual data that included only images collected in the summer. Multi-date analysis also improved accuracy using broad band systems. Although current spaceborne assets are adequate for monitoring bark beetle mortality in a heterogeneous ecosystem, a spaceborne imaging spectrometer would further improve operational accuracy.

1. Introduction

Between the hydrological years of 2012 and 2015, California has been subject to one of the worst droughts in the past several centuries (Diaz and Wahl, 2015). One of the most prominent effects of this drought has been an increase in tree mortality in the Southern Sierra Nevada, prompting California to declare a state of emergency on 30 October 2015. In the Western United States, one of the primary vectors of mortality in conifers during drought is native bark beetles (*Dendroctonus spp.*) killing weakened pines (*Pinus spp.*; Raffa et al., 2008). The effect of bark beetles and subsequent tree mortality on ecosystem services and function (Edburg et al., 2012), fire and fuels (Jenkins et al., 2008), economics (Waring et al., 2009), recreation and scenery (Sheppard and Picard, 2006), public safety, and property values (McGregor and Cole, 1985) has been well documented.

Given that bark beetle driven mortality is generally widely dispersed, remote sensing is an important method for helping to understand the spatial extent, magnitude, and ecological effects of these outbreaks (Wulder et al., 2006). Generally, bark beetle mortality in conifers is broken up into four stages, each with distinct physical and spectral properties. The first stage, healthy vegetation, is the stage all conifers are in before a successful attack. The next stage, green attack, occurs after bark beetles have successfully attacked a tree, but before the tree's needles show visible signs of leaf color change (Wulder et al., 2006). In this stage, the tree is unable to transport nutrients from the roots to the needles and is therefore effectively dead. Six to twelve months after an attack, trees transition to the red stage, wherein all needles on a tree turn visibly red (Wulder et al., 2006). Finally, two to

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five years after an attack, the tree transitions into the gray stage, where most or all of a tree's needles have fallen to the canopy floor and only the gray branches remain. Each of these stages has unique spectral shifts associated with them; however, in some cases, the changes in reflectance between phases are small and only over a small wavelength range (Ahern, 1988; Wulder et al., 2006).

A variety of remote sensing data sources have been used to identify effects of epidemic insect outbreaks. Sensors in the Landsat series have the advantage of a large field of view (FOV), which allows for inexpensive imaging of entire ecoregions repeatedly through time. However, the inherent physical tradeoff of this is a larger pixel size, which in heterogeneous ecosystems results in pixels that are almost always mixtures. Mixed cover pixels make it difficult to separate the target spectral signal (needle senescence and loss in conifers) from background spectral changes, e.g. leaf physiological changes in understory or non-target crown level vegetation. Often, this problem is either overcome by limiting the identification to a pre-defined homogenous target area (White et al., 2007) or by collecting airborne or satellite imagery at finer spatial resolutions and therefore with potentially fewer mixed pixels (Lausch et al., 2013). Both of these methods have limitations in their ability to monitor whole ecoregions, particularly in a cost-effective manner.

Spaceborne imaging spectroscopy, where reflectance is continuously sampled at narrow spectral intervals, could provide sufficient resolution over a wide enough spectral region to identify different cover types and their relative spectral contributions within a pixel (Roth et al., 2012; Ustin and Gamon, 2010; White et al., 2007). With the proper sensor, spaceborne imaging spectroscopy could provide the large FOV necessary for operational ecoregion monitoring, while partially overcoming the problem of mixed pixels intrinsic to a large pixel size. Currently, most research related to imaging spectroscopy and bark beetles has focused on identifying green attack trees at the fine spatial resolutions provided by aircraft platforms (Fassnacht et al., 2014; Lausch et al., 2013; Niemann et al., 2015; Pontius et al., 2005; White et al., 2007). Research on the operational ability of spaceborne imaging spectroscopy to identify red stage mortality has not occurred because it would require a satellite that could collect large FOV images at a global scale with repeat sampling, a high signal-to-noise ratio, and sufficiently small pixel size— no instrument that meets these specifications currently exists. However, several instruments have been proposed, including the Hyperspectral Infrared Imager (HyspIRI, Lee et al., 2015). The National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory's (JPL's) HyspIRI Preparatory Campaign provides a unique surrogate for spaceborne imaging spectroscopy. Although the campaign was conducted with the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), several factors allow it to be analogous to a spaceborne platform for research purposes. These factors include contiguous flightlines acquired over large geographic regions that allow for ecoregion-level monitoring; three seasonal acquisitions flown over a three year period, starting before the widespread tree mortality event, thereby providing a data set that makes time series analysis and change detection possible; and algorithms that have been developed to simulate the signal-to-noise ratio and spatial resolution of the proposed HyspIRI mission (Thompson et al., 2015).

Both single-date and multi-temporal classifications have been shown to produce highly accurate separation between healthy and red stage conifer pixels with multispectral imagery; for example, over 90% accuracy for both temporal paradigms was obtained in Meddens et al. (2013). Largely due to a lack of data availability, multi-temporal imaging spectroscopy studies are uncommon (Dennison et al., 2003; Niemann et al., 2015; Roberts et al., 1997; van Wagtendonk et al., 2004). Given imaging spectroscopy's capability for accurate identification of plant functional types (Ustin and Gamon, 2010), multi-temporal imaging spectroscopy could identify pre-disturbance plant functional units in order to better understand disturbance dynamics. However, using multi-temporal images introduces additional constraints and sources of error. These include the need for continuous acquisition of cloud-free images through time, sensitivity to co-registration errors, and the potential bi-directional reflectance distribution function (BRDF) differences between dates (Chuvieco and Huete, 2009).

In this paper, we test the ability of imaging spectroscopy to identify red stage mortality. Specifically, we generate several reference datasets and examine the effectiveness of imaging spectroscopy versus multispectral data, multispectral versus single-date information sources, and the importance of feature reduction. We also assess which spectral regions are most effective for red stage mortality identification. Finally, we compare the imaging spectroscopy based maps of red stage mortality to other tree mortality data sources, thus providing greater context to our classification results.

2. Methods

2.1. Study area

The study occurred in montane forests on the western side of the Sierra Nevada in California, USA. All areas that met the following criteria were considered part of this study: 1) Areas consistently imaged by the AVIRIS instrument between Spring 2013 and Summer 2015 as part of the HyspIRI Preparatory Campaign, South Sierra flight box; 2) Areas on publically owned National Forest or National Park land (the land management history of privately owned lands during and before this study could not be easily retrieved and these areas were therefore excluded); 3) Areas below 2100 m of elevation, in order to focus primarily on areas with a major ponderosa pine (*Pinus ponderosa)* component; 4) Areas that had not been mechanically thinned between Spring 2013 and Summer 2015 as determined by the Forest Service Activity Tracking System (FACTS); 5) Areas that had not burned in a controlled fire or wildfire between Spring 2013 and Summer 2015, which was also determined by FACTS. Approximately 339,000 ha met these conditions (Fig. 1).

The climate of the study area is Mediterranean, typically consisting of hot dry summers and cool wet winters. The study area is comprised of a variety of different vegetation assemblages (Holland and Keil, 1996). At the lower elevations, there are montane hardwood species such as blue oak (*Quercus douglasii*), valley oak (*Quercus lobate*), interior live oak (*Quercus wislizeni*), and California buckeye (*Aesculus californica*). Also present at these elevations are annual grasslands and shrublands composed of species such as manzanita (*Arctostaphylos spp.*) and California lilac (*Ceanothus spp.*). At around 1000 m above sea level, conifer communities, often dominated by ponderosa pine, are widespread. At higher elevations within the maximum elevation of 2100 m in our study area, conifers are often a mixed assemblage of ponderosa pine, white fir (*Abies concolor*), sugar pine (*Pinus lambertiana*), and incense-cedar (*Calocedrus decurrens*). Conifers are comprised of a variety of densities, age cohorts, and sizes throughout the study area.

As previously stated, during the time period of the study, the region was experiencing intense drought. United States Forest Service aerial detection survey data indicates that, during the summer of 2015, red stage tree mortality was highly elevated from baseline levels (USFS, 2016). By the summer of 2016, after the time frame of this study, the mortality had dramatically spread and intensified.

2.2. Input data

As part of the HyspIRI field campaign, AVIRIS data were collected over the southern Sierra Nevada during the spring, summer, and fall seasons for three years starting in 2013 through 2015. Additional data were also collected in summer 2016. In this study, the aim was to characterize red stage mortality in the summer of 2015, so the fall 2015 and summer 2016 AVIRIS flights were not used. Most of the flight lines in fall 2013 were found to have smoke contamination from the 2013