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Mapping burn severity in a disease-impacted forest landscape using Landsat and MASTER imagery

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ABSTRACT

Global environmental change has increased forest vulnerability to the occurrence of interacting disturbances, including wildfires and invasive diseases. Mapping post-fire burn severity in a disease-affected forest often faces challenges because burned and infested trees may exhibit a high similarity in spectral reflectance. In this study, we combined (pre- and post-fire) Landsat imagery and (post-fire) high-spectral resolution airborne MASTER data [MODIS (moderate resolution imaging spectroradiometer)/ASTER (advanced spaceborne thermal emission and reflection radiometer)] to map burn severity in a California coastal forest environment, where a non-native forest disease sudden oak death (SOD) was causing substantial tree mortality. Results showed that the use of Landsat plus MASTER bundle performed better than using the individual sensors in most of the evaluated forest strata from ground to canopy layers (*i.e.*, substrate, shrubs, intermediate-sized trees, dominant trees and average), with the best model performance achieved at the dominant tree layer. The mid to thermal infrared spectral bands (3.0–12.5 μm) from MASTER were found to augment Landsat's visible to shortwave infrared bands in burn severity assessment. We also found that infested and uninfested forests similarly experienced moderate to high degrees of burns where CBI (composite burn index) values were higher than 1. However, differences occurred in the regions with low burn severity (CBI values lower than 1), where uninfested stands revealed a much lower burn effect than that in infested stands, possibly due to their higher resilience to small fire disturbances as a result of higher leaf water content.

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1. Introduction

Forests play a key role as global terrestrial carbon sinks responsible for an annual uptake of over one quarter of the anthropogenic carbon dioxide (CO_2) from the atmosphere (Pan et al., 2012). Compared to the net carbon sequestration through tree growth, carbon loss may be occurring at a faster pace through natural disturbances including wildfire (Kurz et al., 2008a; Asner, 2013). Recently, increased fire activities have been reported in major forest biomes, such as Brazilian Amazon, Canadian boreal and western USA (Carcaillet et al., 2001; Westerling et al., 2006; Morton et al., 2013). In the short term, forest fires directly transform living and dead organic matter at or above the soil surface to charred and blackened residues (Kokaly et al., 2007), which in the long term may affect the structure and function of the ecosystem, and influence the spatial patterns of ecological succession (Turner et al., 1998; Metz et al., 2012, 2013). Hence, it is critical to understand the combustion degree of organic matters and the impact of heat on soil chemical properties in forests immediately following fire events, where the practice is typically referred to as burn severity assessment (Neary et al., 2005; Key and Benson, 2006; Lentile et al., 2006; Kokaly et al., 2007; Keeley, 2009). Over the last three decades, remote sensing has proven effective in assessing the impacts of fire on forest ecosystems at local, regional and continental scales (Hall et al., 1980; Milne, 1986; Jakubauskas et al., 1990; White et al., 1996; Hudak and Brockett, 2004; Lentile et al., 2006; Veraverbeke et al., 2012). While the detection of fire extents ("where") using remote sensing is relatively well established, recent research efforts have advanced the measurement of "how severely" wildfires change post-disturbance forest landscapes (*i.e.*, burn severity) by capitalizing on the variation in spectral reflectance from burned vegetation and soil shortly after the fire events (Miller and Yool, 2002; Epting

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et al., 2005; Roy et al., 2006; Lentile et al., 2006; Miller and Thode, 2007; Harris et al., 2011; Quintano et al., 2013). Here, we adopted the definition of burn severity as "the degree to which an ecosystem has changed owing to the fire" (Lentile et al., 2006). Statistical regression and image classification are typical approaches used to link spectral reflectance from a burned forest with a field-measured burn severity index, such as composite burn index (CBI) ranging from zero to three or low to high (Key and Benson, 2006; Hultquist et al., 2014).

Although there has been a growing body of literature on the application of remote sensing to assess burn severity across a diversity of environments [see reviews by Lentile et al. (2006) and Keeley (2009)], few studies have discussed the uncertainty in mapping burn severity in a forest that is also subject to severe disturbances caused by invasive pests or pathogens. While increased fire events have been observed mainly due to the impact of warming fostered drought, the intensity and frequency of insect invasions and disease epidemics are likely to be accelerated resulting from global trade (Bergot et al., 2004; Wulder et al., 2006; Kurz et al., 2008b; Lamsal et al., 2011; Olsson et al., 2012). Studies have found that it is becoming more frequent that wildfire affects a forest invaded by an exotic insect or disease (Jenkins et al., 2008; Metz et al., 2013). Since the outbreaks of insect or disease could dramatically increase host fuel abundance and exhibit different patterns (due to patchy dispersal by the pest) (Meentemeyer et al., 2012), accurate assessment of forest burn severity requires a comprehensive investigation of how non-native species, including infectious disease, affect fire behavior. However, relatively little consideration has been given to the role that invasive pests or pathogens play in shaping spatial heterogeneities of burn severity.

To date, remotely sensed data used in the majority of burn severity studies have been from traditional sensors, such as Landsat and SPOT (Satellite Pour l'Observation de la Terre) (*e.g.*, Roy et al., 2006; Fox et al., 2008). Although promising results were reported with these broadband sensors using the VNIR-SWIR (visible to shortwave infrared, 0.4–3.0 μm) spectral region, it remains unclear whether such data sets can provide satisfactory performance mapping burn severity in diseased forests, because post-fire spectral reflectance is complicated by both the degree of burn severity and disease-caused tree mortality. The disturbances of fire and forest disease may change spectral reflectance in similar ways. Recently, researchers found that sensors with an ability to acquire imagery of higher spectral resolution and broader spectral range may provide greater insights into the impact of fires on forests (Wagtendonk et al., 2004Wagtendonk et al., 2004 Kokaly et al., 2007; Veraverbeke et al., 2012). MASTER [MODIS (moderate resolution imaging spectroradiometer)/ASTER (advanced spaceborne thermal emission and reflection radiometer)] airborne simulator is an example of a sensor capable of collecting 50-band imagery covering both the VNIR—SWIR and MIR—TIR (mid to thermal infrared, 3.0–12.5 μm) spectral ranges. Hence, MASTER may have the potential to recognize disturbance related subtle variations in spectral reflectance, and augment burn severity assessments from broadband Landsat data in diseased forests.

Capitalizing on the emerging infectious disease sudden oak death (SOD) as case study of forest health decline prior to fire, we ask two questions that address the potential for combing MASTER airborne and Landsat TM data to assess the impact of a pre-fire biotic disturbance on forest burn severity: (i) what is the performance of combining MASTER and Landsat TM data in burn severity assessments compared to using data from individual sensors? (ii) Does SOD tree mortality influence burn severity measured using CBI in various forest strata from ground to canopy layers (*i.e.*, substrate, herbs, shrubs, intermediate trees, dominant trees and the average)?

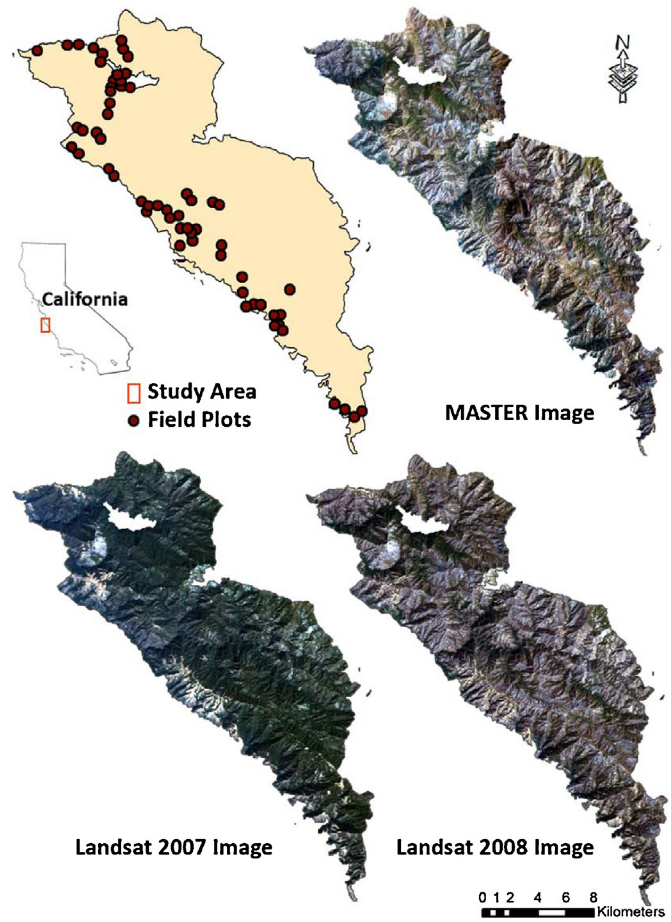

Fig. 1. Study area located in the Big Sur ecoregion on the western flank of the Santa Lucia Mountains in California. The MASTER image is from a color composite using bands 5 (red), 3 (green) and 1 (blue). The 2007 and 2008 Landsat TM images are from a color composite using bands 3 (red), 2 (green) and 1 (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Methods

2.1. Study area

Our study site (centered at: 36°16′N, 121°44′W) was located in the Big Sur ecoregion on the western flank of the Santa Lucia Mountains in California, covering an area of 28,383 ha (Fig. 1). The area featured Mediterranean-type climate and a rugged landscape dissected by steep slopes and drainages with elevations ranging from sea level to 1571 m within 5 km of the coast (Meentemeyer et al., 2008). Mixed coniferous forests, composed primarily of ponderosa pine (*Pinus ponderosa*), sugar pine (*Pinus lambertiana*), Jeffrey pine (*Pinus jeffreyii*), coulter pine (*Pinus coulteri*), and Santa Lucia fir (*Abies bracteata*), were located on upper elevation slopes and rocky ridges; while chaparral shrubland and annual grassland often dominated dry south-facing slopes and ridges at mid elevations (Davis et al., 2010). In addition, mixed oak woodland consisting of coast live oak, Shreve's oak, bay laurel (*Umbellularia californica*), and madrone (*Arbutus menziesii*) occurred on moister slopes, giving way to riparian corridors of redwood–tanoak forest at lower elevations (Davis et al., 2010). Since the mid-1990s, an invasive non-native pathogen *Phytophthora ramorum* – causing the disease sudden oak death (SOD) – has led to substantial mortality in two plant communities – mixed oak woodland and redwood–tanoak forests (Rizzo et al., 2005). Despite the name 'sudden' oak death, the disease is a multi-year process that typically begins with suitable temperature