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Quantifying insect-related forest mortality with the remote sensing of snow

Emily H. Baker [a], Thomas H. Painter [b], Dominik Schneider [a], Arjan J.H. Meddens [c], Jeffrey A. Hicke [d], Noah P. Molotch [a,b,*]

[a] Department of Geography, Institute of Arctic and Alpine Research, University of Colorado at Boulder, Boulder, CO 80303, United States
[b] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, United States
[c] College of Natural Resources, University of Idaho, Moscow, ID 83844, United States
[d] Department of Geography, University of Idaho, Moscow, ID 83844, United States

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ABSTRACT

Greenhouse gas emissions have altered global climate significantly, increasing the frequency of drought, fire, and insect- and pathogen-related mortality in forests across the western United States. The accuracy of satellite-based estimates of canopy change has been limited by difficulties associated with discriminating overstory canopy from understory vegetation. To overcome this issue, we developed a method to quantify forest canopy cover using winter-season fractional snow covered area (F_{SCA}) data from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) snow covered area and grain size (MODSCAG) algorithm. The method utilizes time series of F_{SCA} data to identify images with continuous ground snow coverage and a snow-free overstory, effectively masking out the influence of understory vegetation. Using this method, we determined that MODSCAG-retrieved viewable gap fraction (VGF; i.e. fraction of pixel sub-canopy viewable area) was significantly correlated with an independent product of yearly crown mortality caused by mountain pine beetles derived from Landsat imagery at 25 high-mortality sites in northern Colorado ($\overline{r} = 0.96 \pm 0.03$, $p<0.03$). Additionally, we determined the temporal lag between tree mortality and needlefall, showing that needlefall occurred an average of 2.6 ± 1.2 years after year of attack. The canopy change detection method described herein is the first to utilize snow cover to mask understory impacts on overstory detection. The method can be applied anywhere in the seasonal snow zone and therefore has wide applicability given that 30% of the global land surface is seasonally snow covered. In this regard, the approach addresses significant limitations of previously published methods of canopy change detection and has broad implications with regard to understanding forest mortality and the representation of disturbance within hydrologic, land surface, and climate models.

1. Introduction

Changing patterns of temperature and precipitation have increased the extent and frequency of forest disturbances, and more extreme climate events are expected to increase future forest die-offs (Allen et al., 2010; Weed et al., 2013; Hart et al., 2014). Disturbances alter forest canopy and structure, changing their role in planetary exchanges of carbon, energy, and water (Adams and Macalady, 2010; Hicke et al., 2012a, b; Edburg et al., 2012). In the western United States, disturbances from insect outbreaks and fire are already increasing in both area affected and in severity of disturbance (Westerling et al., 2006; Meddens et al., 2012; Dennison et al., 2014). Since the mid-1990s, outbreaks of aggressive bark beetles have caused extensive forest mortality across > 600,000 km^2 of North-American forests (Bentz et al., 2009; Meddens et al., 2012). The impacts of the mountain pine beetle (Dendroctonus ponderosae Hopkins) have been especially severe, killing trees across an estimated 71,000 km^2 of forest in the western US (Hart et al., 2015). In Colorado alone, the mountain pine beetle has affected roughly 34,000 km^2 of forest (USFS, 2015), including approximately 67% of the state's lodgepole pine stands and 40% of forested watersheds (Bentz et al., 2009; Pugh and Small, 2012).

The three stages of mountain pine beetle-related forest mortality are green-stage, which represents conditions immediately following initial attack in which needles maintain their green color; red-stage, which occurs once the needles have lost their green pigment but remain on the stems; and grey-stage, which occurs once needles have fallen. Efforts to map beetle-caused tree mortality have primarily focused on mapping red-stage mortality, using both aerial surveys and satellite platforms (Coops et al., 2006; Wulder et al., 2006; Johnson and Ross, 2008; Meddens and Hicke, 2014). Though this is the most prominent and easily detected stage of mortality, associated changes in remotely observed spectral reflectance and vegetation indices can be relatively short lived

* Corresponding author at: Department of Geography, Institute of Arctic and Alpine Research, University of Colorado at Boulder, Boulder, CO 80303, United States.
E-mail address: noah.molotch@colorado.edu (N.P. Molotch).

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and species-dependent (Johnson et al., 1997; Wulder et al., 2006). While some recent work has shown success in mapping grey-stage tree mortality (Dennison et al., 2010; Meddens et al., 2011; Hart and Veblen, 2015), these efforts are complicated by the difficulty of separating spectral signatures of overstory and understory vegetation (Coops and Wulder, 2010; Heiskanen et al., 2012; Bright et al., 2013; Buma et al., 2013). In this regard, satellite-based retrievals of leaf area index (LAI) have limited ability to quantify canopy cover given the similarity in spectral characteristics of understory vegetation (Coops and Wulder, 2010; Nolin, 2010; Heiskanen et al., 2012; Bright et al., 2013; Buma et al., 2013). Complicating detection issues, remotely sensed LAI can rebound quickly after disturbance due to an expansion of undergrowth (Buma et al., 2013), depending on severity of outbreak (Bright et al., 2013).

The problem of understory spectral contribution may be reduced in seasonally snow-covered forests. In this context, snow provides significant contrast with overstory vegetation while providing a relatively opaque cover on understory vegetation. This masking of understory vegetation is conceptually illustrated in Fig. 1.

Incorporation of snow information has already improved automated disturbance mapping, but has not been used explicitly to map canopy extent (Stueve et al., 2011). This research seeks to exploit remotely sensed observations of subpixel fractional snow covered area to map the change in canopy extent associated with disturbance. We used the 2000s-era mountain pine beetle epidemic as a test case to illustrate the utility of this method for mapping canopy cover change. In addition, these canopy cover change estimates were combined with independent estimates of red-stage mortality to determine the time required for needlefall.

We analyzed Moderate-Resolution Imaging Spectroradiometer (MODIS) Snow Covered Area and Grain size (MODSCAG) data, which uses spectral mixture analysis on MODIS spectral reflectance data, providing daily snow cover information that can distinguish sub-pixel coverage of vegetation, rock-soil, and snow (Painter et al., 2009). With careful analysis, changes in the relative proportions of these land-surface endmembers through time, especially during winter snow-covered months, hold the potential to identify changes in forest cover fraction through time and over large spatial extents. Using this approach, the study presented here has three objectives: 1) To illustrate that MODIS-observed fractional snow covered area (F_{SCA}) data can be used to quantify changes in canopy extent associated with disturbance at individual focus pixels; 2) To identify, at our focus pixels, the timing of needlefall by evaluating the time-lag between an existing Landsat-based mortality onset dataset (Meddens and Hicke, 2014) and the estimates of canopy extent derived herein; and 3) To map changes in canopy extent over our broader study area in Colorado and Wyoming.

2. Study area

The study area covers an approximately 53,000 km^2 area in northern Colorado and southern Wyoming (Fig. 2). Focus sites were selected within this area to test our ability to measure changes in canopy cover associated with forest mortality. Sites were located inside of the seasonal snow zone, and in high-mortality lodgepole pine forests. The seasonal snow zone was defined as areas in which snow cover was observed by MODIS in over 75% of years (2000 − 2012) (Fig. 2). To define the seasonal snow zone, we use the MODSCAG fractional snow covered area data (Painter et al., 2009), accessible from the NASA/JPL Snow Data Server (http://snow.jpl.nasa.gov/). The product has a lower F_{SCA} detection limit of 15% snow cover (Painter et al., 2009) and has been shown to be more accurate than the standard NASA snow cover product, MOD10A1 (Rittger et al., 2013). For each year, we identified the first day of MODSCAG F_{SCA} on or following April 1 when mean sensor zenith angle was <30° and cloud-cover and other quality issues masked <10% of the image. Additionally, pixels were required to be over 2000 m in elevation in order to ensure that cloud-masking or other spectral unmixing issues did not erroneously map low-lying areas as part of the seasonal snow zone. Sites were further required to be within lodgepole forests based on an AVHRR-derived 1-km^2 dataset of forest types (Zhu and Evans, 1994) (Fig. 2 dark green areas).

Sites were also required to fall in high-mortality areas, defined as 500-m pixels with area composed of at least 75% dead trees in 2011 relative to 1996 as reported in a Landsat-based mortality data set (Meddens and Hicke, 2014), described in more detail in section 3 below. Within these constraints, 50 sites were then randomly selected, and manually screened for anthropogenic disturbances (e.g. salvage logging, road building, exurban development) in Google Earth's Time Machine, leaving a final set of 25 sites, shown as black triangles in Fig. 2. High mortality sites were selected given the experimental nature of the method developed herein and the desire to have a detectable signal of change within the study sites.

Based on the Landsat mortality data, the resulting sites had a mean cumulative mortality from 1996 to 2011 of 80%, ranging from 75% to 91%, and a year of peak mortality ranging from 2005 to 2009, with average timing of 2007. Note that these estimates are used solely as background information as the goal of this paper is to derive estimates of canopy cover changes that are complementary to these Landsat-based mortality estimates. Mean Landsat-derived percent canopy cover as estimated by

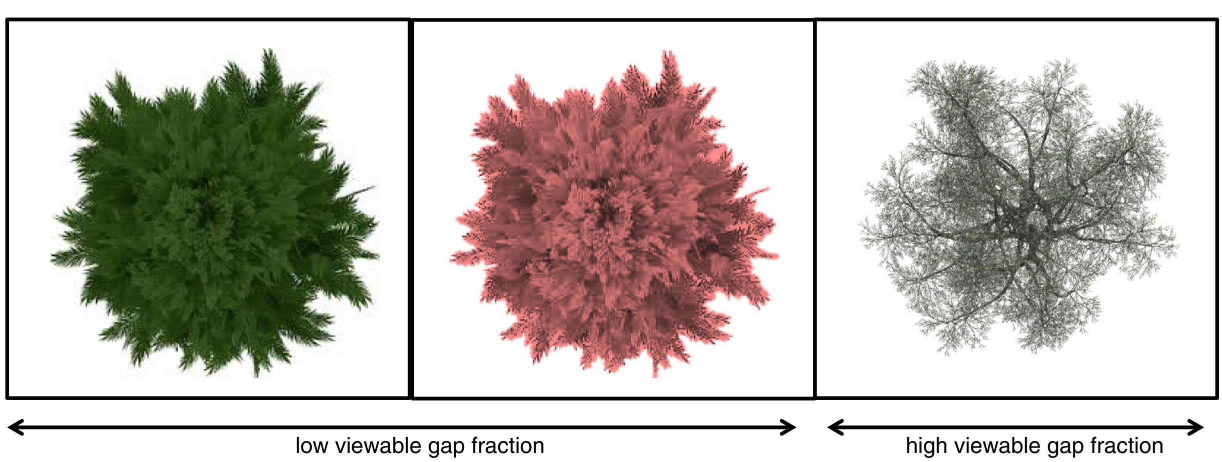

Fig. 1. Conceptual model of tree mortality progression, and timing of needle loss and viewable gap fraction (VGF) increase as viewed from above. The background white color is intended to represent snow cover. In initial green attack and red mortality stages, the tree retains its' needles, and VGF remains unchanged. When the tree drops needles and twigs as it enters the grey stage, more ground area is visible, and VGF increases. There is an inherent temporal lag between red-stage mortality and needle loss/VGF change. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)