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Quantifying tree mortality in a mixed species woodland using multitemporal high spatial resolution satellite imagery

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ABSTRACT

Widespread tree mortality events have recently been observed in several biomes. To effectively quantify the severity and extent of these events, tools that allow for rapid assessment at the landscape scale are required. Past studies using high spatial resolution satellite imagery have primarily focused on detecting green, red, and gray tree canopies during and shortly after tree damage or mortality has occurred. However, detecting trees in various stages of death is not always possible due to limited availability of archived satellite imagery. Here we assess the capability of high spatial resolution satellite imagery for tree mortality detection in a southwestern U.S. mixed species woodland using archived satellite images acquired prior to mortality and well after dead trees had dropped their leaves. We developed a multistep classification approach that uses: supervised masking of non-tree image elements; bi-temporal (pre- and post-mortality) differencing of normalized difference vegetation index (NDVI) and red:green ratio (RGI); and unsupervised multivariate clustering of pixels into live and dead tree classes using a Gaussian mixture model. Classification accuracies were improved in a final step by tuning the rules of pixel classification using the posterior probabilities of class membership obtained from the Gaussian mixture model. Classifications were produced for two images acquired post-mortality with overall accuracies of 97.9% and 98.5%, respectively. Classified images were combined with land cover data to characterize the spatiotemporal characteristics of tree mortality across areas with differences in tree species composition. We found that 38% of tree crown area was lost during the drought period between 2002 and 2006. The majority of tree mortality during this period was concentrated in piñon-juniper (*Pinus edulis-Juniperus monosperma*) woodlands. An additional 20% of the tree canopy died or was removed between 2006 and 2011, primarily in areas experiencing wildfire and management activity. -Our results demonstrate that unsupervised clustering of bi-temporal NDVI and RGI differences can be used to detect tree mortality resulting from numerous causes and in several forest cover types.

1. Introduction

Climate warming and recent severe droughts have resulted in vegetation mortality in various woody biomes across the globe (Allen et al., 2010; Breshears et al., 2005; Carnicer et al., 2011; Phillips et al., 2009; van Mantgem et al., 2009). Changes in ecosystem structure and function resulting from mortality have the potential to significantly alter biogeochemical cycles, energy fluxes, and landscape patterns of vegetation composition at local, regional, and possibly global scales (Adams et al., 2009; Amiro et al., 2010; Hanson & Weltzin, 2000; Huang et al., 2010a; Kane et al., 2011; van der Molen et al., 2011). Our ability to quantify the impacts of vegetation mortality on ecological, biogeochemical, and biosphere–atmosphere dynamics is currently limited due to a fundamental lack of information on where and when mortality events occur across the globe (Allen et al., 2010; McDowell et al., 2011). Even at local scales the extent and magnitude of shifts in vegetation composition and landscape structure resulting from mortality events is difficult to quantify and scale from limited, plot-based information. Remotely sensed imagery obtained from earth-observation satellites has potential to fill these knowledge gaps (Frolking et al., 2009).

The utility of remotely sensed imagery for understanding vegetation mortality has been well documented in coniferous forests of the northern U.S. and Canadian Rockies where regional outbreaks of bark beetles are causing high rates of tree mortality. In these forests, remotely sensed imagery has been used to provide critical information on the extent and progression of bark beetle infestation (Coops et al., 2006; DeRose et al., 2011; Wulder et al., 2008), to predict forest

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susceptibility and insect spread (Coggins et al., 2008; Wulder et al., 2006b), and as a tool for evaluating the performance of management strategies (Wulder et al., 2009). At the stand to landscape level, high spatial resolution (<3 m/pixel), single date (e.g., Dennison et al., 2010; Hicke & Logan, 2009; Meddens et al., 2011) and multitemporal (Wulder et al., 2008, 2009) color infrared imagery have been used for mapping beetle damage. Similarly, high resolution imagery has been applied in other forests to detect mortality from other insects and pathogens as well (e.g., Goodwin et al., 2005; Ismail et al., 2007; Kelly et al., 2004), although detection of bark beetle damage in North American forests has received the most research focus so far.

Beetle- and other insect-caused mortality detection techniques often focus on identifying pixels containing green, red, or gray canopy foliage (Oumar & Mutanga, 2011). Detecting tree canopies at different stages of death requires that imagery be collected during the red attack phase when tree foliage turns red shortly after beetle attack (e.g. Hicke & Logan, 2009; White et al., 2005), or once trees turn gray following needle drop (e.g., Meddens et al., 2011), which typically occurs 2–3 years following infestation (Wulder et al., 2006a). Detecting red foliage, however, may not always be feasible depending on several factors. For example, tree foliage may not necessarily turn red, depending on mortality agent and tree species (e.g., Goodwin et al., 2005). Leaf drop may also occur quicker when the cause of mortality is abiotic (e.g., wind) or involves different insects (e.g., defoliators) and pathogens, limiting the time window for, or preventing altogether the detection of red trees. In cases of especially severe abiotic disturbance, such as hurricanes or harvest, whole trees may be removed rapidly making it impossible to detect changes in foliar coloration. It may also be the case that satellite imagery is contaminated by clouds and aerosols or is not acquired during periods of diagnostic foliar changes, limiting our ability to evaluate past occurrences of tree mortality in many areas with existing methods. Multitemporal image analysis may help overcome the challenges highlighted here, provided that imagery is available prior to the disturbance event so that pre-mortality forest conditions can be quantified. The goal then would be to identify areas of change in subsequent images and determine what spectral change signals tree death.

High resolution imagery has also been used to detect forest disturbances such as burn severity from wildfire (Holden et al., 2010) and the occurrence of standing dead wood or gaps that occur in continuous canopies when one or more trees die (Garbarino et al., 2012; Pasher & King, 2009). Detection of mortality not related to insects or pathogens, however, has only rarely been evaluated with high resolution imagery, and typically involves identification of unique spectral signatures associated with fire burn scars (Holden et al., 2010) or snags (Pasher & King, 2009), or the use of combined spectral and texture features to identify forest gaps (Rich et al., 2010). Forest gap formation is directly related to tree mortality and thus may be a useful indicator of tree death in forests with continuous canopy cover, but would not be suitable in more open forests and woodlands where tree canopy cover in discontinuous. Fire damage is also related to tree death, however, to our knowledge past studies have not used high resolution imagery to explicitly investigate fire caused tree mortality, but have rather focused on quantifying fire affected area. Knowledge of pre-burned forested area could be combined with detection of burned area post-fire to estimate the number of trees killed. Overall, new studies are required that evaluate the utility of high spatial resolution imagery for quantifying tree mortality in areas where the mortality occurs due to several different causes, affects diverse species, or happens during time periods when imagery is not available during periods of foliar fading associated with tree stress or insect and pathogen attack.

The objective of our study was to evaluate the potential of high spatial resolution multispectral imagery for detailed mapping of tree mortality in a southwestern U.S. mixed species woodland. Regional-scale tree mortality was observed in southwestern U.S. woodlands during a severe drought in the early 2000s (Breshears et al., 2005; Shaw et al., 2005; U S Forest Service, 2002, 2003, 2004, 2005). Coarse spatial resolution (≥30 m/pixel) imagery has been used to investigate the extent and ecological implications of this wide-scale die-off (e.g., Huang et al., 2010a; Rich et al., 2008; Vogelmann et al., 2009; Vogelmann et al., 2012) in targeted areas, however, detailed quantification of tree mortality and the landscape response following tree mortality is limited to a sparse number of intensively studied ground-based plots spread throughout the region (e.g., Breshears et al., 2005, Floyd et al., 2009; Shaw et al., 2005). In addition to drought, the study region has also experienced related insect outbreaks and wildfire (Allen, 2007). Here, we used multitemporal, archived satellite imagery acquired before and well after tree mortality occurred during drought and associated beetle outbreak, wildfire, and mechanical tree removal to develop a multistep classification approach for quantifying tree mortality across the landscape. Detailed tree mortality maps can be used for understanding landscape changes, for example, dynamics in stand structure and community composition, resulting from tree mortality. They may also be useful for tuning or evaluating analyses conducted with coarser resolution imagery or for evaluating the performance of hindcast ecosystem model simulations.

2. Methods

2.1. Study area

Our study area is within the Pajarito Plateau region located on the eastern slope of the Jemez Mountains in northern New Mexico, USA (Fig. 1). We focused our study on a 46 km^2 area in Bandelier National Monument (Fig. 1). We selected this region because of the long history of well-documented disturbances (e.g., Allen, 1989, 2007; Allen & Breshears, 1998; Breshears et al., 2005; McDowell et al., 2010) and the relatively high variability in topography, elevation, and species composition. Average elevation of the Pajarito Plateau is approximately 2140 m. Topography of the Pajarito Plateau is characterized by a series of mesas divided by canyons. Piñon pine (*Pinus edulis*) and one-seed juniper (*Juniperus monosperma*) are the dominant overstory species on mesa tops in the mid- to lower-elevations that dominate our study area (Fig. 1). At higher elevations, mesa vegetation becomes more mesic, reflected by a change in vegetation composition with increasing frequency of ponderosa pine (*Pinus ponderosa*), mountain mahogany (*Cercocarpus montanus*), and Gambel oak (*Quercus gambelii*) interspersed with grasslands. Within the canyons, where water is more abundant, the overstory is primarily composed of a mix of ponderosa pine, Gambel oak, some Douglas-fir (*Pseudotsuga menziesii*) and white fir (*Abies concolor*), and narrowleaf cottonwood (*Populus angustifolia*).

The Pajarito Plateau experiences bimodal annual precipitation with peaks as winter snowfall and summer monsoon rainfall. Average precipitation is approximately 400 mm per year. Mean annual air temperature is 9 °C with daily means of −2 °C in January and 21 °C in June (Breshears et al., 2008). Anomalously high air temperatures and low precipitation were observed at a meteorological station located on the Pajarito Plateau in the early 2000s (Fig. 2a). Between 2002 and 2004, plot-level measurements within the Pajarito Plateau indicated that 97% of mature piñon died due to drought and associated piñon ips beetle (*Ips confuses*) attack, whereas a great majority of the juniper survived, with dispersed or patchy mortality in some areas (Allen, 1989, 2007; Breshears et al., 2005, 2008; McDowell et al., 2008).

Time series of Advanced Very High Resolution Radiometer normalized difference vegetation index (NDVI), obtained from a 4.8 km^2 area of the Pajarito Plateau between 1990 and 2006, showed that NDVI declined and exhibited reduced annual variability in the years leading up to the mortality event (Fig. 2b). The lowest summer period NDVI was observed in 2002 coinciding with the lowest precipitation year, with almost no seasonality present during this time. In the years after 2002,