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Combining dendrochronological data and the disturbance index to assess Engelmann spruce mortality caused by a spruce beetle outbreak in southern Utah, USA

R. Justin DeRose *, James N. Long, R. Douglas Ramsey

Department of Wildland Resources and Ecology Center, Utah State University, 5230 Old Main Hill, Logan, UT 84322-5230, United States

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ABSTRACT

Forest disturbances such as bark beetle outbreaks are increasing in severity and extent across western North America. Classification of remote sensing imagery is a powerful way to analyze and detect large-scale disturbances. We used a temporal sequence of four Landsat TM images (1991, 1995, 1999, and 2003) to detect the spatiotemporal change in spectral response of Engelmann spruce (*Picea engelmannii* Parry ex. Engelm.) killed by an unprecedented spruce beetle outbreak in southern Utah, USA. After co-registration and masking out non-vegetation the Disturbance Index (DI) was calculated for each image. DI values associated with Engelmann spruce mortality, determined by comparing each image to a no outbreak baseline image, were then used to classify the images. Dendrochronologically determined dates of spruce death collected from across the outbreak area were used to assess the ability of the DI to accurately differentiate stands of dead spruce from live conifer forest. The overall classification accuracy of the DI varied from 80 to 82% while the accuracy to detect spruce beetle-killed spruce varied from 59 to 71%. Both user's and producer's accuracy to classify beetle infested stands increased over the temporal sequence of image dates. However, confusion matrix-derived statistics varied by image date. Consistent with previous studies, the spruce beetle outbreak began building in multiple, seemingly independent locations across the study area. Over time, areas attacked earlier in the outbreak enlarged and coalesced on the landscape.

1. Introduction

Classification of remotely sensed imagery is commonly used to help characterize disturbance events in temperate forest ecosystems (Goodwin et al., 2008) oftentimes in a change detection context (Coppin et al., 2004; Heikkonen & Varjo, 2004). Techniques of classification vary widely in studies of disturbances but typically have the goal of accurately portraying rapid canopy change over relatively large geographic areas (Jin & Sader, 2005; Woodcock et al., 2001). Consequently, variations in landscape heterogeneity, disturbance type, disturbance intensity and availability of imagery all affect the choice of metrics to describe disturbance-caused change (Hayes & Sader, 2001). In this paper we explore the possibility of using a recently developed disturbance metric, the disturbance index (DI, Healey et al., 2005) to retrospectively characterize Engelmann spruce (*Picea engelmannii* Parry ex. Engelm.) canopy loss (i.e., mortality) resulting from a spruce beetle (*Dendroctonus rufipennis* Kirby) outbreak by comparing DI-classified images with dendrochronologically determined dates of tree death.

The DI is a Tasseled Cap-based (TC) (Crist & Cicone, 1984; Crist & Kauth, 1986) metric that is particularly suited to sensing near-complete canopy removal (Healey et al., 2005). Furthermore, DI is an especially attractive metric because it relies on the readily available and heavily studied Landsat Thematic Mapper (LTM) imagery (Cohen & Goward, 2004). Briefly, the TC reduces the six LTM reflective bands to three: brightness; greenness; and wetness. DI is calculated by subtracting the greenness and wetness from the brightness. This assumes that greenness and wetness in combination best characterize the spectral response of vegetation, whereas brightness best characterizes the non-vegetation spectral response. A frequency distribution of the resulting data structure reveals the range of pixel values with near-complete canopy removal. This allows one to identify a probable disturbance without having to compare between multiple images. The potential for discerning a disturbance based on greenness and wetness versus brightness for a single image date makes the DI attractive for potential retrospective classification of spruce forests killed by spruce beetle outbreaks (sensu Hais et al., 2009).

Another benefit of the Tasseled Cap-based DI metric, is that Engelmann spruce canopies do not exhibit a characteristic 'red-attack' stage (Skakun et al., 2003) like mountain pine beetle (*Dendroctonus ponderosae* Hopkins)-infested lodgepole pine (*Pinus contorta* Dougl ex. Loud), but instead slowly turn green to gray over the course of 1 to 3 years (Schmid, 1976). As a result, remote sensing strategies to detect spruce beetle activity have focused on a different set of techniques (see Hais et al., 2009; Hais & Kucera, 2008).

Spruce beetle outbreaks typically occur over a period of many years; therefore, retrospective classification of the spectral response of beetle-

* Corresponding author. Tel.: +1 435 797 3219; fax: +1 435 797 3796.
E-mail address: rjustinderose@gmail.com (R.J. DeRose).

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caused Engelmann spruce mortality must be conducted in a change detection context. Many forest disturbance change detection studies have relied on multi-date calculations of image-to-image differences, such as linear change detection (Coppin et al., 2004; Coppin & Bauer, 1996) and multiple image comparisons (Muchoney & Haack, 1994). Another approach to change detection is the visual comparison between multiple dates of independently classified and co-registered images (Collins & Woodcock, 1996). We adopted the latter approach in this paper by independently identifying DI across multiple image dates.

Starting in the late 1980s, a spruce beetle outbreak erupted in the high-elevation Engelmann spruce forest (>250 km^2) of the Markagunt Plateau in southern Utah. Early in the outbreak, multiple areas of spruce beetle-caused mortality occurred across the plateau and during the course of the outbreak these areas coalesced so that by the end of the outbreak the entire spruce forest had been affected. Although beetle populations developed across the plateau, there was also a predictable shift in the timing of spruce mortality from the north and west to the south and east of the study area (DeRose & Long, in press). The result was near-complete mortality of Engelmann spruce and, in mature, spruce-dominated stands, a near-complete loss of the canopy (DeRose & Long, 2007). A network of research plots were installed across the plateau where spatially explicit GPS points were paired with precisely dated timing of death for Engelmann spruce killed by the beetle outbreak. Once canopy loss as a result of the spruce beetle outbreak was classified using the DI, the network of ground control points were used to test the classification accuracy. We explicitly chose the DI for two reasons: (1) the DI has been shown to be effective at quantifying stand-replacing disturbances, where a large percentage of the forest canopy is removed or killed, which was the case in Engelmann spruce forests on the Markagunt Plateau; and (2) forest recovery and succession are exceptionally slow in these high-elevation southern Rocky Mountain forests, and the DI reportedly works well in these conditions (Healey et al., 2005).

The goal of this study was to test a remote sensing approach for assessment of the spatiotemporal pattern of landscape-wide Engelmann spruce mortality caused by a recent spruce beetle outbreak. To do this a temporal sequence of LTM imagery was retrospectively classified using the DI for each image in the sequence. Classification accuracy for each image was determined by comparing DI-classified pixels to dendrochronologically determined dates of tree death. We hypothesized that: (1) because DI has been shown to work well for stand-replacing disturbances, the vegetation heterogeneity associated with early outbreak conditions will result in initially poor DI classification accuracy for infested areas, but that accuracy would improve as the outbreak increased in space and proceeded through time; (2) conversely, classification accuracy of non-infested areas would necessarily decrease over time; and (3) subsequently, the area of infested Engelmann spruce forest would increase over time during the outbreak. In addition, we sought to demonstrate the applicability of the relatively novel approach of using dendrochronologically determined dates of tree death as ground truth data to assess classification accuracy.

2. Methods

2.1. Study area

The Markagunt Plateau is a high-elevation area on the western edge of the greater Colorado Plateau in southwestern Utah. A large majority of the plateau is under the jurisdiction of the Forest Service, Cedar City Ranger District, Dixie National Forest. Prior to the recent outbreak, forest vegetation in the study area was heavily dominated by Engelmann spruce but included components of subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) and aspen (*Populus tremuloides* Michx.). In addition, a large part of the landscape is covered with high-elevation, treeless meadows where shrub, herbaceous, or grass communities dominate. The non-vegetated portion of the plateau is a result of the varied and dynamic geologic history of the area. Large expanses of recent (1000–3000 years bp) lava flows occur across the plateau. Cedar Breaks National Monument and other similar eroding geologic formations also occur on the landscape. Precipitation (and associated cloud cover) on the plateau is influenced primarily by Pacific storm patterns in the winter and by the Gulf of Mexico and California (i.e., southwestern monsoons) during the summer (July through September) (Mock, 1996).

2.2. Ground control data collection

Sample sites in Engelmann spruce-dominated forests (ranging in basal area from ~50% to nearly 100% spruce) were selected using restricted random sampling from a grid laid across a map of the plateau. Within each site, plots were established along a smaller, systematic grid with a random starting point. Areas with a history of logging activity were avoided. The plots on the grid were separated by at least 100 m to minimize potential spatial autocorrelation associated with using ~30 m spatial resolution LTM imagery (Jensen, 2005). Spatial location was recorded for each plot center with a global positioning sensor when instrument error was estimated to be <3 m. To characterize individual species proportional contribution to canopy reflectance, variable radius plots were used to select overstory trees for sampling. For all trees >5 cm diameter at breast height status (live or dead) and cause of death (spruce beetle or other) were recorded. Variable radius sampling is a probability proportional to tree size sampling approach and therefore each prism 'plot' varies in area with larger diameter trees having a larger 'plot' than smaller diameter trees (Bell & Dilworth, 2002). In no case did the individual trees measured on a given plot come close to occupying an area of ~30 m^2 (LTM pixel size). Total basal area and basal area by species were determined by counting the number of trees measured on a plot and multiplying by the basal area factor for that plot. All ground control data measurements were taken after the outbreak, therefore, percent basal area composition of immediately pre-outbreak conditions was reconstructed from the Engelmann spruce killed by the outbreak.

Increment cores were extracted from beetle-killed spruce located on each plot as detailed in DeRose and Long (2009). Increment cores were processed using standard dendrochronological techniques, and crossdated using a pre-existing spruce chronology (K. Briffa & F.H. Schweingruber, World Data Center for Paleoclimatology Data Contribution, Ceader [sic] Breaks Engelmann spruce chronology, NOAA/NCDC Paleoclimatology Program, Boulder, Colorado, USA.[1]), that was modified with recent (up to 2007) live spruce tree-ring series, to anchor the annual date of the outermost ring on our cored trees. We assumed the crossdated calendar year associated with the outer ring was the last year of growth and therefore the year of death. Because date of spruce death for individual trees varied by many years within most plots (1–18 years), and we required only a single date for each plot to test the classification accuracy, we used the median value of tree death in each plot for the classification assessment. The median of tree dates of death described when spruce beetle populations had killed enough trees (roughly, one half) on the plot for a spectral response to be detected.

2.3. Image processing

Four LTM images from path 38, row 34 were used. Images were chosen with acquisition dates that temporally spanned the outbreak (September 17th 1991; October 14th 1995; October 25th 1999; and October 20th 2003). Except for 1991, we chose image dates in October, which is the driest and latest-growing season month of the year, so that vegetation response would be as similar as possible, and so that cloud-free imagery could be used. The 1991 image was acquired earlier in the growing season (September) and was defined as the baseline image, i.e.,

[1] URL: http://www.ncdc.noaa.gov/paleo/treering.html.