Forest Ecology and Management 399 (2017) 9–23

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Mapping post-disturbance forest landscape composition with Landsat satellite imagery

Shannon L. Savage[a,*], Rick L. Lawrence[a], John R. Squires[b]

[a] Department of Land Resources & Environmental Sciences, Montana State University, PO Box 173120, Bozeman, MT 59717, United States
[b] Rocky Mountain Research Station, USDA Forest Service, 800 E. Beckwith, Missoula, MT 59801, United States

ARTICLE INFO

Article history:
Received 4 January 2017
Received in revised form 12 April 2017
Accepted 10 May 2017

Keywords:
Forest landscape composition
Spruce beetle
Disturbance ecology
Biotic legacy
Landsat satellite imagery
Percent canopy cover

ABSTRACT

Forests worldwide are impacted by a wide variety of disturbances that are happening more frequently with more intensity than in the past due to global climate change. Forest managers, therefore, need to identify new ways to quickly and accurately predict post-disturbance forest landscape composition. We suggest the use of Landsat satellite imagery and an image processing tool to map percent canopy cover (PCC) by species and sub-canopy species counts to be used in adaptive forest management strategies. We used zero-inflated models to successfully predict PCC and sub-canopy counts (number of regenerating trees per pixel, also called biotic legacies) for 4 tree species, along with overall PCC and percent mortality, for a large portion of the Rio Grande National Forest (RGNF) in 2013. The RGNF had recently been disturbed by spruce beetle (*Dendroctonus rufipennis*) infestation since the early 2000s and the West Fork Fire Complex in 2013. Our PCC models resulted in pseudo median differences between observed and predicted values of 0.2–6.5%, RMSE of 10.9–17.0%, and 95% confidence interval widths of 4.4–24.9%, depending on the species. The percent mortality model resulted in pseudo median differences between observed and predicted values of 1.1%, RMSE of 12.4%, and 95% confidence interval width of 4.6%. The sub-canopy PCC model resulted in a pseudo median differences between observed and predicted values of 1.3%, RMSE of 9.4%, and 95% confidence interval of 3.0%. The sub-canopy count models resulted in mean differences of 0.1–1.4 trees, RMSE of 3.0–13.4 trees, and 95% confidence interval widths of 1.1–5.0 trees, depending on species. By mapping PCC and sub-canopy counts, we have provided forest managers with knowledge of the current surviving forest (PCC) as well as the biotic legacies (sub-canopy counts) that can aid in forming hypotheses as to what the forest might become in the future, adding to the forest manager toolbox for forest management strategies. The methods described can be applied to a variety of issues within the field of disturbance ecology and, combined with change analyses, will provide forest managers with empirical evidence of current and future forest composition along with biological legacies that will impact forest regeneration.

1. Introduction

Large portions of forests worldwide have been disturbed over the past 50 years (Hansen et al., 2013; Hicke et al., 2016), and land managers face the daunting task of determining how these changes will affect their forests ecologically, economically, and historically. Land managers need a new way to quickly and accurately predict forest succession, since successional patterns, fire regimes, and pathogen resistance are evolving with the changes brought on by global climate change (Hicke et al., 2016). Adaptive management strategies that incorporate ecological principles and climate change-related effects are realistically the most appropriate approach for today's land managers (Crisafulli et al., 2005; Millar et al., 2007; Negrón et al., 2008; Schmid and Frye, 1977; Temperli et al., 2015).

Global climate change is a critical driving force in forest ecosystem balance (IPCC, 2014; Kennedy et al., 2014), resulting in severe disturbances in many locations across the globe. Bark beetles in particular have been observed to move to higher latitudes and elevations due to higher temperature suitability as well as depletion of host trees from drought and drought stress, and tree species at these higher locations have not yet adapted to insect outbreaks and are less likely to survive an outbreak (Bentz et al., 2010; Hart et al., 2014; Hicke et al., 2006, 2016; Jenkins et al., 2014; Jewett et al., 2011; Temperli et al., 2015).

* Corresponding author.
E-mail address: shannon.savage@msu.montana.edu (S.L. Savage).

http://dx.doi.org/10.1016/j.foreco.2017.05.017
0378-1127/

Land managers are limited in their ability to plan for economic, ecological, and historic impacts and protection without knowledge of the current species composition of their forests, particularly after a large disturbance. Land managers can make more informed decisions – and perhaps better decisions – when they approach their tasks through the lens of disturbance ecology. Traditional disturbance response/succession models tend to be long term and linear – i.e., moving from stand initiation through stem exclusion to understory re-initiation and finally arriving at an old growth stage with the process taking decades or centuries (Oliver, 1980) – leaving near-term (i.e., shortly after a disturbance) forest composition and structure uncertain, since successional patterns have changed due to global climate change (Derderian et al., 2016; Jewett et al., 2011; Temperli et al., 2015).

Disturbance ecology considers how the dynamic ecosystem might change over time (Bebi et al., 2003; Kennedy et al., 2014; Kulakowski et al., 2003; Lawrence and Ripple, 1999, 2000; McDowell et al., 2015; Walker et al., 2007). We have made great progress in understanding the driving forces and impacts of disturbances (Kennedy et al., 2014; Kulakowski et al., 2003). Biological legacies – vegetation that remains post-disturbance, including regeneration and colonizing vegetation – are among the most important variables influencing forest recovery after a disturbance (Crisafulli et al., 2005; Lawrence and Ripple, 2000; Sibold et al., 2007). Observation of forest vegetation patterns over time is essential for disturbance-related prevention, suppression, and restoration of forest ecosystems (Crisafulli et al., 2005; Fettig et al., 2007; Jenkins et al., 2014; Walker et al., 2007). Mortality of large trees in a forest stand from beetle-kill or stand-replacing fires, for example, could open the stand to faster and more dense regeneration (Derderian et al., 2016; Sibold et al., 2007) through reduction of competition for biological legacies. Efficient mapping of post-disturbance biological legacies using remote sensing has the potential to greatly assist in post-disturbance forest evaluation and planning.

Remote sensing scientists can take advantage of free Landsat satellite imagery to map many different types of ecosystems. Few studies have used Landsat imagery to predict species composition of a young forest after significant disturbance, or more specifically, through the lens of disturbance ecology. Lawrence and Ripple (2000) looked at the response of the Mount St. Helens landscape to the drastic changes caused by the volcanic eruption in 1981 and suggested that landscape-scale understanding of the distribution of biological legacies is critical to understanding post-disturbance vegetation responses. More recent studies have shown promise for mapping species composition and/or mortality as a percentage of each pixel rather than simply presence/absence. Savage et al. (2015) used zero-inflated modeling to accurately map percent canopy cover by species in northwestern Montana. Several recent studies have utilized Landsat imagery to detect tree mortality. Percent mortality within pixels was predicted using zero-inflated modeling for portions of the Helena National Forest in Montana with very accurate results (Long and Lawrence, 2016). A study in Texas was able to accurately detect drought-induced tree canopy loss using zero-or-one-inflated beta regression (Schwantes et al., 2016). In southwestern Colorado researchers successfully applied methods for classing mountain pine beetle-induced tree mortality and ecologically informed post-classification correction to detect spruce beetle-induced tree mortality (Hart and Veblen, 2015).

Our primary goal for this study was to characterize the structure and composition of a mixed conifer forest after major beetle-kill and large fires by using freely available Landsat imagery to evaluate within-pixel percent mortality and predict surviving tree composition by species for both dominant upper canopy species and sub-canopy regeneration. A secondary objective was to test and compare a series of prediction algorithms that have been previously applied to remotely sensed data in order to maximize predictive accuracy (as demonstrated in Savage et al. (2015)). We suggest that remote sensing applications can play a key role in monitoring ecosystems and assisting planning for future management (Nagendra et al., 2013). Our image analysis method is a powerful tool that allows land managers to predict and project compositions of future forests following disturbance (Long and Lawrence, 2016; Savage et al., 2015).

2. Methods

2.1. Study area

The Rio Grande National Forest (RGNF) covers 783,742 ha in Colorado and includes portions of the San Juan mountain range east of the continental divide. The study area covers approximately 347,000 ha, includes much of the RGNF Divide and Conejos Peak ranger districts (Fig. 1), and falls within one Landsat scene. It is a mountainous region ranging from 2550 to 4280 m in elevation with a variety of grassland, brushland, and forest types.

Rapid ecological changes have occurred in the high-elevation spruce-fir (*Picea engelmannii* – *Abies lasiocarpa*) zone within the RGNF due to a spruce beetle (*Dendroctonus rufipennis*) outbreak in the early 2000s that affected a large portion of the spruce-fir forests of the study area. Approximately 85% of the mature spruce-fir habitat on the RGNF had been influenced by the end of 2013 (Blakeman, 2013; RWEACT, 2016). The beetle-kill trees contributed to the dead fuel load of the forest, and the West Fork Fire Complex of 2013 burned approximately 44,515 ha of spruce-fir/aspen (*Populus tremuloides*) mix on the San Juan National Forest (SJNF) and RGNF (USFS, 2014). The fires, initially starting on the west (SJNF) side of the Continental Divide, spread to about 35,612 ha on the RGNF. Much of the burn occurred in spruce-fir cover types that already had significant rates of tree mortality due to the spruce beetle.

2.2. Data

2.2.1. Field data collection

We collected overstory and sub-canopy percent canopy cover (PCC) and sub-canopy tree count reference data in 2015 at 463 field locations randomly located within 500 m from roads and trails within the study area. Points were reviewed to be spatially homogenous and more than 40 m from the edge of a stand. Several points were excluded due to cloud cover in the imagery, providing 454 total reference points for use in modeling, exceeding the results of a Power test for proportion that suggested a minimum of 384 random sample points for our study (Chow et al., 2008).

We used two types of data collection methods: (1) 20-m $\times$ 20-m grid plot to estimate PCC and mortality (per Savage et al., 2015) and (2) line-intercept sampling to estimate sub-canopy count/-composition. Field crews established sample points on a 20-m by 20-m grid oriented to the north. Crews used a moosehorn, a tool for vegetation sampling (Fiala et al., 2006), to identify presence or absence of canopy cover every 5 m within the 20 $\times$ 20 grid (25 readings per field data point). Every tree observed as present with the moosehorn was identified (1) by species, (2) as live, red (dead or dying with red needles that have not fallen yet), or dead, and (3) whether upper canopy or sub-canopy. The total PCC for each species was calculated by adding together the number of times that species was listed as "live" in the upper canopy within the 25-point grid and multiplying that number by 4. Percent mortality was calculated by counting the number of times a tree's condition was listed as "dead" in the upper canopy within the 25-point grid and multiplying that number by 4 (regardless of species). The