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Effects of fire severity and post-fire climate on short-term vegetation recovery of mixed-conifer and red fir forests in the Sierra Nevada Mountains of California

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ABSTRACT

Forest ecosystems in the Sierra Nevada Mountains of California are greatly influenced by wildfire as a natural disturbance, and increased fire severity and drought occurrence may alter the course of post-fire recovery in these ecosystems. We examined effects of fire severity, post-fire climate, and topographic factors on short-term (<5 years) vegetation recovery in mixed-conifer and red fir forests in the Sierra Nevada. We hypothesized that short-term vegetation recovery patterns would be different among patches with varying fire severity, especially between low-moderate and high severity patches, and that post-fire climate would have differing impacts on short-term vegetation recovery in different ecological zones (lower montane forest vs. upper montane forest). 30-meter Landsat time series stacks were used to monitor short-term vegetation recovery following wildfire in mixed-conifer and red fir forest types. Changes in normalized difference vegetation index (NDVI) following thirty-five fires (>405 ha) between 1999 and 2006 were examined. According to the modeling results provided by ordinary least squares (OLS) regressions including spatial variation coefficients, fire severity, post-fire wet eason precipitation, post-fire January minimum temperature, and topographic factors explain variations in short-term post-fire NDVI values (adjusted R-squared = [0.680, 0.688] for red fir forests; adjusted R-squared = [0.671, 0.678] for mixed-conifer forests). The modeling results indicated that burned mixed-conifer forest was sensitive to post-fire drought, while burned red fir forest, with higher summer soil moisture availability, was sensitive to post-fire temperature. We also found that differences in recovery related to fire severity disappeared more quickly in burned mixed-conifer forest than in burned red fir forest. Future efforts should focus on long-term recovery, including competition between forest and shrub species in previously burned areas.

1. Introduction

Wildfire has a key role in shaping patterns and processes in terrestrial ecosystems of the western US (Sugihara, Wagtendonk, Fites-Kaufman, & Andrea, 2006). Fire-prone environments have promoted the adaptation of vegetation species in many western US forests, enabling these fire-adapted species to recover following fire (Sugihara et al., 2006). Nevertheless, post-fire vegetation recovery is still determined by many onsite factors, such as fire severity, different plant regeneration strategies, topography, and local climate (Chappell & Agee, 1996; Collins & Roller, 2013; Crotteau, Morgan Varner III, & Ritchie, 2013; Goforth & Minnich, 2008; Russell, McBride, & Rowntree, 1998; Scholl & Taylor, 2006; Shatford, Hibbs, & Puettmann, 2007; Taylor & Halpern, 1991; Taylor & Skinner, 1998).

Previous work has shown strong effects of fire severity on post-fire vegetation recovery (Chappell & Agee, 1996; Crotteau et al., 2013; Donato et al., 2009) and addressed the important role of landscape position and topography in explaining variations in forest establishment following fire over space and time Collins & Roller, 2013; Shatford et al., 2007. In the southern Cascades mountain range (which shares similarities in climate and vegetation with the Sierra Nevada range), Crotteau et al. (2013) found the highest conifer seedling density in medium fire severity patches, with lower density in high severity patches and intermediate density in low severity patches. However, shrub seedling density increased sharply with fire severity (Crotteau et al., 2013). Similar post-fire patterns of seedling establishment were also found in

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high-elevation forests dominated by red fir in the southern Cascades (Chappell & Agee, 1996).

Post-fire climate might also control forest regeneration and interact with factors such as landscape position to alter post-fire recovery (Chappell & Agee, 1996; Collins & Roller, 2013; Goforth & Minnich, 2008; Russell et al., 1998). Chappell and Agee (1996) found that post-fire red fir seedling establishment was higher in mesic areas and that seasonal drought was an important agent of seedling mortality. Elevation, as a proxy for climate, was found to have a strongly negative correlation with seedling density of mixed-conifer forests in the Sierra Nevada (Mantgem, Stephenson, & Keeley, 2006). Seedling dynamics might be the earliest signal of changing forest conditions and can indicate environmental changes (Mantgem et al., 2006). As a result, post-fire climate in the first growing seasons following fire may be highly important for forest regeneration (Donato et al., 2009).

Previous studies have made substantial contributions to our understanding of vegetation recovery following fire in the Sierra Nevada and southern Cascades, but most of them are ground-based and face logistical limitations in the extent of the areas that could be sampled (Chappell & Agee, 1996; Collins & Roller, 2013; Crotteau et al., 2013; Shatford et al., 2007). In contrast, remote sensing-based post-fire studies can provide insights into controls over vegetation responses to wildfire beyond what can be measured in spatially limited ground surveys (Chen et al., 2011; Chu & Guo, 2013; Díaz-Delgado & Pons, 2001; Gitas, Mitri, Veraverbeke, & Polychronaki, 2012; Lentile et al., 2006; Mitri & Gitas, 2013; White, Ryan, Key, & Running, 1996). Fire can affect the spectral and spatial properties of forests by vegetation removal, soil exposure, and soil color alteration (White et al., 1996). Spectral vegetation indices have been extensively examined to quantify post-fire vegetation recovery (Díaz-Delgado, Lloret, & Pons, 2003; Gitas et al., 2012; Ireland & Petropoulos, 2015; Lentile et al., 2006; Riaño et al., 2002; Veraverbeke et al., 2012; Viedma, Meliá, Segarra, & García-Haro, 1997; White et al., 1996). Imaging spectroscopy, lidar, and synthetic aperture radar data have more recently been incorporated into investigations of post-fire vegetation recovery (Huesca et al., 2013; Kane et al., 2013, 2014; Kane, Lutz et al., 2015a; Tanase, Santoro, de La Riva, Pérez-Cabello, & Le Toan, 2010a; Tanase, Santoro, Wegmüller, de la Riva, & Pérez-Cabello, 2010b; Tanase, de la Riva, Santoro, Pérez-Cabello, & Kasischke, 2011), but have limited spatial and temporal coverage.

Land managers endeavor to identify vulnerable areas with poor post-fire recovery potential, and then restore natural forest conditions with priority intervention (Collins, Kelly, Van Wagtendonk, & Stephens, 2007; Collins et al., 2009; Huesca et al., 2013). Thorough and accurate monitoring, evaluation, and understanding of post-fire forest regeneration are essential for assessing effects of disturbances on ecological processes, modeling vulnerability of forest ecosystems, and studying climate-fire regime interactions (Mitri & Gitas, 2013; Solans Vila & Barbosa, 2010). Using forest gap and climate models, optical remote sensing, and lidar data, a number of studies have recently explored the effects of local climate patterns and topography on fire regime and forest structure in the Sierra Nevada in depth (Kane et al., 2013, 2014; Kane, Cansler et al., 2015b; Miller & Urban, 1999a, 1999b; Schwartz et al., 2015). However, to our knowledge, previous studies have not investigated the effects of fire severity, post-fire climate, and topographic factors on vegetation recovery across a large spatial-temporal scale.

In this study, we examined effects of fire severity, post-fire climate, and topographic factors on short-term (<5 years) vegetation recovery in mixed-conifer and red fir forests in the Sierra Nevada. Normalized Difference Vegetation Index (NDVI) was used to monitor post-fire vegetation recovery trajectories (Clemente, Cerrillo, & Gitas, 2009; Epting & Verbyla, 2005; Henry & Hope, 1998; Hope, Tague, & Clark, 2007; Lee & Chow, 2015; Solans Vila & Barbosa, 2010). Competition between shrubs and trees starts immediately following fire in the Sierra Nevada (Collins & Roller, 2013; Crotteau et al., 2013; Nagel & Taylor, 2005), so vegetation recovery in this study refers to both tree and shrub regeneration. We used our analysis to explore two hypotheses:

(1) We hypothesized that short-term vegetation recovery patterns as measured by NDVI should be different among various fire severity patches, especially between low-moderate and high severity patches, considering the strong effects of fire severity on post-fire vegetation recovery (Chappell & Agee, 1996; Crotteau et al., 2013; Donato et al., 2009; Russell et al., 1998).
(2) We hypothesized that post-fire climate had significant impacts on short-term vegetation recovery as measured by NDVI in mixed-conifer forest at lower elevation (lower montane forest) and red fir forest at higher elevation (upper montane forest).

2. Methods

2.1. Study area

The study area encompassed the extent of two Landsat TM tiles, covering the central portion of the Sierra Nevada mountain range with an area of about 46,500 km^2 (Fig. 1). This region has a Mediterranean climate, with cool, moist winters and warm, dry summers. Most of the annual precipitation is in winter, and in the form of snow at higher elevation (above 1800 m). The native vegetation varies with elevation from chaparral shrubland communities at lower elevation (~380 to 1500 m), mixed conifer forest at mid-elevations (~1100 to 1900 m), and lodgepole pine and red fir forests (~2400 to 3000 m) to subalpine forest and alpine meadows at higher elevations (above around 2650 m) (Storer & Usinger, 1963). This study will focus solely on mixed-conifer and red fir forests derived from the 1977 Classification and Assessment with Landsat of Visible Ecological Groupings (1977 CALVEG, described below). Mixed-conifer forest primarily consist of white fir (*Abies concolor*), Douglas-fir (*Pseudotsuga menziesii*), sugar pine (*Pinus lambertiana*), ponderosa pine (*Pinus ponderosa*), Jeffrey pine (*Pinus jeffreyi*), incense-cedar (*Calocedrus decurrens*), California black oak (*Quercus kelloggii*), and other hardwood species (Collins & Roller, 2013). Mean fire return interval generally increases with elevation, which is a characteristic of the Sierra Nevada fire regime (Swetnam, Baisan, Morino, & Caprio, 1998).

2.2. Datasets

The main dataset applied to characterizing vegetation recovery following fire was based on 30-meter spatial resolution Landsat Time Series Stacks (LTSS) covering the period from 1994 to 2011. LTSS were preprocessed for radiometric normalization and masking of cloud and cloud shadow (Huang, Goward et al., 2010a; Huang, Thomas et al., 2010b). In order to remove potential errors caused by misregistration and terrain relief, each image in the LTSS was registered and orthorectified precisely using a corresponding base image with minimal geolocation errors and a digital elevation model (DEM) (Huang, Goward et al., 2010a). Preprocessing of data used in the LTSS was done through the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) (Gao, Masek, & Wolfe, 2009).

Corresponding maps of forest disturbance history (1984 to 2011) were generated by Vegetation Change Tracker (VCT), an automated algorithm for reconstructing forest disturbance history (Huang, Goward et al., 2010a). Based on the spectral-temporal properties of land cover and forest change processes, VCT disturbance maps record the changes in forests occurring over a particular year, while not providing detailed information on the disturbance type (Huang et al., 2009; Huang, Goward et al., 2010a). The Landsat imagery used for annual NDVI calculation (described below) was also derived from VCT. MTBS (Monitoring Trends in Burn Severity; http://www.mtbs.gov/) data were used to