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Water balance and topography predict fire and forest structure patterns

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ABSTRACT

Mountainous topography creates fine-scale environmental mosaics that vary in precipitation, temperature, insolation, and slope position. This mosaic in turn influences fuel accumulation and moisture and forest structure. We studied these the effects of varying environmental conditions across a 27,104 ha landscape within Yosemite National Park, California, USA, on the number of fires and burn severity (measured from Landsat data for 1984–2010) and on canopy cover at two heights (>2 m and 2–8 m) and dominant tree height (measured with airborne LiDAR data). We used site water balance (actual evapotranspiration and climatic water deficit) and topography (slope position, slope, and insolation) as environmental predictors. Random forest modeling showed that environmental conditions predicted substantial portions of the variations in fire and forest structure: e.g., 85–93% of the variation in whether a location did not burn, burned once, or burned twice; 64% of the variation in the burn severity; and 72% of the variation in canopy cover >2 m for unburned forests, 64% for once-burned forests, and 59% for twice-burned forests. Environmental conditions also predicted a substantial portion of forest structure following one and two fires, even though the post-fire forest structures were substantially different than pre-fire structures. This suggests a feedback mechanism in which local fire regimes and pre-fire forest structures are related to local environments, and their interaction produces post-fire structures also related to local environments. Among environmental predictors, water balance had the greatest explanatory power, followed by slope position, and then by slope and insolation. Managers could use our methods to help select reference areas that match environmental conditions, identify areas at risk for fires that endanger critical habitat or other resources, and identify climate analog areas to help anticipate and plan for climate change.

1. Introduction

Within mountainous regions, variations in precipitation, temperature, aspect, slope, slope position, and soils (Knapp and Smith, 2001; Dyer, 2009; Dobrowski et al., 2009; Greenberg et al., 2009; Urban et al., 2000; Dobrowski, 2011; Holden and Jolly, 2011) create fine-scale mosaics of environmental conditions. These mosaics in turn create and maintain differences in forest processes, composition, and structure (Stephenson, 1998; Urban et al., 2000; Taylor and Skinner, 2003; Hessburg et al., 2007; Meyer et al., 2007; Underwood et al., 2010; Lydersen and North, 2012). Varying environmental conditions may help explain why mountainous regions are biodiversity hotspots (Körner and Ohsawa, 2005) and why these regions can serve as important areas of conservation and refugia under future climate change (Dobrowski, 2011).

Work in the Sierra Nevada Mountains (California, USA), for example, has shown strong effects of site water balance (actual evapotranspiration and climatic water deficit) on forest species composition and structure (Parker, 1982, 1989; Stephenson, 1998; Lutz et al., 2009, 2010). Other work has addressed the effects of topography and landscape position on both fire behavior and forest structure (Collins et al., 2006; Underwood et al., 2010; Lydersen and North, 2012). In previous work by several of us, we found changes in forest structure following fire along an elevation gradient related to the moisture gradient (Kane et al., 2013, 2014).

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Miller and Urban explored these topics in greater depth for the Sierra Nevada range using a forest gap and climate model to simulate the effects of local climate and topography on fire and forests (Miller and Urban, 1999a, 1999b; Miller and Urban, 2000a, 2000b; Urban et al., 2000). Their work emphasized the role of available moisture for creating mosaics of forest biomass and fuel moisture and accumulation. These moisture patterns were primarily driven by the strong elevation gradient but modified by local topography (Urban et al., 2000).

Variations in the actual weather during fires should weaken the relationship between environmental conditions and forest structure (Peterson, 2002; Lydersen et al., 2014). A triangle of equally important and interactive elements – topography, fuels, and weather – control fire behavior and influence its resulting severity and effects on forest structure (Sugihara et al., 2006). The stochastic nature of weather during the course of fires may result in stochastic patterns of burn severity that mask or replace the relationship between the environmental conditions and fire and forest structure (Collins et al., 2006; Collins, 2014). Large fire growth days are commonly caused by extreme fire weather (hot temperatures, high winds, or atmospheric instability) that overwhelms the effects of topography and fuels on fire behavior (Lydersen et al., 2014).

To our knowledge, no study has examined the integrated effects of the environmental mosaic on fire and forest structure patterns using actual data mapped across a real large landscape. A better understanding of the effects of environmental mosaics would explore important ecological relationships and help managers better predict how re-introduced fire may behave and to determine appropriate restoration goals for forest structure.

One reason for the lack of this type of study may be that within most of the western United States it is difficult to fully test the potential influence of environmental heterogeneity on fire patterns and forest structure. Typically, only fires that burn under extreme fire conditions and with high fire severities escape suppression and become large enough to influence landscape forest patterns (Moritz et al., 2005; van Wagtendonk, 2007; Miller et al., 2012; Mallek et al., 2013). Additionally, over a century of timber harvests, fire suppression, grazing, and low-density residential development have substantially altered the physical structure of forests (Hessburg and Agee, 2003; Romme et al., 2009; Naficy et al., 2010; Knapp et al., 2013).

The majority of Yosemite National Park, California, USA, however, has been managed as a wilderness. Since 1972, park managers have allowed many lightning-ignited fires and prescribed fires to burn (Van Wagtendonk and Lutz, 2007). Park managers recognize the importance of restoring fire as an ecological process, but must balance the risk wildfires present to visitor safety, smoke accumulation, infrastructure, wildlife and endemic plant habitats, as well as other ecosystem services. Managers here as in many areas worldwide would benefit from an understanding of how local environmental factors influence fuel moisture and accumulation and forest structure, and how an intact fire regime may influence them.

In this study, we examine the effects of the mosaic of environmental conditions on fire and forest structure across two landscapes within Yosemite, using as many as 35,000 sample locations from continuous maps of environmental variables, fire, and forest structure. We examine a wider breadth of environmental predictors than previous studies, examine fire patterns from 1984 to 2010, and measure forest structure with airborne LiDAR data. We explore three hypotheses:

- A substantial portion variation in fire and forest structure across a mountainous landscape can be explained by variations in the environmental conditions.
- The relationship of environmental conditions to forest structure will substantially weaken with the occurrence of fire because of the stochastic effects of weather on fire.
- Because of the strong elevation gradient in our study area, changes in water balance (moisture availability) will be the strongest environmental predictor for variations in fire and forest structure.

2. Methods

2.1. Study area

Yosemite National Park (3027 km^2) lies in the central Sierra Nevada, California, USA (Fig. 1). The western portion of Yosemite possesses a Mediterranean climate with July (mid-summer) mean minimum and maximum temperatures of 2–13 °C at higher elevations and 16–35 °C at lower elevations. Most precipitation falls as snow with annual precipitation ranging from 800 mm to 1720 mm (Lutz et al., 2010). The park has multiple wildfires each year, and since 1972 many lightning-ignited fires have been allowed to burn (van Wagtendonk and Lutz, 2007) with many fires burning with low and mixed-severities. This practice has resulted in most fires burning under and moderate weather conditions resulting in a mixture of fire severities that may emulate the historic mixed-severity fire regime (van Wagtendonk, 2007; Sugihara et al., 2006; Mallek et al., 2013). This long period of reintroduced fire has allowed large areas to return towards a self-regulated fire regime (van Wagtendonk, 2007; Mallek et al., 2013) and reduced fuel loads and fuel continuity over a considerable area (Miller et al., 2012). (Low-severity fires generally have overstory tree mortalities <25%; mixed-severity fires create patchworks of overstory mortality that can range from none to complete overstory mortality within a patch, with mortalities of 25–75% being common; and high severity fires have overstory tree mortalities >75% (Sugihara et al., 2006).)

We studied two forested areas within the park with a combined area of 27,104 ha that had available airborne LiDAR data. The Northern area runs generally parallel to California State Highway 120, and the Illilouette area encompasses the Illilouette Creek basin. Between 1970 and 2010, the Northern area had 39 fires ⩾40 ha and the Illilouette area 29 fires (Supplement Table 1).

We excluded locations that had burned before 1970 when park managers began allowing fires to burn under low and moderate weather conditions. We assigned forest types within the study areas primarily based on the 1997 park vegetation map (Keeler-Wolf et al., 2012). If the area was not forested in 1997, we used the 1937 vegetation classification (Wieslander, 1935; Walker, 2000) under the assumption that fire had caused a shift in vegetation type. We excluded areas not currently forested, nor forested in 1937.

Three forest types were common between both study areas: sugar pine-white fir (*Pinus lambertiana–Abies concolor*), Jeffrey pine (*Pinus jeffreyi*), and red fir (*Abies magnifica*). Three other forest types occurred primarily in only the Northern area – ponderosa pine (*Pinus ponderosa*) – or the Illilouette area – lodgepole pine (*Pinus contorta* subsp. *murrayana*) and western white pine (*Pinus monticola*). Historically, most of these forest types were dominated by tree species such as ponderosa pine, sugar pine, Jeffrey pine, red fir, and white pine that had high fire tolerance (van Wagtendonk and Fites-Kaufmann, 2006). Since the advent of fire suppression, a less fire tolerant species, white fir, has become common in the ponderosa pine and sugar pine forests.

These forest types are associated with specific elevation ranges with the Illilouette forests types at higher elevations than their Northern study area counterparts (Fig. 2). As elevation increases, mean precipitation increases, mean temperature decreases, fre-