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Assessing fire effects on forest spatial structure using a fusion of Landsat and airborne LiDAR data in Yosemite National Park

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ABSTRACT

Mosaics of tree clumps and openings are characteristic of forests dominated by frequent, low- and moderate-severity fires. When restoring these fire-suppressed forests, managers often try to reproduce these structures to increase ecosystem resilience. We examined unburned and burned forest structures for 1937 0.81 ha sample areas in Yosemite National Park, USA. We estimated severity for fires from 1984 to 2010 using the Landsat-derived Relativized differenced Normalized Burn Ratio (RdNBR) and measured openings and canopy clumps in five height strata using airborne LiDAR data. Because our study area lacked concurrent field data, we identified methods to allow structural analysis using LiDAR data alone. We found three spatial structures, canopy-gap, clump-open, and open, that differed in spatial arrangement and proportion of canopy and openings. As fire severity increased, the total area in canopy decreased while the number of clumps increased, creating a patchwork of openings and multistory tree clumps. The presence of openings >0.3 ha, an approximate minimum gap size needed to favor shade-intolerant pine regeneration, increased rapidly with loss of canopy area. The range and variation of structures for a given fire severity were specific to each forest type. Low- to moderate-severity fires best replicated the historic clump-opening patterns that were common in forests with frequent fire regimes. Our results suggest that managers consider the following goals for their forest restoration: 1) reduce total canopy cover by breaking up large contiguous areas into variable-sized tree clumps and scattered large individual trees; 2) create a range of opening sizes and shapes, including ~50% of the open area in gaps >0.3 ha; 3) create multi-story clumps in addition to single story clumps; 4) retain historic densities of large trees; and 5) vary treatments to include canopy-gap, clump-open, and open mosaics across project areas to mimic the range of patterns found for each forest type in our study.

1. Introduction

In frequent-fire pine and mixed-conifer forests in western North America (hereafter, *dry forests*), historic accounts (Dunning, 1923; Show & Kotok, 1924) and studies of forests with active fire regimes (Collins & Stephens, 2010; Collins, Kelly, van Wagtendonk, & Stephens, 2007; Larson & Churchill, 2012; Stephens & Collins, 2004; Stephens & Gill, 2005) have emphasized the importance of spatial variability in forest structure to maintain ecosystem process and resilience. A recent review of studies of stand-level structure found that fire-frequent dry forests were composed of mosaics of widely-spaced individual trees, tree clumps (two to 20+ trees), and openings (Larson & Churchill, 2012). Historically, these patterns of individual trees, tree clumps, and openings were maintained by fire and insect-driven mortality, and once established, tended towards self-perpetuation. Openings would act to moderate fire and inhibit bark-beetle dispersal (Finney et al., 2007; Pimont, Dupuy, Linn, & Dupont, 2011; Stephens, Fry, & Franco-Vizcaino, 2008) while the fine-scale local variation in canopy height and continuity would impede crown fires (Beaty & Taylor, 2007; Parisien, Miller, Ager, & Finney, 2010; Pimont et al., 2011; Stephens et al., 2008; Thaxton & Platt, 2006). Openings also provided areas for subsequent regeneration, particularly of shade-intolerant, fire-resistant species, creating a fine-scale shifting mosaic maintained by frequent fire (Agee, 1993; Boyden, Binkley, & Shepperd, 2005; Cooper, 1960; Sánchez Meador, Moore, Bakker, & Parysow, 2009).

Today, decades of fire exclusion have altered forest structure and often led to forests with nearly continuous canopies (Hessburg, Agee,

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& Franklin, 2005). Openings, especially large ones that can act as fire breaks and regeneration sites, are less prevalent than they were a century ago (Hessburg et al., 2005; Lutz, Larson, Swanson, & Freund, 2012; Scholl & Taylor, 2010). To restore structure, maintain resilience, and mitigate the possibility of large areas of high-severity fire, managers use mechanical thinning and prescribed and wildland fire across hundreds of thousands of hectares of public forests annually (Miller et al., 2012; North, Collins, & Stephens, 2012; Schoennagel & Nelson, 2011).

Researchers and managers need spatially-explicit measurements of tree clumps and openings over large areas to understand the ecological relationships between fire and the spatial structure of forests. Stem maps of reconstructed pre-Euro-American era forests or active-fire regime sites have been the primary source of information (e.g., Harrod, McRae, & Hartl, 1999). However, only 22 stem-map studies have been conducted on dry forest reference sites from 1960 to 2011 covering a cumulative 294.7 ha (Larson & Churchill, 2012; Lutz et al., 2012). The limited area suggests that the full diversity of spatial structures on western landscapes has been under sampled. Most spatially explicit tree maps are of small areas (0.5 to 4 ha) and thus do not inform managers on how pattern varies over spatial extents commonly used in restoration treatments (10 to 100 ha), or intact landscapes (>1000 ha). In addition, few stem map studies contain height information, and little is known about the vertical structure of tree clumps. Silvicultural methods are being developed to restore stand-level patterns of tree clumps and openings (Churchill et al., 2013; North & Sherlock, 2012), but these lack high resolution spatial reference information over large scales (Larson & Churchill, 2012).

Airborne Light Detection and Ranging (LiDAR) data can assess forest structure over large areas (Hudak, Evans, & Stuart Smith, 2009; Lefsky, Cohen, Parker, & Harding, 2002; Reutebuch, Andersen, & McGaughey, 2005) including patterns of gaps and tree clumps. LiDAR's strength is the high resolution (typically several measurements per square meter) and consistent measurement of ground elevation and canopy heights over large areas with greater fidelity to structural attributes than possible with satellite images (Asner et al., 2011; Hummel, Hudak, Uebler, Falkowski, & Megown, 2011). Researchers have traditionally correlated LiDAR canopy measures with extensive ground-based tree measurements (e.g., for biomass or cubic volume). However, many forest LiDAR acquisitions lack concurrent field data. Lefsky, Hudak, Cohen, and Acker (2005) and Kane, McGaughey, et al. (2010) laid out the theoretical basis and provided a practical example (Kane, Bakker et al., 2010) for interpreting relative differences in forest structure using LiDAR data as a primary data source. Recently, researchers have begun to use LiDAR as a primary data source to study forest canopy structure without reference to field data over large areas (Asner et al., 2013; Kane et al., 2011, 2013; Kellner & Asner, 2009; Whitehurst, Swatantran, Blair, Hofton, & Dubayah, 2013). One of our goals is to identify methods to study openings and tree clumps for acquisitions that lack field data and demonstrate potential use for ecological analysis. Building on methods of Kane et al. (2011), we examine spatial structure of unburned stands and stands following fire. We used Landsat images to estimate fire severity across a 26 year period (1984 to 2010).

In this study, we use LiDAR data to examine the effects of different fire severities on the range of opening and tree clump structures (Fig. 1) found in three unburned and burned forest types (ponderosa pine, white fir-sugar pine, and red fir) common on the Sierra Nevada's western slope. While the role of fire in shaping and maintaining dry forests with active fire regimes is well documented (Collins & Stephens, 2010; Collins et al., 2007; Larson & Churchill, 2012; Stephens & Collins, 2004; Stephens & Gill, 2005), the effect of re-introduced fire following decades of fire exclusion is less well understood (but see Collins, Everett, & Stephens, 2011; Lydersen & North, 2012; Miller & Safford, 2012).

We used the methods identified for this study to address three questions related to the spatial structure of forests with increasing fire severity:

1. How do the spatial structures of clumps and openings change with increasing fire severity for these three forest types?
2. Which model(s) of forest restructuring (thin from below, dispersed mortality of all tree heights, or patchy mortality of all tree heights) best explains changes in structure with increasing fire severity?
3. What are the management implications for forest structural restoration?

2. Methods

We developed new methods for this study to analyze the spatial structures of tree clumps and openings for different fire severities and forest types. We reused the Landsat fire severity measurements and LiDAR data of Kane et al. (2013), who performed complementary analyses focused on changes in canopy profiles with fire, the landscape patterns of fire severity in a mixed severity landscape, and a rudimentary spatial structure analysis that demonstrated the need for this follow on study. In an effort to standardize terminology, our definitions of forest spatial structure are listed in Table 1.

2.1. Study area: Yosemite National Park

Yosemite National Park (3027 km^2) lies in the central Sierra Nevada, California, USA. As a protected area, the forests in Yosemite currently experience no pre- or post-fire logging. A small portion of the land now within park boundaries was logged in the early 20th century, but there has been limited thinning and development since the finalization of the park boundaries in 1937. As a result, Yosemite is one of the best remaining

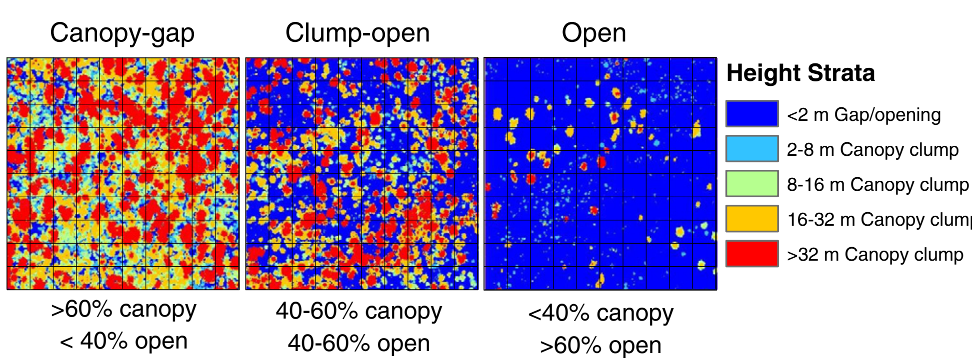

Fig. 1. Examples of the canopy-gap (canopy clumps dominate area and enclose gaps), clump-open (similar area of canopy clumps and openings), and open areas (openings dominate area and enclose small canopy clumps). Each example area is 300 m × 300 m (9 ha) and grid lines show areas of 30 m × 30 m (0.09 ha). Canopy and gap characteristics of individual 30 m × 30 m areas often are not representative of the context at larger scales such as the 90 m × 90 m (0.81 ha) sample areas used in this study.