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Landscape restoration of a forest with a historically mixed-severity fire regime: What was the historical landscape pattern of forest and openings?

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ABSTRACT

Forest management of dry forests in the western US that historically experienced mixed-severity fire regimes is increasingly focused on landscape-scale restoration. However, this restoration effort is constrained by historic range of variation (HRV) reference conditions that lack information concerning the spatial configuration of these forests at intermediate scales (approximately 0.01–100 ha). I used reconstruction methods to map historical (1860) pattern of ponderosa pine-Douglas-fir forests along twenty 1 km long transects on Colorado's Front Range and compared pre-settlement opening and forest patch lengths to current forest configurations to inform restoration reference conditions. Historically, openings were prevalent on south-and east-facing aspects, at lower elevations, and on gentler slopes. Generally, mean forest cover rose from 57% prior to settlement to 83% currently, and the current condition of any one location is 3.7 times more likely to be forested now than prior to settlement. In addition, the mean forest patch length increased from 35 to 118 m long. However, the mean opening length has changed little, increasing from 26 to 27 m long. Changes in the distribution of forest opening lengths suggest that there has been a loss of small openings (<50 m long) producing the small increase in mean patch length; however, the abundance of larger openings (>50 m) across the landscape has been relatively stable. In addition, there has been an increase in large forest patches (>50 m) at the expense of small forest patches (<50 m). Results from this study suggest that forest restoration treatments should focus on recreating small openings (<50 m long) by breaking up large contiguous forest canopy patches within the context of local site conditions.

1. Introduction

The structure and function of dry forest ecosystems of the western United States have changed since European American settlement in the late 19th century, and generally these forests are currently more susceptible to large severe wildfires than they have been historically (Allen et al., 2002; Noss et al., 2006). To address these issues, forest managers are increasingly applying landscape ecology theories to inform silvicultural treatments; however, there is generally a paucity of information regarding the landscape-scale structure and function of these ecosystems.

For example, the montane ponderosa pine (*Pinus ponderosa*) forests of Colorado's Front Range have changed since European American (*circa* 1860) settlement due to historical logging, grazing and fire suppression (Gruell, 1985; Kaufmann et al., 2000, 2003; Marr, 1961; Mast et al., 1998; Sherriff and Veblen, 2006; Veblen and Donnegan, 2005; Veblen and Lorenz, 1986, 1991; Veblen, 2000). While historically these forests were maintained by a mixed-severity fire regime (Brown et al., 1999; Sherriff and Veblen, 2006, 2007; Veblen et al., 2000; Veblen and Lorenz, 1986), the increase in forest density accompanied by the increasingly warm and dry climate have led to undesirably large and severe wildfires on the Front Range in recent decades (e.g., Black Tiger Fire in 1989, Buffalo Creek Fire in 1996, Hi Meadow and Bobcat Gulch Fires in 2000, Hayman Fire in 2002, Four Mile Canyon Fire in 2010, Hewlett Gulch, High Park and Waldo Canyon Fires in 2012, and Black Forest Fire in 2013). Similar changes in disturbance regimes and forest structure have also occurred in

Abbreviations: HRV, Historic range of variation; FR-CFLRP, Front Range Collaborative Forest Landscape Restoration Project.

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other fire-adapted coniferous forests that historically demonstrated low- and mixed-severity fire regimes across the western US (Allen et al., 2002; Noss et al., 2006).

Because of this increased occurrence of undesirable wildfire, forest managers are increasingly focusing on manipulating the structure of these forests at the stand- and landscape-scales with the aim of mimicking or restoring the historical fire regime (Covington, 2000). Typically, these treatments use thinning techniques to reduce canopy fuel loads and break up the continuity of horizontal and vertical fuel complexes to modify fire behavior (Hunter et al., 2007). Forest managers are also seeking to improve wildlife habitat and the diversity of understory plants by reducing forest canopy cover and increasing the structural diversity of the forest (FRLRI, 2010).

In the absence of comprehensive context-specific information about primeval ecosystem functioning of these forests, forest managers have turned their focus to using the forest structures and compositions that existed prior to settlement as reference conditions (Keane et al., 2009; Veblen and Donnegan, 2005). The hope is that this restoration of forest structure and composition will promote sustainable ecosystem function. Specifically, by incorporating elements of pre-settlement forest structures, these managers aspire to recreate fuel complexes similar to those prior to settlement and therefore return the historical disturbance regime. Therefore, the focus of many forest managers has been to create a "natural-looking" heterogeneous landscape with varying proportions of tree groups, openings and single isolated trees among stands (Abella and Denton, 2009; Churchill et al., 2013; Larson and Churchill, 2012).

However, due to the paucity of published studies that quantify the historical landscape-scale forest structure at intermediate scales (approximately 0.01–100 ha) uncertainty and debate surround the reference conditions for restoration, particularly for forest types that historically maintained a mixed-severity fire regime. For example, forest managers working to restore montane ponderosa pine forests on Colorado's Front Range frequently ask "How large should forest openings be?" and "How big should the residual patches of forest be?" Currently, there is limited scientific basis to determine the likely pre-settlement size of these openings and forest patches in these forests, or provide guidance about the appropriate spatial configuration of forest restoration treatments.

A number of studies in the dry forest ecosystems of the western United States have examined the historical fire regime to inform restoration using a range of techniques. Dendrochronological studies of fire scars have been used to reconstruct historical fire frequency and extents (e.g. Brown et al., 1999; Sherriff and Veblen, 2007); however, these studies provide limited information about the appropriate size of openings or forest patches for restoration. Further studies have investigated the fine-scale (<10 m) patterns of trees using point pattern analyses (e.g. Mast and Veblen, 1999), but do not provide information regarding coarser-scale landscape patterns. In addition, studies using early land survey records utilize spatially sparse data and therefore may inform managers regarding broad-scale regional patterns (e.g. Williams and Baker 2012a,b); but, are known to have a number of limitations (Fulé et al. 2013; Schulte and Mladenoff, 2001).

A handful of studies have specifically reconstructed the historic spatial configuration of various dry forest ecosystems in North America. These studies encompass a wide range of forest types, with varying historic fire regimes and opening or forest patch sizes ranging from 6.6 m^2 to 3373 ha (Fry et al., 2014; Lydersen et al., 2013; Stephens and Fry, 2005; Skinner, 1995). In terms of forests dominated by mixed-severity fire regimes specifically, Agee (1998) suggested that these fire regimes may result in a great variety of opening sizes ranging from 0.1 to 300 ha. In contrast, Hessburg et al. (2007) detected a range of forest patch sizes from 4 to 3373 ha using early aerial imagery in eastern Washington. While, Kaufmann et al. (2000) determined that historically forest openings ranging in size from <1 ha to >20 ha probably accounted for 10–20% of the Cheesman Reservoir landscape on Colorado's Front Range prior to settlement.

In addition, a number of spatially-explicit studies of forest ecosystems dominated by mixed-severity fire disturbance regimes have also demonstrated an approximately "reverse-J" distribution of land-cover patch sizes across the landscape, with many small patches that cumulatively occupy a small proportion of the area and few large patches that cumulatively occupy the majority of the landscape (Halofsky et al., 2011; Perry et al., 2011; Collins and Stephens, 2010; Hessburg et al., 2007). Similar distributions have been demonstrated in forests dominated by low-severity fire (Fry et al., 2014; Stephens and Fry, 2005; Piirto and Rogers, 2002; Skinner, 1995; Lydersen et al., 2013) and high-severity fire (Johnson et al., 1998) disturbance regimes.

Whilst these studies inform forest restoration, further information is needed to guide restoration treatments in dry forest ecosystems with historically mixed-severity fire regimes, particularly in terms of opening size and location.

The objective of this study was to investigate the current and historical landscape configuration of montane ponderosa forests that were historically dominated by a mixed-severity fire regime prior to settlement at intermediate scales (approximately 0.01–100 ha), to inform forest restoration activities. Furthermore, it is hoped that this study may provide insight into the historical landscape configurations of dry forests dominated by mixed-severity fire regimes generally. Specifically, I sought to answer the following questions:

1. How open was the montane ponderosa forest on Colorado's Front Range prior to settlement compared to current conditions, and how did forest patches and openings vary with topographic gradients such as slope, aspect and elevation?
2. What was the size distribution of forest patches and openings in montane ponderosa forests of Colorado's Front Range prior to settlement compared to current conditions?

I hypothesize that forest cover in these montane ponderosa forest cover has increased since settlement at the expense of forest openings. In addition, I expect that prior to settlement, openings were more prevalent on drier (south-facing, low elevations) than more mesic sites (north-facing, higher elevations).

Furthermore, I hypothesize that montane ponderosa forests on Colorado's Front Range will exhibit a "reverse-J" distribution of patch sizes similar to those demonstrated in studies elsewhere (Halofsky et al., 2011; Perry et al., 2011; Collins and Stephens, 2010; Hessburg et al., 2007). In addition, I hypothesize that there has been a reduction in the number of large openings since settlement through the incursion of forest regeneration from adjacent forest patches and that the "filling in" of small openings by the invading forest has reduced the abundance of small openings.

To test these hypotheses, I mapped current forest cover and evidence of pre-settlement forest cover (old trees, stumps and eroded coarse woody debris) along extended transects across the landscape, and investigated the lengths of these patches and openings prior to settlement and currently.

2. Materials and methods

2.1. Study sites and data collection

The Arapaho-Roosevelt and Pike National Forests are actively restoring montane ponderosa pine and dry-mixed conifer forests as part of the Front Range Collaborative Forest Landscapes