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Spatially explicit measurements of forest structure and fire behavior following restoration treatments in dry forests

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ABSTRACT

Restoration treatments in dry forests of the western US often attempt silvicultural practices to restore the historical characteristics of forest structure and fire behavior. However, it is suggested that a reliance on non-spatial metrics of forest stand structure, along with the use of wildland fire behavior models that lack the ability to handle complex structures, may lead to uncharacteristically homogeneous rather than heterogeneous forest structures following restoration. In our study, we used spatially explicit forest inventory data and a physics based fire behavior model to investigate the effects of restoration driven, variable retention harvests on structural complexity, both of horizontal and vertical dimensions, and potential fire behavior. Structural complexity was assessed at stand and patch scales using a combination of point pattern analyses, a patch detection algorithm, and nearest-neighbor and tree patch indices of height variation. The potential fire behavior before and after treatment was simulated across a range of open wind speeds using a 3-D physics based fire behavior model, the Wildland-urban interface Fire Dynamics Simulator (WFDS). Our results show that treatments resulted in an aggregated spatial pattern of trees consisting of a matrix of individual trees, clumps and openings similar to descriptions of historical dry forests. Treatments had inconsistent effects on vertical complexity across sites likely due to differences in treatment of ladder fuels; lack of reference conditions hinder evaluation of this structural aspect. Simulation modeling using WFDS suggest that treatments moderated fire rate of spread, fireline intensity and canopy consumption across all wind speeds tested and shifted potential fire behavior towards historical ranges. Our findings suggest that current restoration-based variable retention harvests can simultaneously fulfill objectives of altering structural complexity and of reducing fire behavior, though we recommend further research on desired ranges of vertical complexity to inform treatment design.

1. Introduction

Land management practices such as livestock grazing, fire suppression, and timber-oriented management following Euro-American settlement have contributed to varying degrees of altered forest structure across the western U.S. Changes in forest structure are particularly evident in dry forest types that historically had frequent low to moderate severity fire regimes (Brown et al., 2015; Franklin et al., 2013; Fulé et al., 2009; Naficy et al., 2010; Veblen et al., 2000). As a result, modern forests are often thought to have increased surface and canopy fuel loads and less complex forest structural patterns (Tuten et al., 2015). These changes are believed to result in an increased potential for extensive uncharacteristic wildfires exceeding historical ranges of fire behavior and severity with impaired ecosystem function and lower long term forest resiliency (Fulé et al., 1997; Hessburg et al., 2005; Savage and Mast, 2005). Concerns over the potential impacts of changes in forest structure have resulted in an increased emphasis on utilizing forest treatments to modify forest structure such that both contemporary forest structure and potential fire behavior are similar to historical patterns (Allen et al., 2002; Fulé et al., 1997; Moore et al., 1999; Schultz et al., 2012; Underhill et al., 2014; Youngblood et al., 2004).

These treatments seek to restore the historic patterns of forest structure and potential fire behavior to contemporary forests often using variable retention harvesting as a silvicultural practice. Several restoration-focused variable retention harvest implementation

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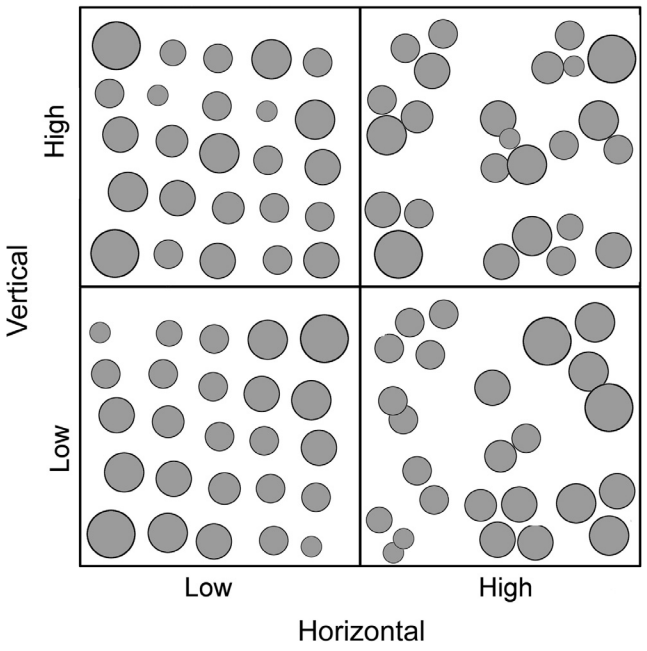

Fig. 1. Overhead view of the same rearranged trees (filled dots), scaled by height, across two levels of horizontal and vertical complexity.

strategies have been developed (Churchill et al., 2013a; Fulé et al., 2001; Graham et al., 2006; Moore et al., 1999; Reynolds et al., 2013; Youtz et al., 2008). Common to all of these is treatments using variable retention harvesting for the purpose of restoration specifically differ from other silvicultural strategies such as traditional fuel hazard reduction treatments in that they seek to create complex forest structures analogous to the natural range of variation in forest structure by modifying two interrelated components of forest structure: the type, number and size of individual elements (e.g. trees) that make up the forest and their structural complexity (Churchill et al., 2013b).

Structural complexity refers to the degree of spatial heterogeneity of forest structure (Zenner, 2004). Structural complexity can be characterized across both horizontal and vertical dimensions and at multiple scales (Fig. 1). Given that forest management typically operates at the spatial scale of a stand (O'Hara and Nagel, 2013) we focused this work on describing complexity at the stand and tree patch (i.e. within-stand) scales (Fig. 1). At the stand scale, horizontal complexity is often described by classifying the general spatial pattern exhibited by trees (e.g. Harrod et al., 1999) while patch scale measures describe the horizontal mosaic of different sized patches of trees, generally ranging from 2 to 20 trees, individual trees, and openings (Larson and Churchill, 2012). Vertical complexity at stand scales focus on the degree to which differently sized trees spatially intermingle over a stand (Franklin and Van Pelt, 2004), while at a finer scale, variability in tree heights within patches of trees is often measured (Cooper, 1960; Mast and Veblen, 1999; White, 1985).

Several previous studies have shown that restoration treatments can be effective for meeting non-spatial forest structure restoration objectives and reducing potential fire behavior (Fulé et al., 2012; Harrod et al., 1999; Hudak et al., 2011). However, there is concern that the lack of spatially explicit reference conditions across the geographic range of dry-forest types lead to a reliance on non-spatial measures of forest structure such as trees per acre or basal area which do not account for the juxtaposition of trees or of their attributes. This could result in uniform implementation of treatments and lead to homogeneous stands with low structural complexity (Churchill et al., 2013b; Larson and Churchill, 2012; North et al., 2009; Underhill et al., 2014). In such cases, the resulting forest structure may not mimic desired conditions which are considered to consist of a spatially aggregated, or sometimes random, pattern of overstory trees within a matrix of canopy openings intermixed with individual trees, and various sized tree patches (Abella et al., 2007; Brown et al., 2015; Harrod et al., 1999; Larson and Churchill, 2012; Reynolds et al., 2013; Sanchez-Meador et al., 2011; Youngblood et al., 2004). These forests historically also demonstrated some degree of vertical complexity, as tree sizes de-coupled from ages owing to variable growing conditions (Mast and Veblen, 1999). Unfortunately, as Larson and Churchill (2012) pointed out in a review of spatial patterns in dry forests, the effects of restoration treatments on spatial aspects of forest structure remain largely undocumented. Some studies have been conducted in the Sierras (B. Collins, unpublished), northern Rocky Mountains (Larson et al., 2012), and the Southwest (Abella et al., 2006), though these have had limited geographic scopes and had not focused on effects of treatments on vertical complexity.

Wildland fires have been shown to have considerable fine scale spatial variability in their rate of spread and intensity because of heterogeneity in wildland fuels (Anderson, 1982; Cheney and Gould, 1995; Fernandes et al., 2000), as well as complex interactions between forest structure and the environment. Furthermore, local variations in fire behavior due to fine scale structural complexity in forest structure may result in non-uniform fire effects leading to a range of post-fire conditions (Thaxton and Platt, 2006). Much of the previous research evaluating effects of restoration treatments on fire behavior utilize non-spatial fire behavior models. While such modeling approaches can be useful in fire management planning, the lack of consideration of fuel heterogeneity or the interactions between the pattern of fuel, the wind, and the fire may limit applications of non-spatial fire behavior models (Hoffman et al., 2012; Linn et al., 2013; Parsons et al., 2011). More recently, several studies have used physics based fire behavior models such as the Wildland Urban Interface Fire Dynamics Simulator (WFDS; Mell et al., 2007, 2009) or FIRETEC (Linn et al., 2002). Results from these recent studies have suggested both non-spatial and spatial aspects of forest structure play an important role in determining fire behavior (Hoffman et al., 2012, 2015; Linn et al., 2013; Pimont et al., 2011). Despite the increasing evidence of the importance of structural complexity on fire behavior, no studies to date have directly measured and accounted for the spatial structures resulting from restoration treatments on potential fire behavior.

The overall goal of this study was to explore how aspects of structural complexity and potential fire behavior were changing, on balance, as a result of variable retention harvesting across a range of restoration treatments. We were interested in finding were treatments were having consistent effects and where treatments may provide mixed results. To meet this goal, we applied spatial statistics and spatially explicit fire modeling to field derived, stem mapped data from restoration treatments across the Colorado Plateau and southern Rocky Mountains. Three questions were investigated: First, how did non-spatial metrics of forest structure and fuels change?; Second, how did treatments alter vertical and horizontal structural complexity at stand and patch scales?; And third, how was potential fire behavior altered following treatment?

2. Methods

2.1. Study areas

We sampled seven sites that had been treated within the past 10 years across the Colorado Plateau and southern Rocky