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# Historical spatial patterns and contemporary tree mortality in dry mixed-conifer forests

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ABSTRACT

Management and restoration of the dry, frequent-fire forests of the North American west depend on sound information about both historical and contemporary conditions to adequately address repercussions of fire suppression and changing climate. The purpose of this study is to quantify historical tree spatial patterns and assess recent mortality trends for old and large tree populations in dry mixed-conifer forests of the Northern Rocky Mountains. We analyzed historical reconstructions of forest spatial structure across six 1.0 ha plots located in mixed ponderosa pine/Douglas-fir stands in western Montana, USA. Across plots, 10–23% of trees occurred as widely spaced individuals (no neighbors within 6 m), with the remaining 77–90% of trees occurring in clumps (groups of two or more trees spaced less than 6 m apart). Mean clump size was 2.2–4.2 trees per clump, although large clumps (>10 trees) were common. Global spatial analysis with the pair correlation function indicated that ponderosa pine patterns were spatially random at all scales, while Douglas-fir trees were spatially aggregated at scales less than 6 m. The proportion of plot area farther than 9 m from the nearest tree ranged from 1% to 20% across the six study plots. Mortality rates between 1991 and 2012 averaged 0.8% $yr^{-1}$ for old ponderosa pine and 2.1% $yr^{-1}$ for old Douglas-fir. We found limited evidence of density-dependent mortality for both species pooled and for ponderosa pine individually. Douglas-fir that died between 1991 and 2012 had higher local Stand Density Index (SDI) of Douglas-fir neighbors than did Douglas-fir that survived ($P = 0.003$), indicating conspecific density-dependent mortality. When compared to ponderosa pine and dry mixed-conifer forests in other regions, trees were distributed much more evenly across clump sizes in our Montana study sites. Our analysis provides an estimate of the historical range of variability for spatial aspects of forest structure in dry mixed-conifer forests of the northern US Rockies and is relevant to the design of restoration and climate change adaptation treatments in such forests.



## 1. Introduction

Forest ecosystems have a rich history with fire in the Northern Rocky Mountain and Inland Northwest regions of the western United States (Habeck and Mutch, 1973). High to moderate frequency, low- and mixed-severity fires historically played a critical role in the maintenance of stand structure and species composition in dry, low-elevation forest types (Agee, 2003; Schoennagel et al., 2004). Since Euro-American settlement, many of these forests have experienced land-use change, grazing, timber harvesting, and fire suppression, which have greatly altered the structure and composition of forestlands (Lunan and Habeck, 1973; Agee, 1993; Naficy et al., 2010; Hessburg and Agee, 2003). With disturbance regimes predicted to change as a result of climate change, management of much of these dry forest landscapes now emphasizes restoration of resilient forest structures, patterns, and processes (Reynolds et al., 2013; Larson et al., 2013; DeRose and Long, 2014; Hessburg et al., 2015). Here, we use the definition of resilience provided by Walker et al. (2004), "... the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks."

In the frequent-fire forests of the West, many studies emphasize the importance of variation in species composition and structural attributes, while only a portion quantify the spatial pattern of

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trees (Larson and Churchill, 2012) or spatial patterns of fire severity (Cansler and McKenzie, 2014). Recent research has begun to provide forest pattern information in order to guide spatial aspects of forest restoration and climate change adaptation treatments, documenting the predominance of aggregated or clumped tree patterns in both pure ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) and dry mixed-conifer forests in a variety of regions (e.g., Harrod et al. 1999; Abella and Denton, 2009; Sánchez Meador et al., 2011; Churchill et al., 2013; Lydersen et al., 2013; Fry et al., 2014; Tuten et al., 2015). Conspicuously absent from this body of literature is information on spatial aspects of stand structure for the dry forests of the Northern Rocky Mountains (Larson and Churchill, 2012). Relative to the Southwest, Sierra Nevada, and Cascades, many (but not all) dry mixed-conifer and ponderosa pine forests of the Northern Rocky Mountains historically experienced longer mean fire return intervals, ranging from 26 to 52 years (Arno et al., 1995, 1997). We were therefore interested in whether the current conceptual model for stand dynamics in frequent-fire forests (Larson and Churchill, 2012; Reynolds et al., 2013) applies to dry ponderosa pine and Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Mirb.) Franco) mixed-conifer forests of this region.

A major challenge of dry forest restoration and fuel reduction treatments has been reconciling the need to reduce competitive stress and potential mortality of old and large trees of fire-tolerant species with the spatially aggregated or clumped patterns apparent in most reference datasets. General principles and guidelines for forest restoration and fuels reduction emphasize conservation of old and large-diameter trees of fire tolerant species (Agee and Skinner, 2005; Franklin and Johnson, 2012; Franklin et al., 2013; Reynolds et al., 2013; Lindenmayer et al., 2014; Hessburg et al., 2015). Yet many old trees are found in clumps, often in medium (5–9 trees) and even large (10 or more trees) clumps, and some managers and stakeholders express concerns over the potential for competition-induced mortality in these situations, even to the point of proposing to harvest some large, old trees occurring in clumps. Conflicts over proposals to thin out groups of large, old trees can often hinder restoration efforts (e.g., DellaSala et al., 2003, 2013). While there is evidence for increasing rates of tree mortality in old-growth forests across western North America (van Mantgem et al., 2009), there is little available data for rates of old tree mortality in dry mixed-conifer forests of the Northern Rockies. Forest stand dynamics theory suggests that tree mortality should be density-dependent (i.e., trees in groups are more likely to die than those with few neighbors) in most forests (Oliver and Larson, 1996). However, the available evidence suggests that density-dependent mortality is not as typical of old and large tree subpopulations in conifer forests (Acker et al., 1996; Das et al., 2011; Aakala et al., 2012; Silver et al., 2013; Larson et al., 2015) as it is in the smaller size classes (Das et al., 2011; Lutz et al., 2014). The extent to which old tree mortality in Northern Rocky Mountain dry mixed-conifer forests is density-dependent is not currently known.

The purpose of this study is to quantify historical tree spatial patterns, and to assess recent mortality trends for old, large tree populations in dry mixed-conifer forests of the northern US Rocky Mountains. This work informs forest restoration and climate change adaptation efforts, including prescription development and monitoring (Churchill et al., 2013), and also serves as a test of the current model for forest stand dynamics in ponderosa pine and dry mixed-conifer ecosystems (Larson and Churchill, 2012; Reynolds et al., 2013). Our specific goals were to (1) quantify historical tree spatial patterns using stand reconstruction plots, (2) place the dry forest ecosystems of western Montana in the context of historical stand structure in ponderosa pine and dry mixed-conifer ecosystems across the West, and (3) quantify recent old tree mortality rates and assess the extent to which mortality is density-dependent. Because our study sites are co-dominated by ponderosa pine and Douglas-fir we consider spatial patterns and mortality trends for individual species and all species pooled.

## 2. Methods

### 2.1. Study area

Our analyses are based on forest reconstruction stem map plots installed in 1991 by Arno et al. (1995), which we relocated and remeasured in 2012. Arno et al. (1995) established six 1.0 ha plots in unlogged, old-growth dry mixed-conifer stands situated on south- and southwest-facing sites with 45–55% slopes and distributed between 1520 m and 1830 m in elevation. All six plots were co-dominated by ponderosa pine and Douglas-fir in the overstory with pine grass (*Calamagrostis rubescens* Buckley) in the understory.

Three of the six plots are in located in the Bitterroot National Forest, approximately 37 km southwest of Darby, Montana. The last fire in the area was in 1889. In the 300 years prior to 1889, plots burned at average intervals of 47–52 years. The other three plots are located on the Lolo National Forest approximately 40–50 km west of Missoula, Montana. Previous to the establishment of the plots in 1991, plot Lolo 1 had burned twice since 1889 (in 1919 and 1953), Lolo 2 had last burned in 1919, and Lolo 3 had not burned since 1897. Average historical fire return interval in the Lolo plots was 26–32 years (Arno et al., 1995). Plot Lolo 1 currently supports a more intact fire regime as it experienced surface fire in 1997, as evidenced by melted tree tags and remote-sensing based fire detection.

### 2.2. Field methods

Species, diameter, and location (Fig. 1) were recorded for trees established prior to 1900 (Arno et al., 1995). Live trees of this age class were tagged in the field at the time of plot installation (1991). The year 1900 was chosen as the primary reconstruction year because a large body of research indicates that by this time the disturbance regime of most ponderosa pine forests of the West were in the first stages of disruption (Arno et al., 1995). To determine age, tree cores were collected 0.3 m above the ground using a power borer, mounted and glued to grooved boards for viewing. In 2012, five of the six plots were relocated and every tagged tree was revisited and assessed for survival. Plot Lolo 3 was not remeasured because the site was treated with commercial timber harvest and subsequently burned in a high-severity management-ignited fire in 1998, killing virtually all trees in the plot (Hillis et al., 2001). Detailed information on the age structure, historical stand dynamics and disturbance regimes, and historical and 1991 forest structure and composition are provided in Arno et al. (1995).

### 2.3. Spatial analysis

Because spatial patterns are scale-dependent we report results of spatial analyses across the full range of scales available in our data (e.g., Fig. 2, Appendix A). However, because many ecological phenomena are also scale-dependent, we emphasize particular scales when reporting our results, for example an intertree distance of 6 m, which corresponds to the crown radius of a typical co-dominant tree in our study system.

We used a spatial clump detection algorithm (Plotkin et al., 2002; Larson and Churchill, 2008; Sánchez Meador et al., 2011) to assess local tree patterns by a given intertree distance, *d*. This method aggregates trees into clumps if the center of a given tree is $\leqslant d$ from a neighboring individual or tree in a clump. As such,