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Long-term effects of prescribed fire on mixed conifer forest structure in the Sierra Nevada, California

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ABSTRACT

The capacity of prescribed fire to restore forest conditions is often judged by changes in forest structure within a few years following burning. However, prescribed fire might have longer-term effects on forest structure, potentially changing treatment assessments. We examined annual changes in forest structure in five 1 ha old-growth plots immediately before prescribed fire and up to eight years after fire at Sequoia National Park, California. Fire-induced declines in stem density (67% average decrease at eight years post-fire) were nonlinear, taking up to eight years to reach a presumed asymptote. Declines in live stem biomass were also nonlinear, but smaller in magnitude (32% average decrease at eight years post-fire) as most large trees survived the fires. The preferential survival of large trees following fire resulted in significant shifts in stem diameter distributions. Mortality rates remained significantly above background rates up to six years after the fires. Prescribed fire did not have a large influence on the representation of dominant species. Fire-caused mortality appeared to be spatially random, and therefore did not generally alter heterogeneous tree spatial patterns. Our results suggest that prescribed fire can bring about substantial changes to forest structure in old-growth mixed conifer forests in the Sierra Nevada, but that long-term observations are needed to fully describe some measures of fire effects.

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1. Introduction

Fire exclusion in many forests across the western U.S. has led to changes in forest structure, such as high surface fuel loads, high densities of small stems that act as ladder fuels to promote crown fires, and increasing dominance of shade-tolerant species. These changes are particularly acute in forests that historically had low severity/high frequency fire regimes (Allen et al., 2002; Brown et al., 2004; Agee and Skinner, 2005; Noss et al., 2006). In response to high fuel accumulations, managers have used prescribed fire to reduce surface fuels and small tree density, particularly for shade-tolerant species, while preserving large trees (i.e., individuals presumed to have established prior to Euro-American settlement, ca. 1850). Changes to forest structure following prescription burning should also reduce risks for stand replacing fires while maintaining the majority of above-ground live tree carbon stocks (van Wagtendonk, 1996; Stephens and Moghaddas, 2005; Hurteau and North, 2009; North et al., 2009).

How effective is prescribed fire at restoring forest structure? Large-scale trials have shown that prescription burning results in reduced fuel loads and stem density, but that a single application of prescription burning (even in combination with mechanical thinning) is unlikely to recreate presumed historic forest structure (North et al., 2007; Schwilk et al., 2009). Judgments of prescribed burning as a restoration tool might be improved by considering the long-term effects of fire. Studies generally measure the effects of prescribed fire only a few years following fire (Hood, 2010), although delayed mortality of trees can occur over longer intervals, as pathogens or other stressors kill fire-damaged trees (Schwilk et al., 2006, 2009; Hood and Bentz, 2007; Hood, 2010) (but see Youngblood et al., 2009). Although the bulk of fire-caused tree mortality occurs immediately after burning, it is unclear how long mortality rates remain elevated following burning, and if these delayed effects constitute an important influence on post-fire forest structure.

An additional concern, at least in some forest types of the Sierra Nevada of California, is that fire exclusion is thought to have altered the spatial arrangement of trees within stands. The spatial arrangement of stems (the degree to which the distribution of trees in a stand can be considered clumped, random or uniform) is an important structural element of stands, in that it defines local competitive

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Table 1
Characteristics of forest monitoring plots.

Plot identifier	Lat. (°N)	Long. (°W)	Elevation (m)	Plot area (ha)	Establishment year	Species comprising >1% of stems[a]
FFS2	36.6	−118.7	2128	1.00	2001	ABCO 65%; ABMA 26%; CADE 1%; PILA 8%
FFS5	36.6	−118.8	2030	1.00	2001	ABCO 57%; CADE 25%; PILA 18%
FFS6	36.6	−118.8	2018	1.00	2001	ABCO 62%; CADE 3%; PIJE 1%; PILA 24%; PIPO 1%; QUKE 10%
LOTHAR	36.6	−118.7	2167	1.13	1984	ABCO 74%; ABMA 1%; PIJE 1%; PILA 16%; QUKE 6%; SEGI 2%
UPTHAR	36.6	−118.7	2202	1.00	1984	ABCO 95%; PIJE 2%; PILA 2%

[a] Species composition of stems at time of plot establishment. Percentages may not add to 100 due to rounding. ABCO = *Abies concolor*, ABMA = *A. magnifica*, CADE = *Calocedrus decurrens*, PIJE = *Pinus jeffreyi*, PILA = *P. lambertiana*, PIPO = *P. ponderosa*, QUKE = *Quercus kelloggii*, SEGI = *Sequoiadendron giganteum*. Naming conventions follow Hickman (1993).

environments, which in tern influences individual tree growth rates (Biging and Dobbertin, 1992) and mortality risks (Das et al., 2008). Within the Sierran mixed conifer, fire exclusion has resulted in high densities of small trees, particularly of shade-tolerant *Abies concolor* (white fir), a development that can result in an increase in clumping of the spatial pattern of stems (North et al., 2007). The reduction of stem clumping, particularly for small trees, has been identified as a restoration goal in the Sierra Nevada (Taylor, 2004; North et al., 2007).

Here we examine if prescribed fire results in forest structure that is consistent with common restoration targets. We present changes to forest structure as measured by eight years of annual monitoring at five stands (1 ha) burned in four separate fires in old-growth mixed conifer forests in the Sierra Nevada. Our study is notable in that we consider multiple fires separated both in space and time, and can account for long-term delayed tree mortality. Specifically, we describe the effects of prescribed fire on stand density, live stem biomass, stem size distributions, species composition, and spatial arrangement of stems.

2. Materials and methods

2.1. Study sites

We compared pre- and post-fire forest structure for all living trees greater than 1.37 m in height in five 1 ha plots of old-growth mixed conifer forest in the Giant Forest area, Sequoia National Park (Table 1). Prior to prescription fires, the Giant Forest area last burned in the 1860s or 1870s (Schwilk et al., 2006; Swetnam et al., 2009). The climate of this area is Mediterranean, with wet, snowy winters and long, dry summers. The mean annual precipitation of the Giant Forest area is 1255 mm at an elevation of 1950 m, with approximately half of this precipitation arriving as snow (Stephenson, 1988). Average January and July air temperatures are 0 °C and 18 °C, respectively. The plots lie at a minimum of 300 m and a maximum of 3700 m apart and are of comparable size, shape, average slope steepness, average slope aspect, and soil parent material (granodiorite) (Table 1). Prior to burning the plots were dominated by *A. concolor* (average of 70% of stems), but with considerable representation of *Pinus lambertiana* (average of 14% of stems). Further details on the plots can be found in Knapp and Keeley (2006), Knapp et al. (2007), and Mutch and Parsons (1998).

Three plots (FFS2, FFS5, and FFS6, hereafter called the FFS plots) were randomly located within larger areas that were burned in September or October of 2001 in separate fires, while two other plots (LOTHAR and UPTHAR, hereafter called the Tharp plots) were haphazardly placed within a larger prescribed fire unit that was burned in a single fire in October of 1990. Air temperatures during ignition ranged from 10 to 18 °C, relative humidity ranged from 20 to 63%, and wind speed ranged from 0 to 7 km/h. Average fuel moistures for litter and duff were ∼18%, for 100-h fuels ∼12% and for 1000-h fuels ∼32%. All plots were burned by a combination of strip headfires and backing fires. Flame lengths were generally less than 1 m, with occasional flame lengths up to 2 m. Total pre-fire fuel loads were relatively high (∼200 Mg ha^{-1}), composed primarily of large (>7.6 cm diameter [1000-h]) woody fuels, and litter and duff. Fuel consumption was high, with fires reducing total fuel loads to ∼13% of pre-fire levels. Percentage of crown volume scorched (PCVS) within the plots was highly variable (within all plots: minimum PCVS = 0%, maximum PCVS = 100%; plot level average PCVS = 36 to 82%). See Knapp et al. (2005) and Mutch and Parsons (1998) for details.

Prior to burning all trees ≥1.37 m in height in the plots were tagged, mapped, measured for diameter at 1.37 m height (diameter at breast height, DBH), and identified to species; we had a total of 2236 trees for analysis. All plots were censused annually for tree mortality. We remeasured live tree stem diameter at the 5th year post-fire, which was used to calculate post-fire annual diameter growth increment. We recorded new recruitment (trees reaching 1.37 m in height) annually in the FFS plots, and at the 5th year post-fire in the Tharp plots. For consistency in methods across all plots we included the recruits in the data at the 5th year post-fire. Recruitment of trees was low in all plots up to five years after the fires (and likely represent stems that escaped the fire), with a total of 10 recruits across all plots (eight of which were in the FFS2 plot and the remaining two in the LOTHAR plot).

The goals for white fir mixed-conifer forest structure restoration at Sequoia National Park stipulate stand density to range between 50 and 250 trees ha^{-1} for stems <80 cm DBH, and 10 and 75 trees ha^{-1} for stems ≥80 cm DBH by the 5th year following initial treatment with prescribed fire (Fire and Fuels Management Plan, Sequoia and Kings Canyon national parks, *Unpublished report*). Additionally, forest composition goals call for treated stands to contain 40–80% *Abies*, and 15–40% *Pinus*, with the remainder made up from other species (target conditions for species composition were mostly in place prior to burning in our study plots, Table 1). The plan does not explicitly consider desired biomass retention amounts, nor does it consider the alteration of stem spatial arrangement as a management objective.

2.2. Data analysis

We assessed changes in forest structure in terms of stand density (stems ha^{-1}, including recruitment) and aboveground living stem biomass (Mg ha^{-1}, including post-fire growth), estimated from standard allometric equations tailored to the Sierra Nevada (Means et al., 1994). Biomass changes from growth were interpolated between stem diameter measurement years. We described trends in post-fire stand density and live stem biomass using mixed models (Pinheiro and Bates, 2004). Visual inspection of trends suggested that stand density and live stem biomass declined nonlinearly following the fires. We tested several model forms (e.g., linear, exponential decline, saturating) with and without random differences among plots, and with and without temporally correlated error terms. Selection using *AIC* (Burnham and Anderson, 2002) showed most support for modeling the trend in stand density as a mixed model with an asymptotic (Michaelis–Menten) regres-