Forest Ecology and Management 422 (2018) 190–198

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Thinning, tree-growth, and resistance to multi-year drought in a mixed-conifer forest of northern California

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ARTICLE INFO

Keywords:
Drought
Fuel treatments
Pinus ponderosa
Pseudotsuga menziesii

ABSTRACT

Drought is an important stressor in forest ecosystems that can influence tree vigor and survival. In the U.S., forest managers use two primary management techniques to promote resistance and resilience to drought: prescribed fire and mechanical thinning. Generally applied to reduce fuels and fire hazard, treatments may also reduce competition for resources that may improve tree-growth and reduce mortality during drought. A recent severe and prolonged drought in California provided a natural experiment to investigate tree-growth responses to fuel treatments and climatic stress. We assessed tree-growth from 299 ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) in treated and untreated stands during severe drought from 2012 to 2015 in the mixed-conifer forests of Whiskeytown National Recreation Area (WNRA) in northern California. The treatment implemented at WNRA removed 34% of live basal area through mechanical thinning with a subsequent pile burning of residual fuels. Tree-growth was positively associated with crown ratio and negatively associated with competition and a 1-year lag of climate water deficit, an index of drought. Douglas-fir generally had higher annual growth than ponderosa pine, although factors affecting growth were the same for both species. Drought resistance, expressed as the ratio between mean growth during drought and mean growth pre-drought, was higher in treated stands compared to untreated stands during both years of severe drought (2014 and 2015) for ponderosa pine but only one year (2014) for Douglas-fir. Thinning improved drought resistance, but tree size, competition and species influenced this response. On-going thinning treatments focused on fuels and fire hazard reduction are likely to be effective at promoting growth and greater drought resistance in dry mixed-conifer forests. Given the likelihood of future droughts, land managers may choose to implement similar treatments to reduce potential impacts.

1. Introduction

Climate change is predicted to increase the frequency, duration and severity of drought events in many bioregions (Settele et al., 2014, Trenberth et al., 2014, Cook et al., 2015). Drought, or a prolonged reduction of available water resources, is an important stressor in forest ecosystems that can influence tree vigor and survival. Several recent studies have linked observed increases in tree mortality to the occurrence of drought stress (e.g., Gitlin et al., 2006, van Mantgem et al., 2009, Allen et al., 2015). Trees weakened by drought stress are also more susceptible to attack from pathogens and insects, such as bark beetles (Weed et al., 2013). Prolonged periods of severe drought can lead to large-scale forest die-off, altering the structure and function of forest ecosystems (Breshears et al., 2005). While a reduction in available water is the primary driver of drought stress, an increase in temperature can lead to higher rates of evapotranspiration that can enhance drought stress (Adams et al., 2009, Allen et al., 2015). The impacts of drought on forests may be further exacerbated by the legacy of past land use policies and practices that resulted in substantial increases in stand density (e.g., fire exclusion; Safford et al., 2012).

In response, forest managers have applied large-scale fuel reduction treatments focused on thinning low to mid-canopy trees to reduce basal area and pile burning or prescribed burning to reduce fuels (Agee and Skinner, 2005). In recent years, forest management goals have shifted more broadly towards enhancing ecosystem resiliency under future climate conditions (USDA-FS, 2011, Franklin and Johnson, 2012). To assess the effectiveness of fuel treatments in this context, understanding whether management activities enhance forest resistance (remaining unaltered during disturbance) and resilience (ability to recover to pre-disturbance conditions) to disturbance events such as drought is a

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https://doi.org/10.1016/j.foreco.2018.03.043
Received 14 December 2017; Received in revised form 28 February 2018; Accepted 20 March 2018

critical need (Folke et al., 2004).

Tree-growth responses can effectively measure drought resistance, where resistant individuals show relatively little change in growth patterns (e.g., Lloret et al., 2011). Empirical investigations of fuel treatment impacts on growth and drought response have yielded mixed results. Fuel treatments can enhance tree-growth rates and improve resistance to short-duration droughts (1–2 years) (Kerhoulas et al., 2013, Thomas and Waring, 2015), but responses can vary with species, tree size and time since treatment (Latham and Tappeiner, 2002, D'Amato et al., 2013). In many forest ecosystems and drought conditions, higher stand density often negatively affects tree-growth and drought resistance (Bottero et al., in press, Bradford and Bell, 2017). Trees experiencing greater competition can have reduced radial growth (Das, 2012, Sánchez-Salguero et al., 2015), and in many cases, higher probabilities of mortality (Cailleret et al., 2016). Few studies, however, have directly examined the effects of competition reduction on tree-growth under prolonged and severe drought conditions.

A recent prolonged drought in California (2012 through 2015) was one of the most severe events in the instrumental record (Williams et al., 2015, Luo et al., 2017). Average winter precipitation was among the driest on record, while average winter temperatures for the same period were among the highest (Seager et al., 2015). Extensive forest mortality resulting from prolonged drought conditions was observed in the southern Sierra Nevada (Young et al., 2017). However, the impacts and responsiveness of trees in more northern locations in California (e.g. Klamath Mountains), where mortality was less severe, have not been well studied.

We used this drought event as a natural experiment to investigate the influence of thinning and pile burning on tree-growth responses for two widespread conifer species, ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*), to a recent multi-year drought in dry, mixed-conifer forests of Whiskeytown National Recreation Area in the Klamath Mountain ecoregion of northern California. We analyzed our data at two different scales: individual tree and treatment-levels. For individual trees, we investigated the factors (e.g. tree characteristics, climatic stress, competition) influencing tree-growth responses during the study period (2008–2015) and the factors influencing drought resistance in 2015 (the fourth consecutive year of drought). At the treatment-level, we assessed whether thinning treatments influenced forest resistance to drought stress and how the growth response changed over successive years of severe drought. Results from our study will help land managers assess whether fuels treatments enhance forest resistance to future drought events.

2. Methods

2.1. Study area

This study was conducted in the dry, mixed-conifer forests of Whiskeytown National Recreation Area (WNRA), located in the southeastern Klamath Mountains, approximately 13 km west of Redding, California (Fig. 1; 40.595997, −122.592651). WNRA was established in 1965 and encompasses 17,200 ha of forest and shrubland, including the 1200 ha Whiskeytown reservoir, and includes a diverse range of plant communities and topography (USDI, 2003). The climate in WNRA is Mediterranean, characterized by cool wet winters and warm dry summers, with a mean annual temperature of 14.4 °C (USDI, 2003). Mean annual precipitation is 152 cm, falling primarily in the form of rain (USDI, 2003).

Both human and lightning ignited wildfires historically occurred in WNRA with fire regimes varying depending on vegetation communities, topography and human habitation (Fry and Stephens, 2006). Prior to Euro-American settlement, the mean fire return interval was reported to range from 4.8 to 7.4 years in ponderosa pine-mixed conifer forests (Fry and Stephens, 2006). Land-use activities of Euro-American settlers included mining, livestock grazing and intensive timber harvesting (Toogood, 1978). Fire suppression and other disturbances have greatly reduced the frequency of fire and led to altered forest structure and composition (Leonzo and Keyes, 2010).

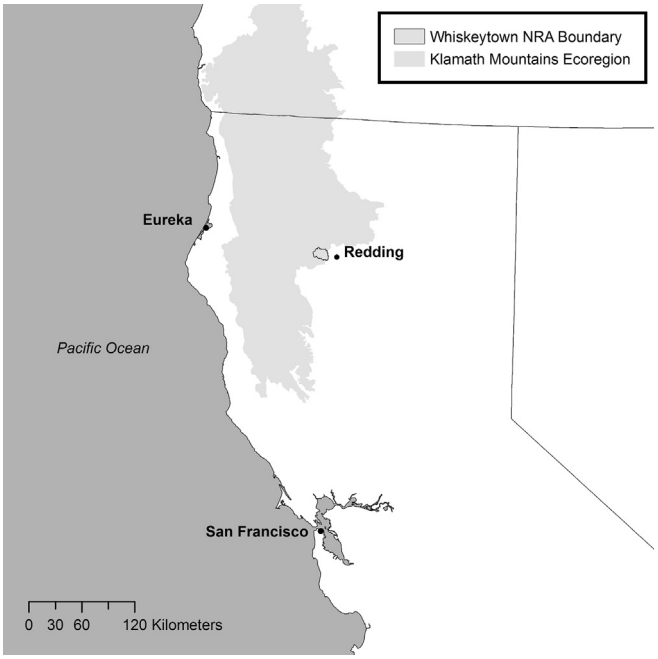

Fig. 1. Study area at Whiskeytown National Recreation Area in northern California.

These changes have prompted park managers to carry out fuel reduction treatments (2010) aimed at restoring historical forest structure and reducing the potential for high severity wildfire (USDI, 2003). Treatments at WNRA reduced live basal area (BA) by 34% (based on pre-treatment data) through thinning young conifers (< 30 cm diameter at breast height; DBH) and tanoak (*Notholithocarpus densiflorus*) while maintaining other hardwood species (e.g., *Quercus kelloggii*, *Quercus chrysolepis*, *Acer macrophyllum*) and promoting residual conifer vigor through crown release. Thinning was conducted in 2010 with a feller-buncher and harvested material was removed using a rubber-tired skidder. Residual fuels were subsequently piled and burned in the winter of 2011. The treatment units (D, F, G) ranged in size from 0.9 to 3 ha, totaling 6.5 ha.

Tree and stand conditions varied by species and treatment (Table 1). Mean focal DBH for ponderosa pine and Douglas-fir ranged from 48.0 to 57.8 cm and 42.1 to 53.1 cm, respectively. Mean treatment-level basal area was 43% lower in treated stands (23.8–31.6 $m^2\,ha^{-1}$) compared to untreated stands (48.3–52.9 $m^2\,ha^{-1}$). Mean treatment-level competition index was 59% lower in treated stands (1.5–1.7) compared to untreated stands (3.1–4.7). Mean tree age varied between species, 103 years for ponderosa pine and 69 years for Douglas-fir, but was similar across units and treatments.

2.2. Field data collection and sample processing

In 2016, approximately 150 Douglas-fir and ponderosa pine (focal trees) with DBH > 30 cm were sampled using random GPS points from three treated and three untreated stands of similar elevation, aspect,