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# Stand composition and aspect are related to conifer regeneration densities following hazardous fuels treatments in Colorado, USA

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ABSTRACT

Hazardous fuels reduction treatments often reduce the likelihood of undesirable fire behavior (e.g. crown fire) through some combination of tree thinning and surface fuel reduction. However, fuels treatment effectiveness declines over time as fuels re-accumulate and new tree cohorts of trees establish and grow. Fuels treatment longevity therefore depends in part on post treatment tree regeneration rates, which vary depending on characteristics of sites and treatments as well as on stand composition. We used a chronosequence of 3–12 year old fuels treatments to investigate the impact of site ("wet" north aspects versus "dry" south aspects), treatment type (thinning with and without follow up slash burning), and stand composition on conifer regeneration following treatments in stands of ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) and Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *glauca* [Beissn.] Franco) in Colorado, USA. We found conifer regeneration density was > 500 trees $ha^{-1}$ on average by 10 years post treatment. While stands on north aspects had twice the regeneration density of those on south aspects, the rate of increase since treatment was similar. Instead, there was significantly more regeneration on north aspects because these stands contained a considerable amount of Douglas-fir, which was largely absent on south aspects. Ponderosa pine regeneration density increased with time since treatment, while Douglas-fir regeneration density did not, which suggests that treatments promoted reproduction of ponderosa pine. Conversely, Douglas-fir regeneration density was related to the amount of Douglas-fir basal area in stands, which was not the case for ponderosa pine, probably because all stands had ample amounts of ponderosa pine basal area. There was no difference in regeneration density between burned and unburned stands. Our results highlight the influence of stand composition and site characteristics on tree regeneration following fuels treatments. In this study, fuels treatments acted much like shelterwood regeneration treatments for ponderosa pine, pairing favorable establishment environments for this species with a seed source. This resulted in ponderosa pine trees establishing even on relatively dry south aspects, while Douglas-fir regeneration may have been inhibited by seed availability and was largely confined to wetter north aspects. Despite similar tree regeneration rates across aspects, fuels treatment effects may nonetheless deteriorate more quickly on north aspects because of this Douglas-fir regeneration, much of which predated treatments. Indeed, advance regeneration was common in all of our stands, suggesting the longevity of fuels treatment effects will depend substantially on whether these trees are eventually able to release.

## 1. Introduction

Forest fuel hazard reduction treatments typically seek to alter fuel profiles to reduce crown fire potential (Agee and Skinner, 2005). In western US forests, this is often accomplished by thinning small trees and trees of late seral species and/or burning, chipping, or removing surface fuels (Graham et al., 2004). Many fuels treatments in this region have restoration objectives and may also involve deliberate creation of openings (Churchill et al., 2013, Reynolds et al., 2013, Underhill et al., 2014), while in other cases allowing wildfires to burn can be an effective means to achieving fuel hazard reduction objectives (North et al., 2012, Van Wagtendonk, 2007). The elements of post treatment stand structure and composition that are critical for resistance and resilience to fire include low surface fuel loads, high average crown base heights, low canopy bulk densities, few ladder fuels, and the presence of large trees of fire tolerant species (Agee and Skinner, 2005, DeRose and Long, 2014). In the presettlement era, stand structures with these elements were naturally perpetuated in many dry Western forests by

*Abbreviations:* BA, basal area; TST, time since treatment

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relatively frequent, low to moderate severity fires (Dellasala et al., 2004, Keane et al., 2002). Fuels treatments emulate these stand structures, but in the absence of natural fire regimes they must be periodically re-treated to maintain treatment effectiveness (North et al., 2012, Reinhardt et al., 2008).

Published estimates of the duration of fuels treatment effectiveness vary from about one to three decades (Battaglia et al., 2008, Chiono et al., 2012, Finney et al., 2003, Stephens et al., 2012, Vaillant et al., 2015). It is likely that this wide range in reported treatment longevity partly reflects methodological differences between studies, and partly reflects real differences between treatments. The longevity estimate for a given treatment is likely to vary substantially depending on methodological factors such as whether effectiveness is represented by fuels characteristics (e.g. surface fuel load) versus predictions of potential fire behavior from models, and also depending on whether longevity is characterized as the time to return to pretreatment conditions versus time to reach an objective standard of effectiveness that is independent of pretreatment conditions. A number of factors could contribute to real differences in longevity, including the post treatment stand density and surface fuel load; rate of biomass production, deposition and decomposition; and the type and frequency of post treatment disturbances (Keane, 2008, Reinhardt et al., 2008, Tinkham et al., 2016). Fuels tend to accumulate over time in the absence of fire, causing treatment effectiveness to decline, because fuel accumulation outpaces decomposition in many dry forests (Dodge, 1972). Fuels treatments also degrade because residual trees grow and reproduce following treatments. Thinning vacates growing space for residual trees and new seedlings to occupy, and heavy equipment use and burning cause surface disturbances that create microsites suitable for seedling establishment (Bonnet et al., 2005, Fajardo et al., 2007, Shepperd et al., 2006). Tree regeneration rate is an especially important aspect of post treatment biomass accumulation because seedlings eventually turn into ladder fuels, which can contribute substantially to fire hazard (Keeley et al., 2004).

Fundamentally, regeneration rates depend on the availability of tree propagules and of suitable establishment environments. These can vary between different locations depending on site and stand characteristics, and between different years depending on year-to-year differences in weather and tree seed production (Brown and Wu, 2005, Dodson and Root, 2013, Turnbull et al., 2000). Conifer regeneration is also episodic in many western US forests. Regeneration events have been attributed to changes to disturbance regimes as well as periods of favorable weather for cone development and subsequent seedling establishment (Brown and Wu, 2005, Savage et al., 1996). These factors contribute to wide variation in conifer regeneration rates across dry forests in the interior western US. Observations of ponderosa pine regeneration densities 5–10 years after fuels treatments span two orders of magnitude, from tens of trees $ha^{-1}$ in a study in northern Arizona near Flagstaff (Bailey and Covington, 2002), to thousands in a study in the Black Hills of South Dakota (Battaglia et al., 2008).

Regeneration rates can be strongly influenced by site characteristics such as seasonal drought that can prevent seedling establishment (Feddema et al., 2013). Site characteristics vary predictably at large scales (e.g. differences in climate between regions), but also at stand scales ( ~ 1–50 ha) due to differences in things such as elevation, aspect, and soil type that affect temperature and water availability (Daubenmire, 1943). Elevation and aspect are strong drivers of stand scale climate in the western US. For a given geographic area in this region, stands on north aspects and at higher elevations are generally cooler and wetter than stands on south aspects and at lower elevations. In dry mixed conifer forests where tree regeneration may be limited by high temperatures and drought (Petrie et al., 2016), regeneration rates are likely to be influenced by aspect and elevation, with relatively higher rates in stands on north versus south aspects, and in stands at higher versus lower elevations (Chambers et al., 2016, Dodson and Root, 2013).

Regeneration rates are also influenced by the structure and composition of stands. Stand density and other structural elements such as dead woody material on the forest floor, understory vegetation, and surface disturbances can also promote or impede tree regeneration through their influence on the characteristics of microsites and level of competition in post treatment stands (Bonnet et al., 2005, Ouzts et al., 2015, Bolton and D'Amato, 2011). Stand composition can influence regeneration rates if co-occurring tree species differ in seed production rates and/or likelihood of establishment success in the post treatment environment. New cohorts of trees following fuels treatments logically stand to reflect the composition of the post treatment overstory because overstory trees are the seed source for future generations. Stand composition can also include advance regeneration, which when present and capable of releasing, has a "head start" over seedlings that establish post treatment, and consequently may accelerate stand development (Pothier et al., 1995). Other factors may be locally important controls on conifer regeneration rates in the interior West, including seed predation and herbivory (Harrington, 1977, Shepperd et al., 2006).

Dry mixed conifer stands are high priorities for fuels treatments throughout the semi-arid west because many of these stands have elevated fuel hazards (Schoennagel and Nelson, 2010), and because dry mixed conifer forests frequently have high value to humans (Dellasala et al., 2004). Ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) and interior Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *glauca* [Beissn.] Franco, hereafter 'Douglas-fir') frequently co-occur in these stands, although dry mixed conifer forests encompass myriad combinations of tree species throughout the region (Jain et al., 2012). Ponderosa pine and Douglas-fir occupy different positions on continuums of fire and shade tolerance, with Douglas-fir being somewhat less fire tolerant and somewhat more shade tolerant than ponderosa pine (Long, 1994). Douglas-fir tends to be more prominent on north-facing slopes that receive less direct sunlight, retain more soil moisture due to less evaporative drying, and have lower surface temperatures relative to south-facing slopes (Adams, 1994). Douglas-fir establishes more readily in undisturbed stands than ponderosa pine and maintains longer crowns (Hermann and Lavender, 1990), leading to ladder fuel development and increased torching potential. Consequently, fuels treatments in this region often seek to reduce the proportion of late seral species such as Douglas-fir in stands. This may also satisfy restoration objectives related to historical stand composition (Brown et al., 2015).

In this work, we investigated conifer regeneration following fuels treatments in ponderosa pine dominated stands with varying amounts of Douglas-fir along the Rocky Mountain Front Range of northern Colorado, USA. It is not clear whether patterns of ponderosa pine regeneration differ appreciably from those of Douglas-fir following fuels treatments. Evidence that saplings of these species share a common recruitment niche (Fajardo et al., 2006), along with Douglas-fir's apparent seed dispersal superiority (Chambers et al., 2016) suggest they may respond similarly, despite the likelihood that treatments preferentially removed Douglas-fir during thinning. Consequently, our expectations were that regeneration would reflect moisture availability in these droughty forests and that patterns of regeneration would be broadly similar for ponderosa pine and Douglas-fir. To assess this, we measured regeneration density in stands on north and south aspects that were either thinned or thinned and then subsequently burned 3–12 years prior to sampling. We chose to evaluate thinning with and without follow up prescribed fire primarily because these fuel hazard reduction approaches have historically been common on the Front Range. Focusing on common treatment types allowed us to obtain a sample of treated stands that spanned a broader range of treatment ages than if we had focused on less common treatments such as prescribed fire without thinning. Our hypotheses were that (1) regeneration density would be greater on wetter north aspects relative to dry south aspects and that differences between aspects would be more pronounced for Douglas-fir than for ponderosa pine; (2) regeneration density of both species would increase with time since treatment in stands on both