THESIS

FUEL TREATMENT LONGEVITY IN A DRY MIXED CONIFER FOREST ON THE COLORADO FRONT RANGE

Submitted by

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In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Spring 2017

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ABSTRACT

FUEL TREATMENT LONGEVITY IN A DRY MIXED CONIFER FOREST ON THE COLORADO FRONT RANGE

Hazardous fuel treatments have been occurring on an increasingly large scale throughout the western US in response to uncharacteristically severe wildfires in recent decades. These treatments have been shown to be effective in the short term but how long they remain effective, and the factors that affect this, is less clear. As these treatments are often very expensive to implement, knowing when a treated unit will return to pre-treatment fire risk is of critical importance for prioritization of sites and long-term forest planning. The majority of these treatments have occurred in dry mixed conifer forests as they have been the most affected by fire suppression policies, allowing fuels to accumulate and create high fire risk potential, and are often close to human settlement. We examined treatments that used thinning with and without follow-up prescribed fire in mixed stands of ponderosa pine and Douglas-fir. These treatments were examined on north and south aspects at times from 3-12 years after treatment. As hypothesized, we found conifer seedlings densities increased with time since treatment. Our data suggest a density of 500 seedlings ha^{-1} could be observed on southern aspects 10 years post-treatment. North aspects had twice the seedling density of south aspects at 10 years post-treatment, driven by the presence of Douglas-fir. Ponderosa pine seedling density was found to increase as a result of treatment, with the regeneration rate not being significantly affected by aspect or treatment type. In contrast, Douglas-fir regeneration was not promoted through treatment but was most correlated to the amount of Douglas-fir overstory basal area and found mainly on north aspects. We also found that neither fine or coarse surface fuels nor litter or duff depths had begun showing a significant increasing trend a decade after treatment. Conifer regeneration is diminishing the treatment effectiveness within a decade of treatment and will require retreatment in the future to reduce severe fire potential. While ponderosa pine regeneration can be expected to increase as treatments create more favorable establishment conditions, Douglas-fir regeneration can be expected to be higher when more Douglas-fir is left in a stand during treatment. Advance regeneration was also found to comprise a considerable portion of encountered seedlings and should be removed during treatment to increase treatment longevity.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Seth Ex, for the opportunity to expand my academic knowledge and research capabilities. His commitment to my success has allowed me to become a better steward to our natural world and will serve me invaluably in the future. I would also like to thank my committee member, Dr. Chad Hoffman, for his assistance in designing and analyzing my research project. Dr. Patrick Martin also served on my committee and I would like to thank him for his insight from a perspective that may have gone unseen. My field and lab technicians (Golden Rains, Montie Reese, Guilherme 'Luiz' Fernandes, Ed Hill) also showed unrivaled dedication to our research mission even when I was uncertain and doing some learning of my own. Finally, I would like to thank the rest of the faculty and staff within the Forest and Rangeland Stewardship Department of the Warner College of Natural Resources. This department is providing world-class research on the ever-changing frontier of environmental science. It is my hope that this mission is embraced and continued into the future, with nothing short of excellence being the goal for whatever the task may be.

This work was supported by the USDA National Institute of Food and Agriculture, McIntire Stennis project 1006421

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1.1 Introduction

The effects of wildfire suppression throughout the twentieth century have recently culminated into an outbreak of severe forest fires in the western United States that are often environmentally devastating (Keane et al., 2002). In response to these events, hazardous fuel reduction treatments have been occurring on an increasingly large scale (J. K. Agee & Skinner, 2005). These treatments aim to decrease the likelihood of uncharacteristically severe fire behavior by reducing the biomass of fuels available to burn on the forest floor and in the forest canopy (Stephens, McIver, et al., 2012). Studies have documented that these treatments are generally effective at accomplishing this goal in the immediate post-treatment environment (Hudak et al., 2011). Less clear is how this effectiveness will diminish through time, termed treatment longevity, as forests return to pre-treatment conditions through tree regeneration and biomass production. The rates of these processes are highly variable and are affected by factors such as ecosystem productivity, species composition, and local topography (slope steepness, slope position, aspect, etc.) (Schoennagel, Veblen, & Romme, 2004). Identifying how these site-specific factors affect forest fuel dynamics and tree regeneration following fuels treatments is of critical importance in order to gauge the longevity of treatments. This will allow for prioritization of treatment areas and the ability to anticipate patterns of forest growth in long-term ecological and fiscal planning.

Historically, wildfires occurred throughout the western United States; however, they varied widely in frequency and severity across the landscape due to climatic and species composition differences. At smaller scales, this variation diminishes and distinct patterns of wildfire occurrence emerge, known as fire regimes (Schoennagel et al., 2004). Fire regimes, in conjunction with the resulting effects of fires on forests, form the basis of a historical range of variability (HRV) (Swetnam, Allen, & Betancourt, 1999). The HRV describes the cyclical relationships between forest metrics including surface fuel load, overstory density, and overstory composition in relation to disturbances like wildfires (Swetnam et al., 1999). Examining the HRV of dry-mixed conifer forests shows that their historical, high frequency fire regime (burning every 1-30 yrs) has been altered due to nearly a century of fire suppression policies (Pyne, Andrews, & Laven, 1996). Under these policies, these forests have ‘missed’ numerous wildfire events leading to higher stem densities of trees, enhanced tree regeneration rates, and the accumulation of surface fuels (Barrett et al., 2010). This then causes these forests to burn at much higher severities than expected under the HRV causing large scale environmental damage (Baker, 1992).

The most significant deviation from the HRV in dry conifer forests is in the structure and composition of tree species (Keane et al., 2002). Structural changes include higher stem densities, decreased crown base heights (CBH), increased canopy bulk density (CBD), and the loss of spatial heterogeneity. Composition has shifted to include more late-seral, shade-tolerant species. In addition, a lack of fire has allowed organic matter to build-up within this forest type as accumulation outpaces decomposition (Dodge, 1972). This leads to more fuel available to burn in the event of a wildfire than expected under the HRV, resulting in severe fire behavior with more damaging effects than if regular burning were to occur (Keane et al., 2002).

Hazardous fuel treatments specifically address these issues in order to restore conditions more reflective of the past and prevent fire severities that are uncharacteristic.

Ponderosa pine (*Pinus ponderosa*) has been the most heavily treated forest type throughout the semi-arid west as it is the most common dry forest type in this region and most deviated from its HRV (Hudak et al., 2011; Potter, Hipkins, Mahalovich, & Means, 2015). Ponderosa pine is mostly shade intolerant and is adapted to hot, dry sites. It is often the dominant overstory species within its range, due to its ability to tolerate drought better than most competing species (Long, 1994). In many stands supporting ponderosa pine, relatively frequent, low severity fires act to limit the occurrence of other late seral conifer species, as they are less fire resistant as seedlings and mature trees. Ponderosa pine seedlings are able to grow bark thick enough within the first 15 years of establishment that will resist surface fire with flame lengths up to one meter, with both bark thickness and fire resistance continuing to increase over time (Battaglia, Smith, & Shepperd, 2008). Frequent fire also exposes mineral soil by consuming surface fuels and decreases shading by increasing CBH through the scorching of low branches which promotes ponderosa pine regeneration over other species (J. K. Agee & Skinner, 2005; Long, 1994).

In the middle and northern Rockies, it is the encroachment of shade-tolerant interior Douglas-fir (*Pseudotsuga menziesii*) into formerly ponderosa pine dominated stands that has caused the greatest compositional deviation from the HRV (Arno & Fiedler, 2005). The encroachment of this species into a stand and canopy was formerly regulated by frequent fire as it is less fire-resistant (Keane et al., 2002). Douglas-fir is also moderately shade tolerant, enabling retention of lower branches under lower light conditions than ponderosa pine in the absence of frequent fire (Long, 1994). This favors Douglas-fir regeneration over ponderosa pine regeneration by increasing shading, decreasing surface temperatures, and increasing moisture availability (Isaac, 1943).

The culmination of effects from fire exclusion in ponderosa pine forests has resulted in uncharacteristically severe forest fires that began occurring around the turn of the twenty first century (Adams, 2013). Compared to the HRV, these fires burn much larger areas and exhibit more severe behavior (Adams, 2013). The main effects of severe fire behavior include increased soil surface heating and higher tree mortality (Keeley, 2009). Increased surface heating can kill tree roots, cause decimation of soil microbial and fungal communities, and eliminate any soil seedbank (Certini, 2005). High rates of tree mortality substantially reduce seed production potential and significantly delay forest regrowth.

In response to the extreme short and long term negative effects of severe fires, forest managers have made it a priority to mitigate the susceptibility of forests to these uncharacteristically severe fire events. This is done by utilizing hazardous fuel reduction treatments. The overarching goal of these treatments is to decrease the probability of severe fire behavior. Treatments focus on reducing the biomass available to burn on the forest floor (surface fuels) and in the canopy as well as decreasing the continuity between the two (J. K. Agee & Skinner, 2005).

Treatments are usually applied following silvicultural prescriptions. The most common technique is thinning to eliminate small trees and seedlings in addition to some larger trees to reduce the canopy fuel load and decrease the horizontal canopy continuity (J. K. Agee &

Skinner, 2005). The slash generated from these treatments is also managed to reduce surface fuel loadings (Hirsch, Meyer, Radloff, & Forest, 1979). Prescribed fire is another approach that managers can use either as a primary treatment or as a follow-up treatment after thinning (Pollet & Omi, 2002). This technique is only suitable as a primary treatment in stands where there is a low probability of excessive torching or crowning (fire consuming the canopies of individual trees or groups of trees, respectively). Treatment prescriptions include basal area (BA) targets, specific species compositions, and targets for surface fuel loadings (Bahro, Barber, Sherlock, & Yasuda, 2007). An effective treatment not only satisfies these measurable goals, but accomplishes the inherent goal of decreasing potential fire severity (Cochrane et al., 2013). The period of time that a fuel treatment remains effective is referred to as the treatment longevity, or the time that must elapse for the potential fire behavior to reach some undesirable threshold.

Fuel treatment longevity is highly variable and is most related to rates of surface fuel accumulation, surface fuel decomposition, and tree regeneration (Oliver & Ryker, 1990; Sackett & Haase, 1998). Post treatment, the initial surface fuel loading should reflect the treatment goal and reflects the difference of activity fuel (slash) creation and removal. There may be some delayed effects after treatment such as the shedding of scorched material where prescribed fire is used or the decomposition of fine fuels left after mechanical treatments (Stephens et al., 2009). These effects will diminish through the first few years following a treatment and fuel loading increases will become a function of site-specific understory and overstory productivity, offset by the rate of decomposition (J. K. Agee & Skinner, 2005; Stephens et al., 2009). Increases in fine fuels will be driven by the recruitment of grasses, forbs, and shrubs in the understory and needle cast or branch shedding by the overstory (Stephens, McIver, et al., 2012). Delayed tree mortality may increase large surface fuels after treatment, but other increases in large fuels will likely be delayed until a significant mortality agent acts on the treated stand such as drought, bark-beetle outbreaks, or competition induced mortality (James K Agee, 2003; Fule, Roccaforte, & Covington, 2007). Decomposition rates of surface fuels will be highest in warm, moist environments such as that of the Sierra Nevada Range (Dodge, 1972; Weatherspoon & Skinner, 1996). Areas that experience low winter temperatures and do not retain much moisture through the summer, similar to California's Mediterranean climate, will have slower rates of decomposition (Dodge, 1972; Weatherspoon & Skinner, 1996).

Post treatment, the remnant low-density overstory combined with a surface disturbance creates ideal conditions for prolific tree regeneration and allows the release of any remaining advanced regeneration (Battaglia et al., 2008; Oliver & Ryker, 1990). As seedlings establish and grow, they increase the connectivity between surface fuels and the forest canopy, allowing for an increase in crown fire potential. In the Black Hills of South Dakota, ponderosa pine regeneration densities can exceed several thousand seedlings ha^{-1} within 5-10 years after treatment (Shepperd & Battaglia, 2002). However in northern Arizona, ponderosa pine regeneration 5 years after treatment has been documented to occur at densities of 14-75 seedlings ha^{-1} (Bailey & Covington, 2002). This incredible range demonstrates that treatment longevity, as related to pine regeneration, will be profoundly variable across the landscape.

The rates of tree regeneration for ponderosa pine and Douglas-fir in the middle Rockies are reflective of site conditions such as seed production potential, time between mast years, moisture availability, and temperature patterns (Long, 1994). Many factors limit successful regeneration, including: drought, seed predation, browsing by rodents and ungulates, sunscald, frost heaving, fire, disease, and competition from herbaceous plants (Harrington & Kelsey, 1979; Larson & Schubert, 1969; Pearson, 1923; Shepperd, Edminster, & Mata, 2006). Further, in semi-arid climates, climatic conditions must be favorable for a series of years to foster cone and seed development, followed by germination and establishment of seedlings (Larson & Schubert, 1969; White, 1985). Following seed production and germination, ponderosa pine has the highest establishment success under conditions with little or no shading and scarified soil (Shepperd et al., 2006). Douglas-fir, however, experiences higher establishment success with higher moisture availability and an increased level of shading (Isaac, 1943; Long, 1994).

Although hazardous fuel treatments have been occurring on an increasingly large scale, there has been little empirical research regarding their ecological outcomes through time (Hudak et al., 2011). Identifying areas where treatments will be most effective or have the most extended longevity is critical to efficient management. Resources are often not available to treat entire management areas and prioritization must occur that maximizes the return on investment (Calkin & Gebert, 2006). At a regional scale, broad differences in forest dynamics and productivity will contribute to major differences in long-term management planning. This is evidenced by planning in the Black Hills being driven by the utilization of higher growth rates to produce merchantable timber in contrast to areas that are slow growing and not productive where management is focused more on ecological maintenance of the wildland-urban interface, wildlife, aesthetics, etc rather than material production. At smaller scales, such as within an individual forest, variation in structure and composition will require management plans and treatment prescriptions to be developed at a stand level as the responses to management activities will vary.

Site-specific factors including aspect, slope position, slope steepness, and the resulting micro-climates can lead to even adjacent stands having distinct properties (Reinhardt, Keane, Calkin, & Cohen, 2008). These factors will affect individual species' rates of regeneration and growth within each stand and as such, treatment longevity is unlikely to be uniform across a forest. Aspect can create microclimate differences as north-facing slopes receive less direct sunlight, retain higher soil moisture due to less evaporative drying, and have lower surface temperatures relative to south-facing slopes (Everett, Schellhaas, Keenum, Spurbeck, & Ohlson, 2000). Slope position and steepness will influence the position of the water table and the ability of a stand to retain soil moisture. Drier stands, like those on south facing slopes above the water table, will have low establishment and growth rates of ponderosa pine while competitors, including Douglas-fir, will be further limited, leading to increased treatment longevity (Harrington & Kelsey, 1979). In stands on north aspects, Douglas-fir and other species will be more competitive with ponderosa pine and in the absence of fire can come to dominate the stand (Isaac, 1943; Shepperd et al., 2006). This decreases treatment longevity not only due to higher tree growth and establishment rates but through the increase in crown fire risk facilitated by the physiological characteristic of lower branch retention in shade tolerant species.

Many studies have investigated fuel treatment effectiveness while far fewer have examined treatment longevity for ponderosa pine dominated forests, leaving many questions related to treatment longevity unanswered (Hudak et al., 2011). These questions pertain to the factors that promote or diminish longevity not only across regions but on a stand-to-stand level within each region. Comparisons of studies from the Sierra Nevada by Stephens, Collins, and Roller (2012); western Montana by Fajardo, Graham, Goodburn, and Fiedler (2007); the Black Hills by Battaglia et al. (2008) and Shepperd and Battaglia (2002); and northern Arizona by Bailey and Covington (2002) and Fulé, Laughlin, and Covington (2005) show regional differences in the climate metrics of temperature and precipitation likely explain the variation in their measures of treatment longevity. The majority of these studies focused on how long the effects of different treatment types lasted (generally thinnings with and without prescribed burning), while none examined aspects of local topography that may have stand-level effects on longevity.

Here, we examined fuel treatments that have occurred since 2003 in ponderosa pine dominated stands along the Front Range of Northern Colorado. The climate in this region is semi-arid and the forests are not productive. This suggests that forests here may have extended treatment longevity in comparison to areas of higher productivity. Notably, tree regeneration densities are likely to be limited by climate and surface fuels will accumulate slowly due to limited growth rates of plants. We measured surface fuel loading, tree seedling density, and overstory density on north and south aspects in stands that were only thinned or were thinned and burned. These stands had treatments completed 3-12 years prior to sampling. We hypothesized that surface fuel loadings and tree seedling densities would be higher on north aspects relative to south aspects. Additionally, we speculated that fuel loading and seedling density would increase with time since treatment in stands on both aspects, but that the rate of increase would be higher on north aspects. Finally, we hypothesized that stands treated with prescribed fire after thinning would have lower surface fuel loadings and higher seedling densities than stands that were not burned.

1.2 Methods

1.2.1 Study Area

The study area was located in the Canyon Lakes Ranger District of the Arapaho-Roosevelt National Forest (ARNF) near the town of Red Feather Lakes, Larimer County, Colorado (Figure 1). Study sites ranged in elevation from 2350 – 2650 m. The climate is semi-arid, averaging 45.2 cm of precipitation per year. Mean temperatures range from -4.5°C in December to 16.4°C in July (PRISM, April 19, 2016).

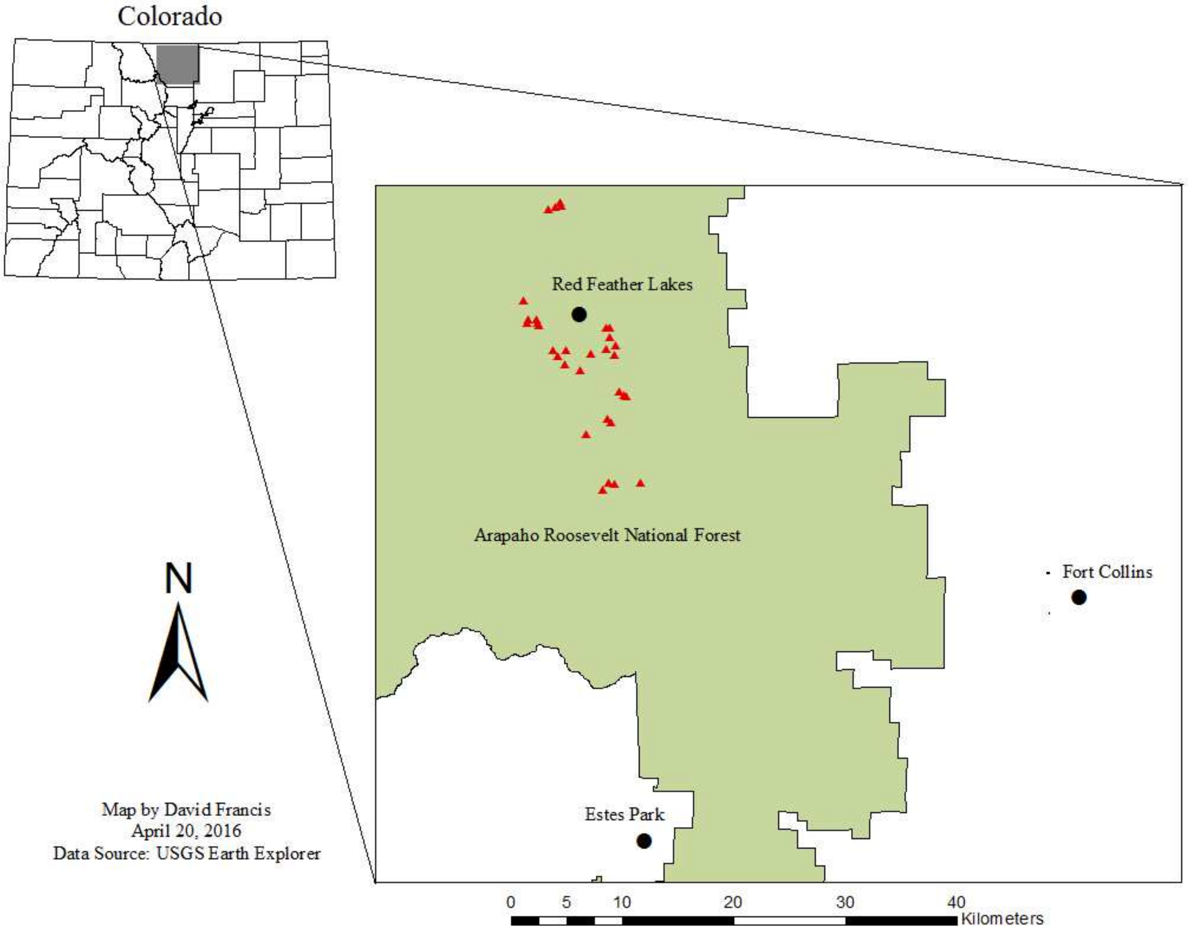

Figure 1: Study sites located in northern Colorado

1.2.2 Treatment selection and sampling

To examine changes over time, treatments were stratified by time since completion into bins of 3-4 yrs, 7-8 yrs, and 10-12 yrs post treatment. Within each age bin, two treatment types were examined: thinning only and thinning with follow-up prescribed burning. Slash had been removed either by whole-tree harvest or pile and burn, with the piles having already been burned. Additionally, each treatment type within each age bin was also sampled on north and south aspects. All sites were sampled from June – August of 2015. Treatment area boundaries were obtained through the US Forest Service Activity Tracking System database. A total of 32 sites were sampled. Each aspect, treatment, and time since treatment interval combination (2x2x3=12) was sampled in 2 or 3 stands (Table 1). In addition, 4 reference (untreated) stands were sampled with 2 each on north and south aspects (Table 1).

Within treatment units, areas of at least 5 ha in size with a slope between 5-20% and an aspect facing +/- 30 degrees of true N/S were identified as possible study sites. The slope constraint prevents bias from the effects of steep slopes, such as soil erosion making areas unstockable or non-local seed dispersal affecting seed pressure, and prevents sampling in flatter drainage areas. The aspect constraint allowed for accurate representation of north – south contrasts and eliminates effects of east – west sun exposure. Following field verification of suitability, a random point was placed within the suitable area meeting the above criteria. From this point a systematic grid of 20 plots spaced 35 m apart was established following cardinal directions. Some stands had less than 20 plots established due to violations of the sampling constraints (Table 1).

Table 1: Stand characteristics representing all treatment type, aspect, and time since treatment (TST) combinations *min – max stand means for quadratic mean diameter (QMD), basal area (BA) of live trees, and site index in meters with base age 100 years

Treatment	Aspect	TST (yrs)	# Stands	Total Plots	QMD (cm)*	BA (m^2 ha^{-1})*	Site Index*
Thin	South	10	3	60	24.8 - 38.2	10.6 - 11.0	10.7 - 13.7
Thin	North	10	3	60	26.4 - 31.0	7.8 - 11.9	10.7 - 12.2
Thin	South	7	2	40	31.2 - 34.9	9.6 - 10.1	9.1 - 12.2
Thin	North	7	3	60	33.3 - 36.6	11.9 - 15.6	10.7 - 12.2
Thin	South	3	3	60	34.5 - 41.8	10.1 - 10.6	9.1 - 12.2
Thin	North	3	2	40	25.3 - 27.8	5.5 - 9.6	10.7 - 12.2
Thin + Burn	South	12	2	40	38.9 - 46.3	11.0 - 13.3	12.2 - 13.7
Thin + Burn	North	12	2	36	29.4 - 30.0	8.6 - 11.9	12.2
Thin + Burn	South	8	2	40	36.1 - 40.1	5.5 - 7.8	10.7 - 12.2
Thin + Burn	North	8	2	40	31.6 - 39.1	6.9 - 7.3	12.2
Thin + Burn	South	4	2	40	35.2 - 42.1	9.2 -15.2	12.2 - 13.7
Thin + Burn	North	4	2	33	27.2 - 30.4	9.2 - 9.7	12.2 - 13.7
Reference	South	-	2	40	29.2 - 40.1	11.9 - 14.7	13.7
Reference	North	-	2	37	24.3 - 26.8	17.3 - 17.5	12.2

1.2.3 Seedling Sampling

At each plot center, a 78.5 m^2 fixed-radius plot was used to sample tree seedling densities. Seedlings were characterized as having a height <137 cm (breast height). Each encountered seedling was identified by species and placed in one of nine height classes (0-5 cm, 5-10 cm, 10-15 cm, 15-20 cm, 20-30 cm, 30-50 cm, 50-70 cm, 70-100 cm, 100-137 cm). Only established seedlings (>1 yr old) were counted, germinate seedlings were excluded from this study. At each plot, the first seedling encountered for each species and height class combination was collected for aging in the laboratory.

1.2.4 Overstory Sampling

At every-other plot, a 4.6 m^2 ha^{-1} (20 ft^2 ac^{-1}) BA factor prism was used to estimate BA of live trees and snags >137 cm in height. Each tree was recorded by species and measured for diameter at breast height, CBH, and total height. Height measurements were taken using a laser hypsometer. CBH was defined as the distance from the ground on the upslope side of the tree to the point where the first live branch connected to the tree-bole. 5 ponderosa pine site trees were identified within each stand that were the tallest and most dominant with no intensive competition from other trees and cored to the pith for aging in the laboratory to determine site indexes following Meyer (1938).

1.2.5 Surface Fuel Measurements

Dead surface fuel loading was sampled following Brown (1974) and Bradshaw, Deeming, Burgan, and Jack (1984). Two transects were established with the first following a random azimuth and the second oriented 180° in the opposite direction. Litter and duff depths were recorded at 1, 2, and 3 meters from plot center along each transect. 1 and 10 hour fuel classes (0-0.635 cm and 0.635-2.54 cm diameter, respectively) were tallied for the first 4 m along each transect. 10 hour fuels (2.54-7.62 cm diameter) were tallied for the first 6 m along each transect. 1000 hour fuels (7.62+ cm) had diameters recorded for 20 m along each transect and were also individually recorded as sound or rotten. The data from both transects were combined and fuel loadings were calculated for each plot following the formula and estimates presented in Brown (1974), except for estimates of squared diameters which came from Vakili (2015).

1.2.6 Statistical Analysis

We used multiple linear regression to examine how seedling densities, surface fuel loadings, and CBH changed with time since treatment. Separate models were analyzed for the each of the following response variables: duff depth, litter depth, fine fuel loading (sum of 1h, 10h, and 100h fuels), coarse wood loading (sum of 1000h+ sound and rotten fuels), total fuel loading (sum of fine and coarse loadings), tree seedling density (summed and by individual species), and CBH. To examine differences in aspects and treatment types, these variables were included as categorical predictors while time since treatment was treated as a continuous predictor variable. Modeling began with all possible interactions between the predictor variables and backwards elimination was used to eliminate the highest order term, the term with the most variables in an interaction (e.g. aspect*treatment type*time since treatment), with the lowest F-value test statistic one at a time until all interactions were significant or eliminated at alpha = 0.05. If an interaction was significant, all lower order terms containing the interaction variables were kept in the model. Backwards elimination was stopped if all interactions were removed, leaving the individual terms of aspect, treatment type, and time since treatment.

The multiple linear regression (above) resulted in one of three scenarios for each response variable: a significant relationship to time since treatment (with or without significant aspect and treatment type differences); no relationship to time since treatment but a significant difference for aspect and/or treatment type; and no relationship to time since treatment nor differences for aspect or treatment type. When a significant relationship to time since treatment was found, the multiple linear regression model became the final model for a given response variable. When no significant differences were found, the conclusion of no differences for a given response variable was made. No relationship to time since treatment but a significant difference for aspect or treatment type led to further analysis. We concluded that simply finding a significant difference for aspect or treatment type was not adequate as the context of time was not included in the interpretation e.g. total fuel load was greater on north than south aspects in contrast to total fuel load was greater in each treatment age bin on north aspects. To do this, we used an analysis of covariance to compare least square means for aspect and/or treatment type within each binned age class. This allowed us to view if differences were consistent over time or only occurred in specific age classes.

A second multiple linear regression analysis was used to examine relationships between seedling densities and live overstory BA, excluding reference sites. Total live conifer BA was tested for significant relationships to total conifer seedling density, Douglas-fir seedling density, and ponderosa pine seedling density. Douglas-fir and ponderosa pine live BA were used as proxies for their respective species' seed pressure and were tested for relationships to their respective species' seedling densities. Seedling density was used as the response variable, live BA as the continuous predictor, and aspect and treatment type as categorical predictors. Modeling began with all possible interactions and backwards elimination was used to eliminate the highest order term with the lowest F test statistic one at a time until all interactions were significant or eliminated at alpha = 0.05.

Multiple regression techniques were also used to estimate seedlings ages from seedling height for ponderosa pine and Douglas-fir (other species did not have an adequate sample size). Each model began with all possible interactions between the predictor variables of seedling height (the midpoint of each height class in the analysis), treatment type, aspect, and treatment age group. Height class was treated as a continuous variable, while treatment type, aspect, and treatment age group were categorical variables. This resulted in a linear model to predict the age of seedlings based on height, with adjustments to the slope or intercept for any significant variables or variable interactions. Using this model, all nine seedling height classes were assigned a predicted age. These predicted ages were then plotted against observed seedling densities to produce seedling age distributions for each species. This same approach was used for the reference stands to create age distributions for comparison, excluding the treatment age class and treatment type predictor variables.

1.3 Results

1.3.1 Seedling Densities Post Treatment

We encountered seedlings from five tree species during field sampling: ponderosa pine, Douglas-fir, limber pine (*Pinus flexilis),* lodgepole pine (*Pinus contorta* subsp. *latifolia),* and quaking aspen *(Populus tremuloides).* Aspen was removed from total seedling density estimates as it was not central to research questions and was not a major overstory or understory component in any sampled stand, occurring only in small dense patches. Ponderosa pine and Douglas-fir were the only species examined independently as they comprised the vast majority of encountered seedlings (Table 2).

Table 2: Mean seedlings ha^{-1} by species. Ranges represent min – max of stands in each classification. TST represents time since treatment.

			Species				
Treatment	Aspect	TST* (yrs)	Ponderosa Pine	Douglas-fir	Limber Pine	Lodgepole Pine	Quaking Aspen
Thin	South	10	286 - 331	0 - 146	6 - 63	0 - 0	273 - 567
Thin	North	10	140 - 1407	89 - 458	76 - 159	166 - 541	700 - 1267
Thin	South	7	38 - 76	0 - 45	0 - 0	0 - 0	32 - 102
Thin	North	7	38 - 235	45 - 178	0 - 0	0 - 0	32 - 388
Thin	South	3	31 - 146	0 - 19	0 - 19	0 - 0	0 - 337
Thin	North	3	127 - 318	95 - 388	0 - 25	0 - 0	165 - 1305
Thin and Burn	South	12	840 - 987	0 - 0	0 - 0	0 - 0	13 - 19
Thin and Burn	North	12	88 - 891	820 - 4870	0 - 0	8 - 13	366 - 464
Thin and Burn	South	8	102 - 446	0 - 6	0 - 0	0 - 0	0 - 6
Thin and Burn	North	8	140 - 961	19 - 32	0 - 0	0 - 0	273 - 1019
Thin and Burn	South	4	95 - 223	0 - 6	0 - 0	25 - 45	0 - 50
Thin and Burn	North	4	48 - 226	191 - 589	0 - 21	8 - 255	477 - 523
Reference	South	-	64 - 197	25 - 89	0 - 0	0 - 0	13 - 484
Reference	North	-	120 - 140	442 - 847	13 - 180	0 - 22	434 - 509

Total conifer seedling density significantly increased with time since treatment (Fig. 2). Mean conifer regeneration densities were calculated at the stand level and square-root transformed to normalize the distribution from a skew to the right. In the full model, one point was identified as a significant outlier (studentized residual = 4.9, Bonferonni adjusted p-value = 0.0029) due to an exceptionally high seedling density of Douglas-fir. The analysis was done with and without the outlier and both models contained the same significant predictor variables of time since treatment and aspect. The model not including the outlier was chosen as the excluded point had a large influence on the resulting relationship. Total conifer seedlings ha^{-1} CS can be estimated using

$$\sqrt{CS} = \beta_0 + \beta_1 * (Years\ since\ treatment) \qquad (1)$$

where β_0 and β_1 are numerical coefficients (Table 3).

Table 3: Parameter estimates and model fit statistics for Eq. (1). The p-value for β_0 represents the significant difference of the intercept for each aspect. The p-value for β_1 represents it is significantly different from zero

Aspect	β_0	Std Err	p	β_1	Std Err	p	R^2
North	12.3599	3.9583	0.003	1.7652	0.4722	0.0010	0.5051
South	2.9622	2.9583					

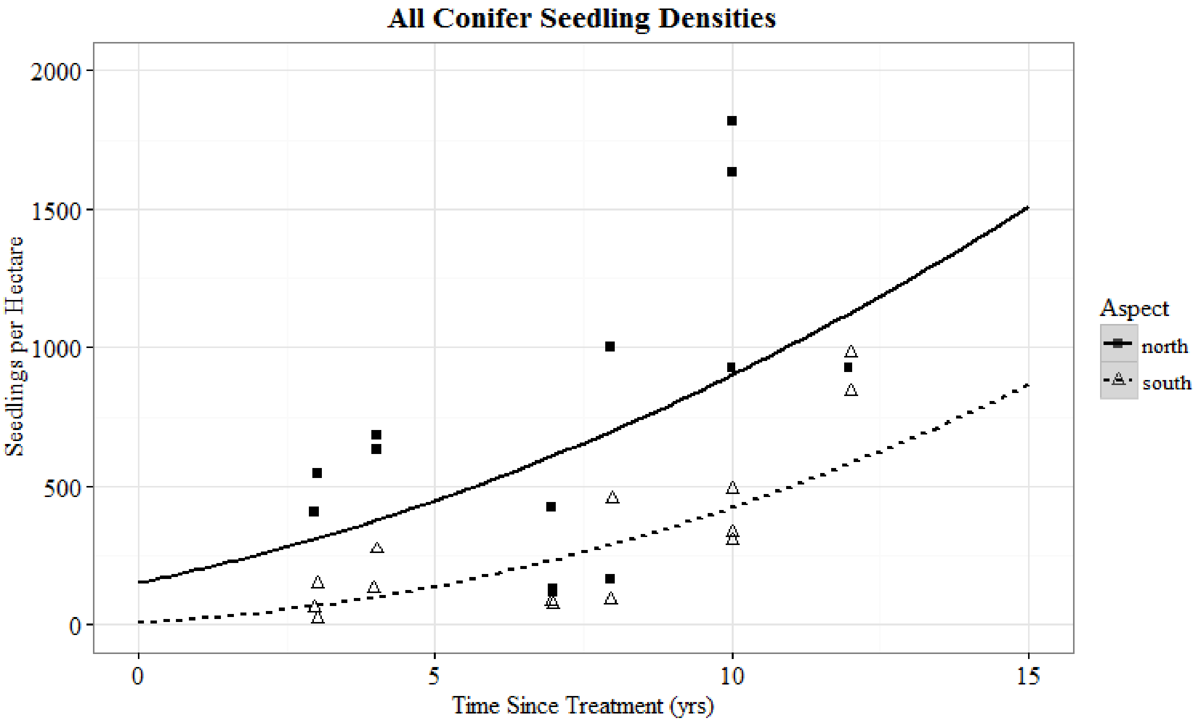

Figure 2: Observed conifer regeneration densities with back-transformed regression lines overlaid. Lines are described by Equation (1), parameter estimates and fit statistics are in Table 3.

Ponderosa pine seedling densities also significantly increased with time since treatment (Fig. 3). Stand level mean ponderosa pine seedling densities were square root transformed for analysis to normalize the distribution from a large right skew. No interactions between time since treatment, aspect, or treatment type were significant, nor was there a significant effect of aspect or treatment type. This resulted in a final regression model with time since treatment as the only significant predictor of ponderosa pine seedling density PP

$$\sqrt{PP} = \beta_0 + \beta_1 * (Years\ since\ treatment) \qquad (2)$$

where β_0 and β_1 are numerical coefficients (Table 4). Douglas-fir seedling densities did not have a significant relationship to time since treatment ($p = 0.25$).

Table 4: Ponderosa pine seedling density regression parameter estimates and model fit statistics. The p-value for β_0 shows it is not significantly different from zero. The p-value for β_1 represents it is significantly different from zero

β_0	Std Err	p	β_1	Std Err	p	R^2
2.7296	3.8216	0.48	1.7816	0.4785	0.0001	0.3477

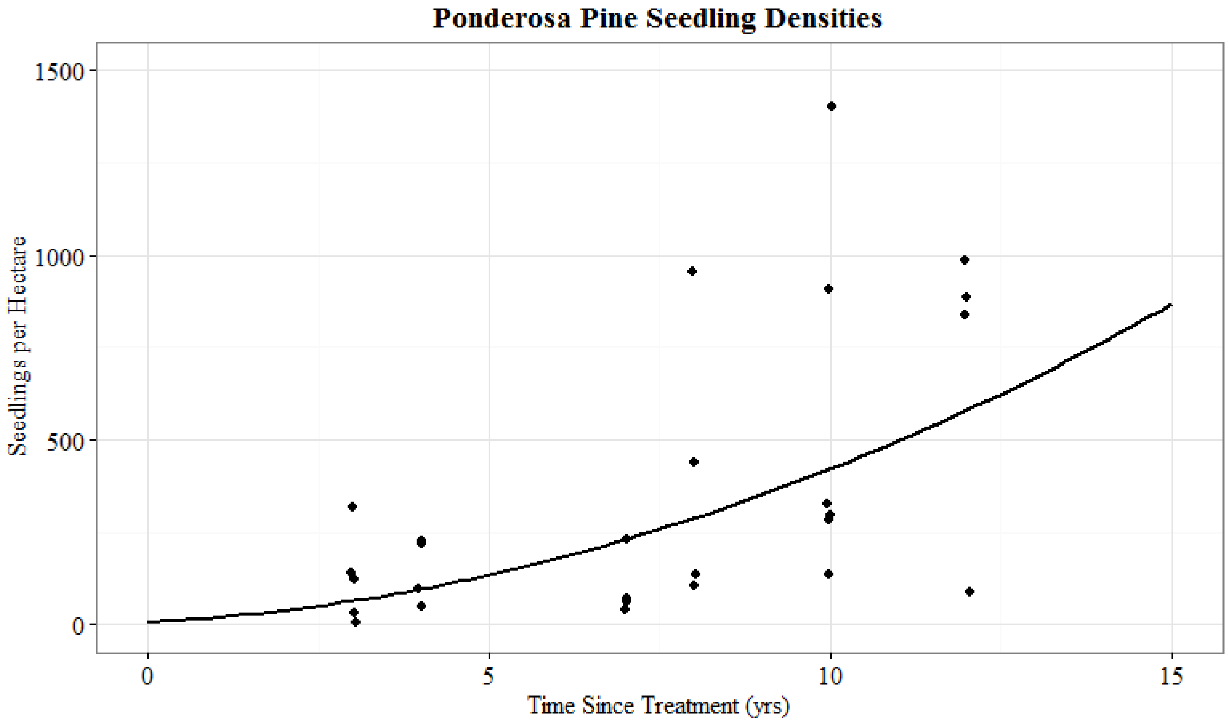

Figure 3: Ponderosa pine seedlings densities with back-transformed regression line overlaid (Eq. 2). Parameter estimates and fit statistics are in Table 4.

1.3.2 Seedling Age Distributions

A total of 570 ponderosa pine seedlings were collected and aged. Ponderosa pine seedling height was a significant predictor of seedling age. Both seedling ages and seedling heights were log transformed to satisfy regression assumptions. A significant relationship between height and age was found ($p<<0.001$) and backwards elimination was stopped at a significant three-way interaction between treatment age class, treatment type, and aspect ($p=0.032$) ($R^2 = 0.839$). This model was then used to predict the average age of ponderosa pine seedlings in each height class for each of the 12 combinations of aspect, treatment type, and treatment age class. Age distributions were then created using these predicted ages and observed regeneration densities (Figure 4). Reference stands were analyzed in the same way to create an age distribution for comparison to the age distributions of treated stands (Figure 5). As the analysis above found significant differences for each treatment age class, treatment type, and aspect combination, a simplified analysis was done to produce an equation for estimating ponderosa pine seedling age in years $PPSA$ based on seedling height

$$ln(PPSA) = \beta_0 + \beta_1 * ln(Ponderosa\ Pine\ Seedling\ Height\ (cm)) \quad (3)$$

where β_0 and β_1 are numerical coefficients (Table 5).

Table 5: Parameter estimates for Eq. (3) predicting ponderosa pine seedling age from seedling height and model fit statistis. P-values indicate both parameters are significantly different from zero

β_0	Std Err	p	β_1	Std Err	p	R^2
0.41166	0.07088	>>0.0001	0.58535	0.02107	>>0.0001	0.8149

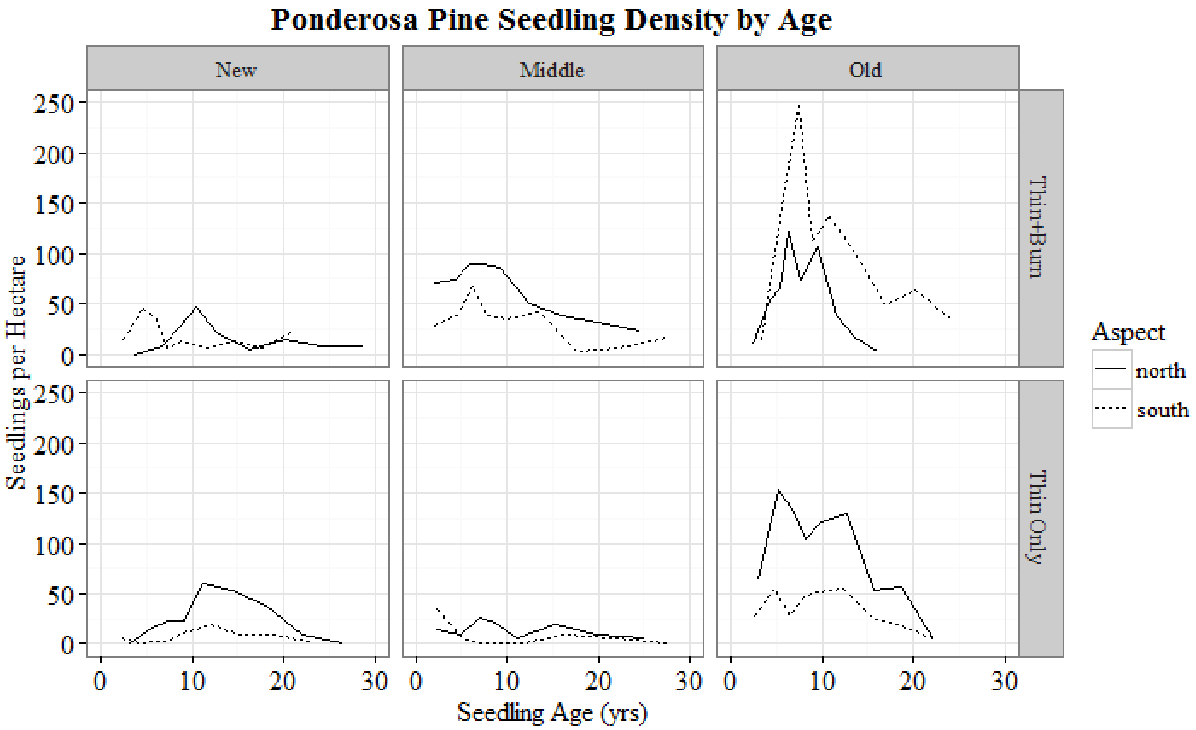

Figure 4: Predicted mean ages of ponderosa pine plotted against observed regeneration densities. Lines connect the midpoints of each height class and line termini signify the predicted age at which a seedling reaches breast height.

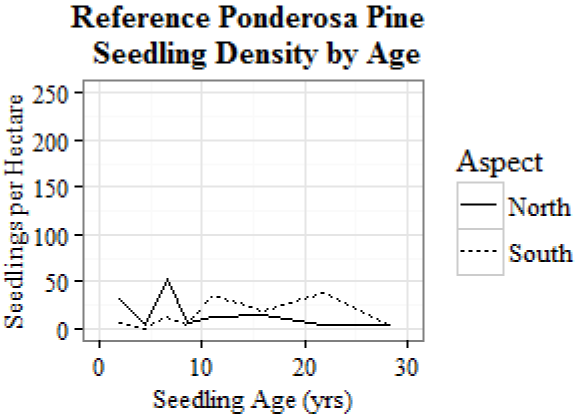

Figure 5: Predicted mean ages of reference ponderosa pine seedlings plotted against observed densities.

A total of 329 Douglas-fir seedlings were collected and aged; the ages of Douglas-fir seedlings were also significantly predicted by seedling heights. This seedling age prediction model examined only north aspects; southern aspects did not have enough seedlings collected to create a model (44 of 329 seedlings). Both seedling heights and ages were natural log transformed for analysis to satisfy model assumptions. The final model had a significant three-way interaction between seedling height, treatment type, and treatment age (p=0.0002, $R^2 = 0.868$). This model was then used to predict ages for each height class by treatment type and treatment age for north aspects. Seedling age distributions were then created using these predicted ages and observed regeneration densities (Figure 6). Data from reference sites on north aspects was used to create an age-distribution for comparison (Figure 7). As the analysis above found significant differences for each treatment age class and treatment type combination on north aspects, a simplified analysis was done to produce an equation for estimating Douglas-fir seedling age in years *DFSA* based on seedling height for north aspects

$$ln(DFSA) = \beta_0 + \beta_1 * ln(Douglas - fir\ Seedling\ Height\ (cm)) \tag{4}$$

where β_0 and β_1 are numerical coefficients (Table 6).

Table 6: Parameter estimates for Eq. (4) predicting north aspect Douglas-fir seedling age from seedling height and model fit statistics. P-values indicate both parameters are significantly different from zero

β_0	Std Err	p	β_1	Std Err	p	R^2
0.58658	0.09781	>>0.0001	0.58202	0.03028	>>0.0001	0.8144

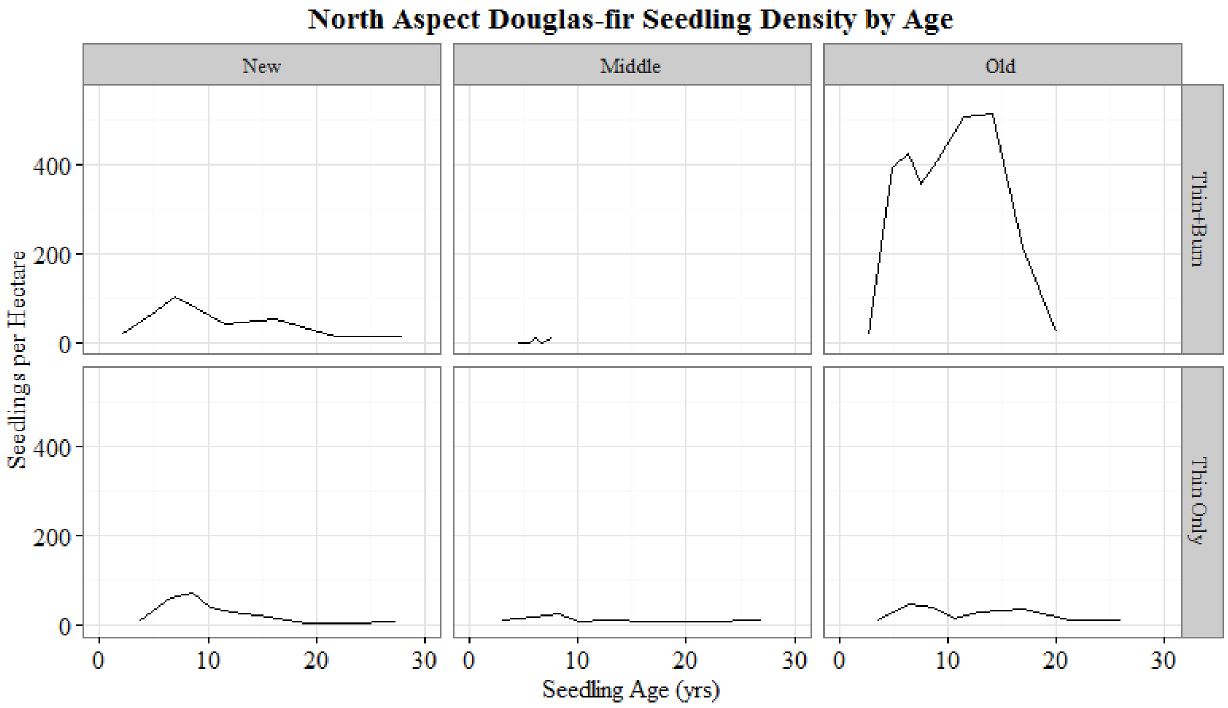

Figure 6: Predicted mean ages of Douglas-fir seedlings plotted against observed seedlings densities. Lines connect height class midpoints while line termini represent the age at which a seedling reaches breast height.

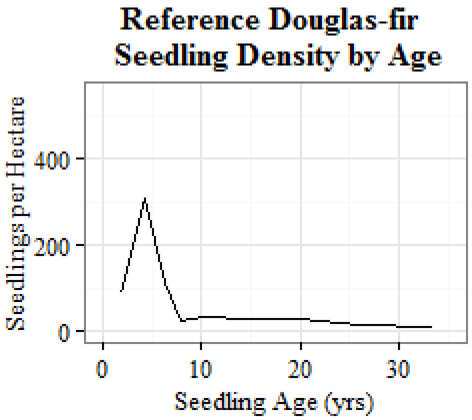

Figure 7: Predicted ages of Douglas-fir seedlings plotted against observed seedling densities for reference sites on north facing aspects.

1.3.2 Overstory Relationships

There was no significant relationship between total conifer seedling density and total conifer BA ($p = 0.77$), ponderosa pine BA ($p = 0.79$), or Douglas-fir BA ($p = 0.84$). Total conifer seedling densities were square root transformed for analysis. There was no significant relationship between ponderosa pine seedling densities in relation to total conifer BA ($p = 0.69$) or to ponderosa pine BA ($p = 0.79$). Ponderosa pine seedling densities were also square root transformed for analysis.

Douglas-fir seedling density significantly increased with Douglas-fir BA (Figure 8). Douglas-fir seedling densities were square root transformed for analysis. There was also a significant difference between north and south aspects (Table 7). Douglas-fir seedlings ha^{-1} *DFS* can be estimated from Douglas-fir BA using

$$\sqrt{DFS} = \beta_0 + \beta_1 * (Douglas - fir\ BA\ (m^2\ ha^{-1})) \qquad (5)$$

where β_0 and β_1 are numerical coefficients (Table 7). There was no significant relationship between Douglas-fir seedling density and total conifer BA ($p = 0.58$).

Table 7: Parameter estimates and model fit parameter for Eq. (5). The p-value for β_0 represents the significant difference in intercepts between aspects. The p-value for β_1 represents the slope is significantly different from zero.

Aspect	β_0	Std Err	p	β_1	Std Err	p	R^2
North	8.2251	2.1214	0.012	2.1104	0.6404	0.0030	0.6566
South	1.7095	2.4117					

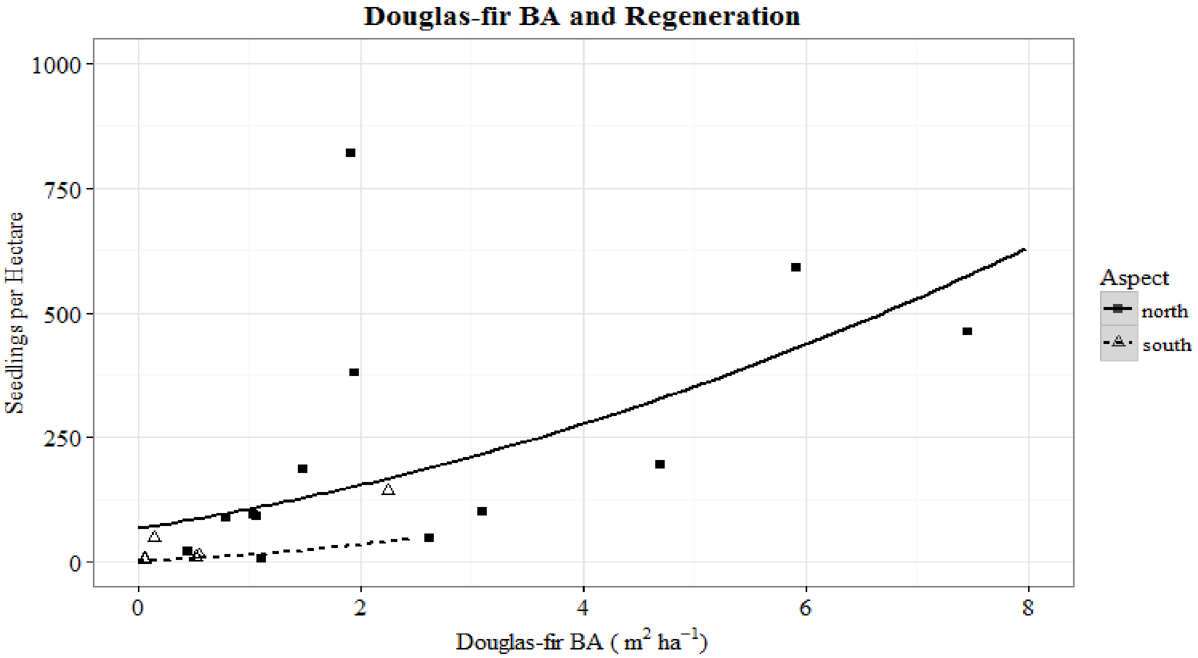

Figure 8: Douglas-fir live basal area and regeneration densities with back-transformed regression lines overlaid. Regression lines are presented in Eq. (5) with parameter estimates in Table 7.

Mean CBH was significantly higher in thinned and burned stands than in thin only (p=0.017) and reference stands (p=0.047); thin only was not significantly different from reference stands (p=0.83) (Figure 9).

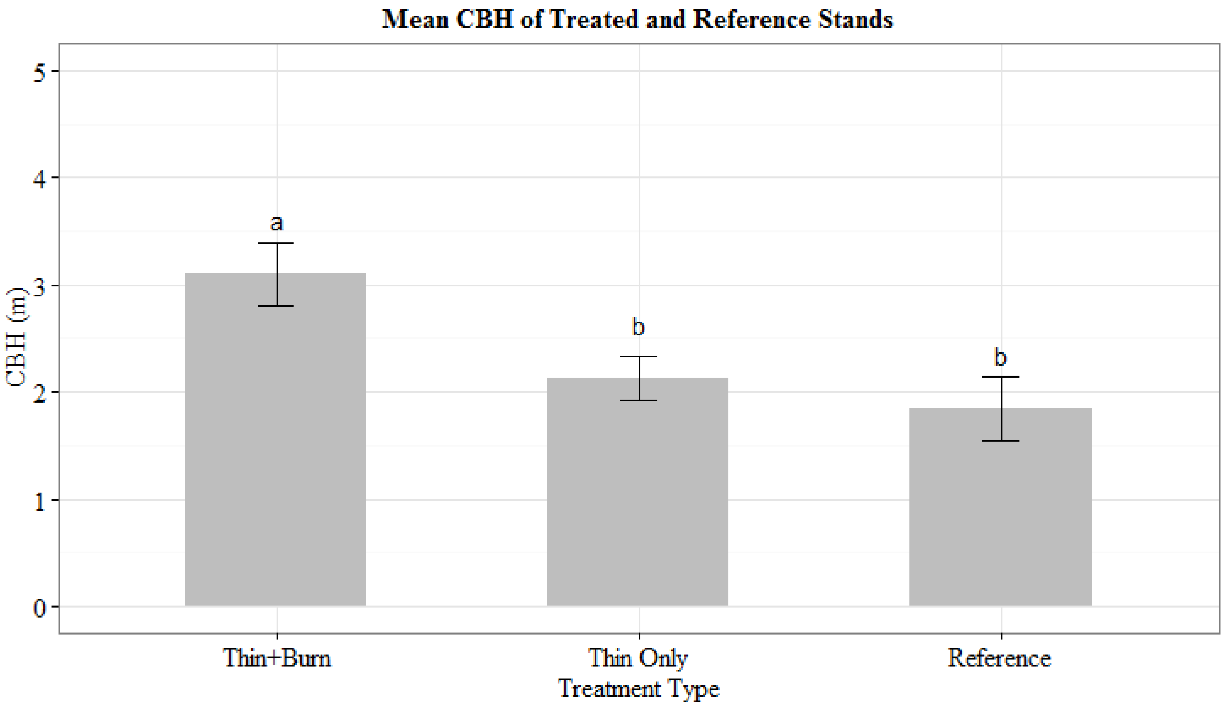

Figure 9: Mean CBH of treated and reference stands. Error bars are +/- one standard error. Letters denote significant differences at α = 0.05.

1.3.3 Surface Fuels

All fuel loadings and depths are reported below in Table 8. There were no significant relationships between time since treatment and any fuel classification examined; fine loading, coarse loading, and total loading were significantly different across aspects; duff depth and fine loading were significantly different between treatment types (Table 9). Comparisons of least squared means, within each treatment age class, for the above significant differences are shown in Figures 10-14. Fine fuel load, coarse fuel load, and total fuel load were square-root transformed for analysis

Table 8: Mean fuel loadings for treatment type, aspect, and time since treatment (TST) combinations

Treatment	Aspect	Time Since Treatment (years)	Duff Depth (cm)	Litter Depth (cm)	Fine Load (Mg ha^{-1})	1000+ Load (Mg ha^{-1})
Thin	South	10	0.64	0.99	3.70	4.26
Thin	North	10	0.74	1.02	6.38	11.04
Thin	South	7	0.51	0.76	3.12	4.39
Thin	North	7	0.59	1.11	3.64	9.88
Thin	South	3	0.57	1.10	4.47	5.73
Thin	North	3	0.69	1.38	5.32	9.87
Thin and Burn	South	12	0.33	0.81	2.20	3.27
Thin and Burn	North	12	0.56	1.23	4.90	17.71
Thin and Burn	South	8	0.23	0.61	2.10	5.55
Thin and Burn	North	8	0.19	0.58	2.32	2.72
Thin and Burn	South	4	0.50	1.33	1.88	8.80
Thin and Burn	North	4	0.67	1.04	2.76	11.01
Reference	South	-	0.47	0.98	2.16	8.14
Reference	North	-	0.92	1.21	4.56	10.91

Table 9: Multiple linear regression results for each fuel classification.

Fuel Type	Time Since Treatment	P-value	Aspect	P-value	Treatment Type	P-value
Duff Depth	no relationship	0.75	no difference	0.19	thin > thin+burn	0.016
Liter Depth	no relationship	0.21	no difference	0.35	no difference	0.47
Fine Fuel Loading	no relationship	0.28	north > south	0.015	thin > thin+burn	0.001
Coarse Fuel Loading	no relationship	0.76	north > south	0.012	no difference	0.82
Total Fuel Loading	no relationship	0.98	north > south	0.001	no difference	0.51

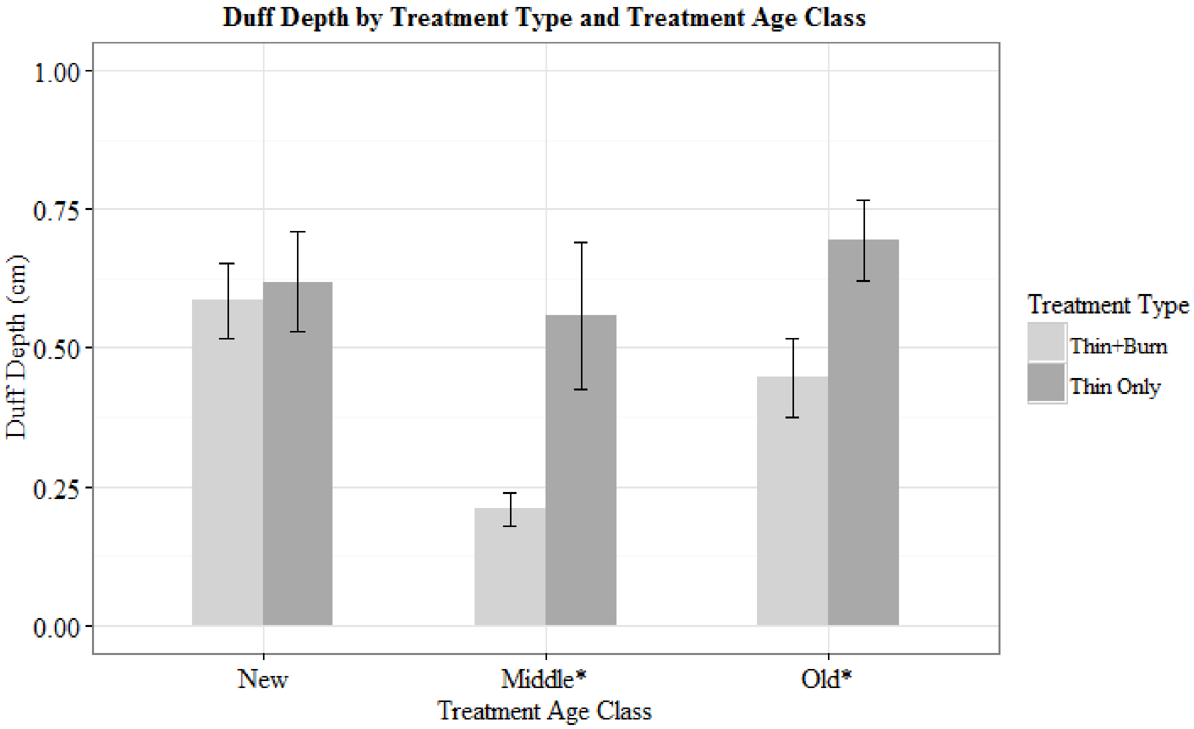

Figure 10: Mean duff depth by treatment age and treatment type, averaged over aspect. Error bars are +/- one standard error. Asterisks denote significant differences between treatment types within a treatment age class. P-values for new, middle, old contrasts are 0.72, 0.012*, and 0.049* respectively.

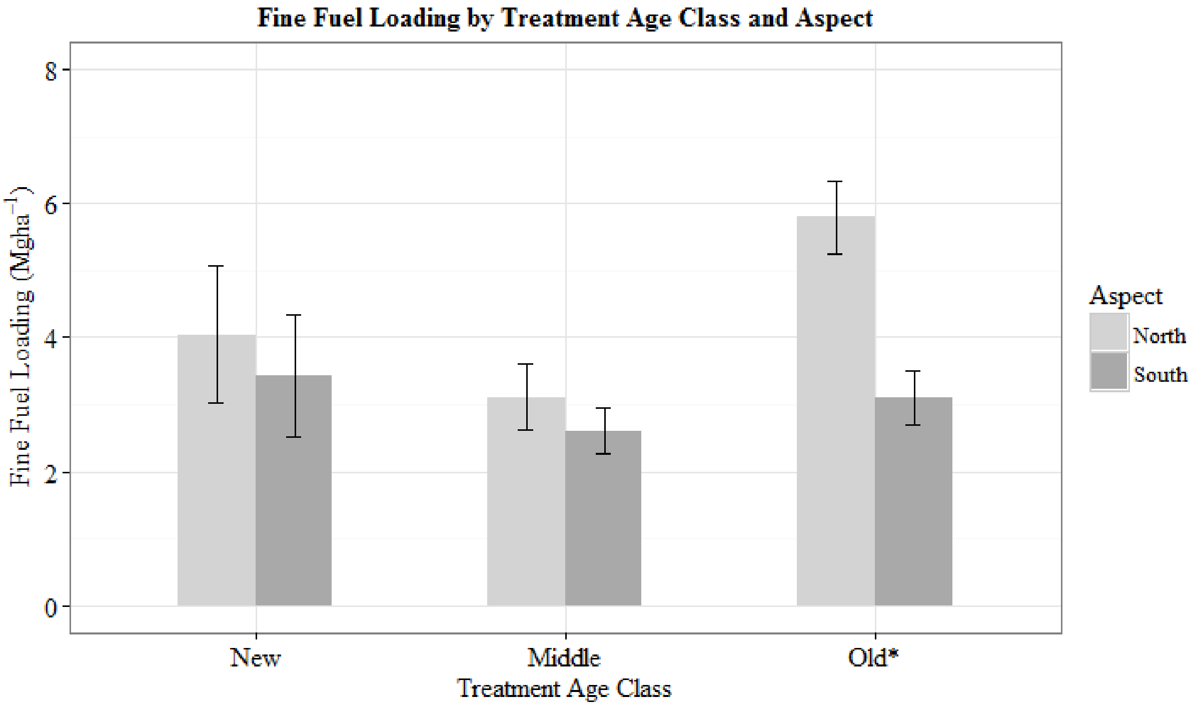

Figure 11: Mean fine fuel loadings by treatment age class and aspect, averaged over treatment type. Error bars are +/- one standard error. Asterisks denote significant differences between aspects within a treatment age class. P-values for new, middle, old contrasts are 0.21, 0.60, and 0.001* respectively.

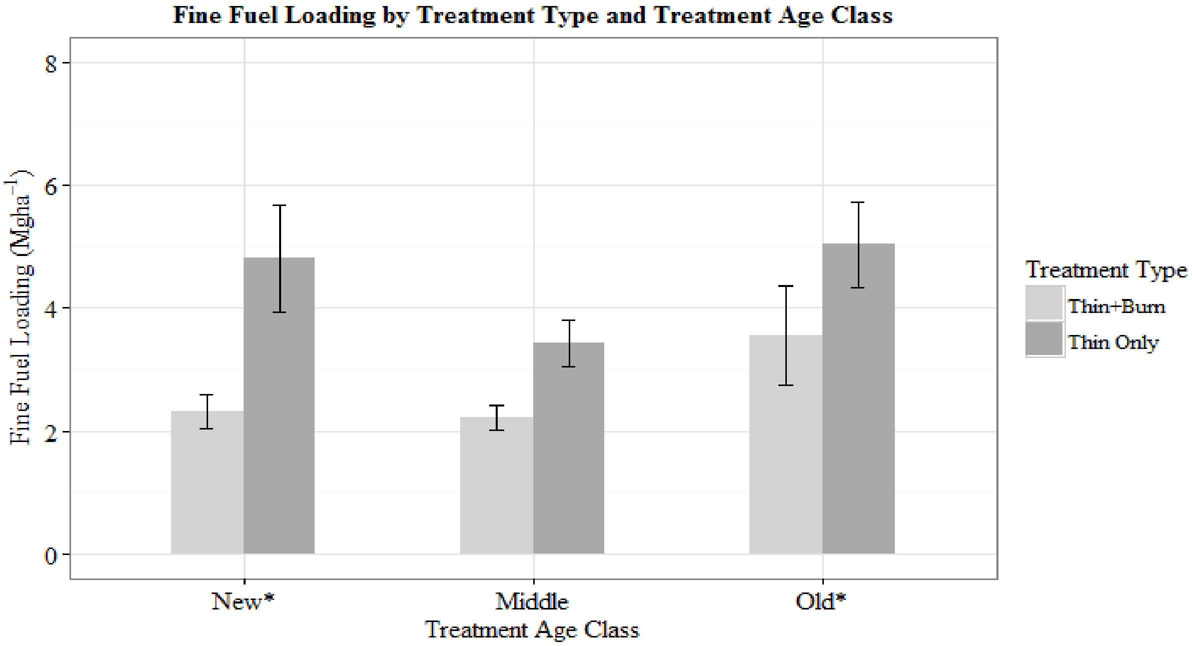

Figure 12: Mean fine fuel loadings by treatment age class and treatment type, averaged over aspect. Error bars are +/- one standard error. Asterisks denote significant differences between treatment types within a treatment age class. P-values for new, middle, old contrasts are 0.002*, 0.10, and 0.048* respectively.

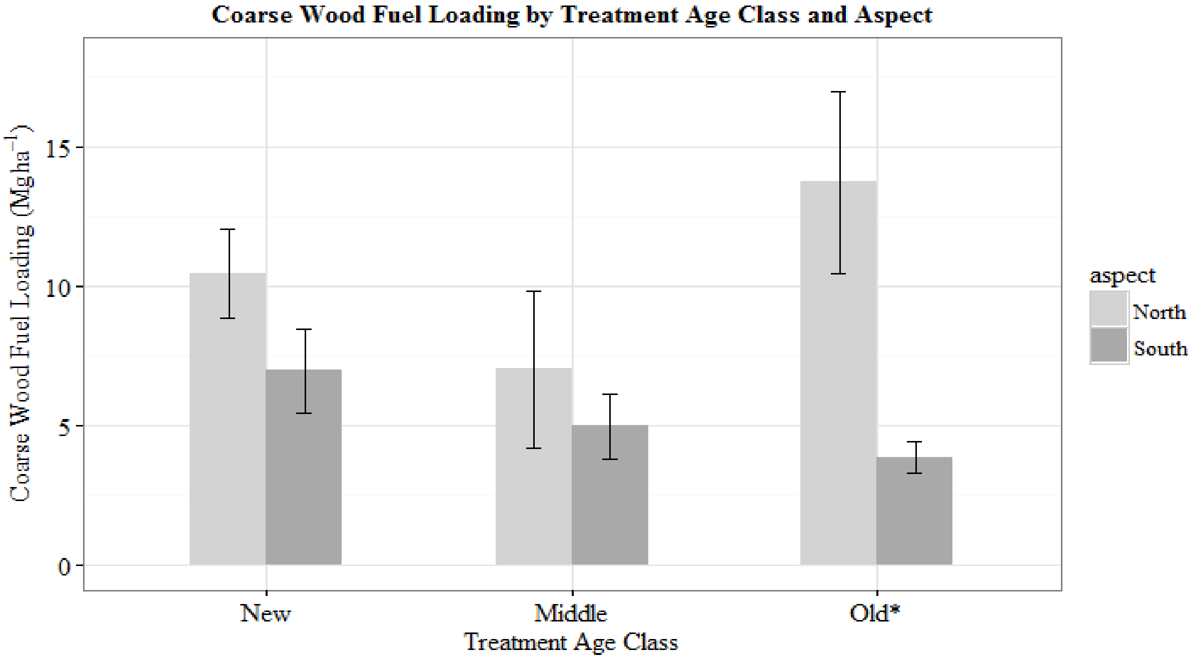

Figure 13: Mean coarse wood loadings by treatment age and aspect, averaged over treatment type. Error bars are +/- one standard error. Asterisks denote significant differences between aspects within a treatment age class. P-values for new, middle, old contrasts are 0.24, 0.57, and 0.003* respectively.

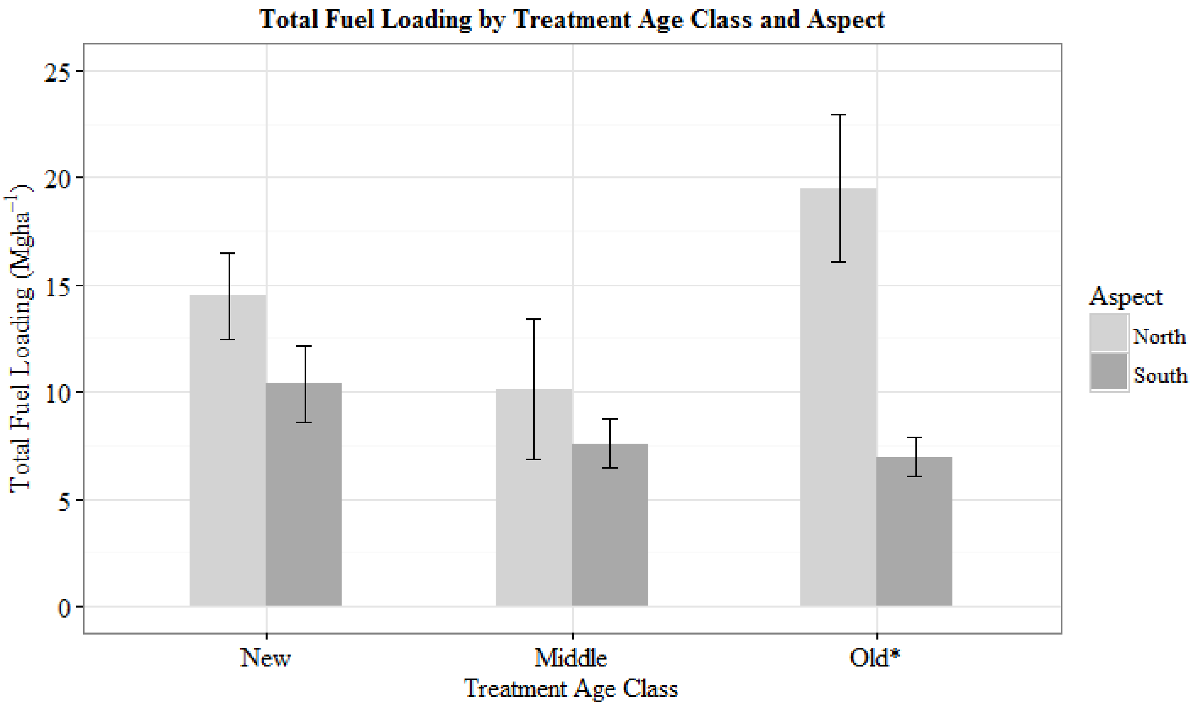

Figure 14: Mean total fuel loading by aspect and treatment age, averaged over treatment type. Error bars are +/- one standard error. Asterisks denote significant differences between treatment types within a treatment age class. P-values for new, middle, old contrasts are 0.20, 0.54, and 0.001* respectively.

1.4 Discussion

1.4.1 Seedling Densities and Overstory Relationships

In ponderosa pine stands treated to reduce hazardous fuels along the northern Colorado Front Range, there was an increase in conifer seedling densities within a decade following treatment. Further, the increase in conifer seedling density was greater on north facing aspects than south facing aspects, as hypothesized. This was driven by the presence of Douglas-fir seedlings on north-facing slopes as ponderosa pine seedling densities were not different across aspects through time. Contrary to our hypothesis, thinning and thinning with prescribed burning treatments did not result in different regeneration responses. The most notable difference found here between these treatment types was a higher CBH in thinned stands with prescribed burning

(Figure 9). This will increase treatment longevity as seedlings must be taller and fuel loadings higher to foster crowning or torching.

Ponderosa pine seedling densities increased with time since treatment implying that regeneration also increased post-treatment. By examining the seedling age distributions of treated stands, there is generally a higher proportion of younger/smaller seedlings than older/taller seedlings and these younger seedlings would have established after treatment (Figure 4). The seedling age distributions of the reference stands do not have a large quantity of young seedlings, implying that regeneration was accelerated through hazardous fuel treatment. The ponderosa pine seedling age distributions of treated stands also show that many seedlings were advance regeneration, having established before treatment. This highlights that long term seedling ingrowth and resulting fire potential will be affected by the amount of seedlings removed during treatment application.

Douglas-fir seedling densities did not significantly increase relative to time since treatment. There were also much higher Douglas-fir seedling densities on north aspects. This could be due to greater establishment success on north aspects, but the absence of any overstory Douglas-fir in many southern facing stands also presumably reduced or eliminated seed pressure. Similar to ponderosa pine, the age distributions of Douglas-fir seedlings showed a large proportion of seedlings were smaller/younger, establishing after treatment. However, reference stands also showed a similar pattern, implying that regeneration success was not increased through treatment, unlike ponderosa pine. As Douglas-fir is moderately shade tolerant, regeneration would not be as hindered as ponderosa pine in a denser, untreated stand. Seedling densities also significantly increased with Douglas-fir overstory BA, which serves as a proxy for seed production, demonstrating that seed availability likely has the largest influence on Douglas-fir regeneration rates through time. This informs managers that Douglas-fir regeneration will be higher when more Douglas-fir is left in a stand during treatment (Figure 8).

Conifer seedling densities we observed on the Colorado Front Range following fuels treatments were much greater than those observed in similar studies conducted in western Montana by Fajardo et al. (2007) and in northern Arizona by Fulé et al. (2005) and Bailey and Covington (2002). However, Colorado seedling densities were much lower than densities found in the Black Hills of South Dakota by Battaglia et al. (2008). The lower range of seedling densities we observed was similar to the maximal densities found in the mixed ponderosa-pine, Douglas-fir stands of western Montana where ponderosa pine seedling densities ranged from 33-86 seedlings ha^{-1} and Douglas-fir ranged from 8-156 seedlings ha^{-1} ten years after treatment (Figures 2 and 3) (Fajardo et al., 2007). Ponderosa pine seedling densities observed in northern Arizona ranged from 14-75 seedlings ha^{-1} at five years post-treatment, also similar to the lowest densities we observed in Colorado (Figure 3) (Bailey & Covington, 2002; Fulé et al., 2005). In the Black Hills, ponderosa pine seedling densities exceed several thousand stems ha-1 within a decade of treatment, much higher than the maximal densities found in Colorado (Figure 3) (Battaglia et al., 2008). Combined, this implies that treatment longevity on the Colorado Front Range, as related to conifer regeneration, will fall between the expected longevity in Arizona/Montana where treatments may persist longer and the Black Hills where longevity will be more quickly diminished.

1.4.1 Surface Fuels

Duff and litter depths following treatment were generally the same across aspects with no significant trends through time (Tables 8 & 9). Litter depths were not different across treatment types while duff depths were lower in burned stands for the middle and old treatment age classes (Figure 10). Our results do not follow the expected pattern that burning significantly reduces litter and duff following treatment before accumulating through time as trees shed scorched branches and understory plants reestablish and shed non-woody material (Stephens et al., 2009). While changes may have occurred through time, the space for time substitution approach used here may not have been adequate to detect these changes

Fine fuel loads, overall, were greatest on north aspects and in the thin only treatments with no change detected through time (Table 9). However, the higher fine fuel load on north aspects was only significant in the oldest age class, implying that a decade may be necessary before the rates of accumulation or decomposition begin to diverge across aspects following treatment (Figure 11). Thin+burn treatments had significantly reduced fine fuel loadings in the newest and oldest treatments (the middle treatments were also reduced but not statistically significant) where prescribed fire likely consumed these fuels, as hypothesized (Figure 12). The fine fuel loadings we observed are about half those documented for a comparable ponderosa pine – Douglas-fir forest of the Sierra Nevada seven years post-treatment for the same treatment types (Stephens, Collins, et al. (2012) and are similar to those observed five years after thinning treatments followed by prescribed fire in Northern Arizona ([2-4 Mg ha^{-1}] (Fulé et al., 2005)).

Coarse fuel loadings were unaffected by treatment type and did not change over time (Table 9). Though fine fuel loadings were reduced in burning treatments, these prescribed fires likely were unable to completely consume larger woody materials before extinguishing. The coarse wood loadings, like the fine fuel loadings, were generally higher on north aspects but only significantly greater than south aspects in the oldest treatment age class (Figure 14). These loadings also are smaller than those found in similar treatments in the Sierra Nevada range 7 years post-treatment (Stephens, Collins, et al., 2012) and in northern Arizona 5 years post-treatment (Fulé et al., 2005). Total fuel loading showed the same general results as coarse wood loadings as these comprise the majority of the fuel loadings. Overall, neither surface fuel loadings nor litter and duff depths seem to have increased within the time period observed. This implies that accumulation is a slow process on the Colorado Front Range and that reductions in surface fuels from treatments can be expected to persist for at least a decade.

1.5 Conclusion

The relationships we observed in stands 3-12 years after hazardous fuel treatments show that conifer regeneration has likely increased due to hazardous fuel treatment. These thinning treatments with and without follow-up prescribed burning appear to have enhanced ponderosa pine regeneration by emulating forest conditions associated with a frequent fire regime including decreased shading and increased ground scarification. In contrast, Douglas-fir regeneration was most correlated to BA, a proxy for seed availability, and mostly occurred on northern aspects. This informs managers that when more Douglas-fir is retained in a stand during treatment, a higher regeneration response can be expected; we estimated this rate to be an additional 100 seedlings ha^{-1} per one-unit increase in BA m^2 ha^{-1}. This will also lead to treatment effects diminishing more quickly on northern aspects, as the total conifer seedling density may be 500 seedlings ha^{-1} greater 5-10 years post-treatment. In addition, the finding that many of the seedlings found in treated stands established before treatment highlights the importance of their removal during treatment in order to increase treatment longevity. The only significant benefit we observed from the use of prescribed fire was the increase of CBH. Based on our seedling height growth model, this one-meter increase in CBH could prolong treatment longevity by as much as a decade. In the post-treatment time period we observed, there had not yet been any significant increases in surface fuel loadings; it is unclear if this is the actual dynamic that had occurred or if our study approach was unable to capture any existing trend.

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