THESIS

IMPACTS OF COARSE WOODY DEBRIS AND EDGE EFFECTS ON ENGELMANN SPRUCE REGENERATION

Submitted by

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ABSTRACT

IMPACTS OF COARSE WOODY DEBRIS AND EDGE EFFECTS ON ENGELMANN SPRUCE REGENERATION

Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) is a notoriously difficult species to regenerate, and there has been a history of regeneration failures following group selection cuts on the Uncompahgre Plateau. Our goal was to investigate edge effects and coarse woody debris management on regeneration success in group selection openings. Group selection is an uneven-aged system used in the West to regenerate high elevation spruce-fir forests with small (<1 ac) openings. We implemented an Engelmann spruce germination study on the Uncompahgre Plateau in group selection openings. Permanent plots were installed in spring of 2015. We altered microsite conditions by manipulating coarse woody debris amounts at varying distances from the north and south edges in combination with scarification. Findings show that the southern edge provides a benefit to spruce germination through 23 meters. Coarse woody debris was significantly beneficial at all distances from edge, and without coarse woody debris germination was extremely low.

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CHAPTER 1: IMPACTS OF COARSE WOODY DEBRIS AND EDGE EFFECTS ON ENGELMANN SPRUCE REGENERATION

1.1 Introduction

Forest management increasingly seeks to create structural heterogeneity and resilience through the development of a variety of age classes within stands. This leads to a need for increased knowledge of the impacts of silvicultural techniques on regeneration. Group selection is one method that can deliver increased structural heterogeneity and resilience by increasing diversity in age classes and species within stands by providing a variety of regeneration environments within stands (Lafond, et al. 2014,York, et al. 2003). Managers in the West have turned to group selection when looking to balance objectives including species diversity, operational efficiency, aesthetics, and timber yield (Lafond, et al. 2014,USFS 2013). Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) regenerates poorly in large openings. With this study, we quantified the effect of coarse woody debris loading and distance from edge on germination and first year survival of Engelmann spruce seedlings in openings. Manipulation of these factors can provide insight on how to improve regeneration success in small openings. We used this data to develop guidelines for management of Engelmann spruce stands using group selection with site preparation methods on the Uncompahgre Plateau.

Silviculturists have a suite of even and uneven-aged regeneration methods available to them with which to manipulate structure of stands. Even-aged methods include clearcut, seed tree, and shelterwood methods. These create a single cohort of regeneration in the stand. The clearcut method removes all of the trees, and therefore provides no microsite protection or seed source from residual trees other than along the edge of the opening. Historically this method has been used in western forests to regenerate shade intolerant species such as lodgepole pine (*Pinus contorta* Dougl. Ex. Loud) (Lotan and Critchfield 1990). The seed tree method retains seed trees that provide a seed source from residual trees in the opening, but little to no microsite protection. This method is utilized when an adequate seed source is not available after a clearcut. Shelterwood treatments provide both a seed source and microsite protection from residual trees. This method can be applied in a large variety of environments. By altering the number of residual trees providing shelter, retaining trees in a uniformed or grouped manner, and the varying timing of when they are removed, a shelterwood system can be used to accomplish a wide variety of goals (Smith, et al. 1997). Uneven-aged systems include group selection and single-tree selection. These create multiple age classes within stands. Single-tree selection creates gaps similar in size to an opening that would be left by removing a mature tree. This provides shelter and a seed source for each small opening. Single-tree selection is often used for shade-tolerant species (Nyland 2002).

Group selection creates an uneven-aged stand while retaining microsite changes (e.g. increased solar radiation) that overstory removal provides with even-aged methods. This technique creates gaps in the canopy by cutting multiple adjacent trees (Malcolm, et al. 2001). Group selection has been shown to increase structural diversity of a stand as well as enhance natural regeneration in mixed stands of Engelmann spruce and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) (Lafond, et al. 2014). Compared to clearcuts, group selection leads to a greater proportion of the opening being under the influence of edge trees (York, et al. 2004). Group selection openings provide higher light conditions than in untreated stands. In addition, due to the concentration of harvesting in one area, group selection reduces damage to residual trees during harvesting and increases operational efficiency as compared to individual tree selection (Roach 1974). Group selection has historically been used to regenerate Engelmann spruce stands because it has been found to provide adequate resource availability (Noble and Alexander 1977,Barrett 1995,Ronco 1972).

The goal of the spectrum of silvicultural methods is to change the regeneration environment, or microsites, in a way that increases germination success and seedling survival of target species. Microsites are important because the environmental factors at the scale of seedlings are critical for germination success and survival. Soil moisture is altered, and soil temperature and photosynthetically active radiation (PAR) are increased when canopy caps are created. These environmental factors depend on proximity to the edge of openings (York, et al. 2003). Light and resource availability for regeneration increases within the openings similar to clear cuts (Canham 1988). Environmental factors that are driven by the edge effect influence where species regenerate in an opening. There are a variety of microsites in openings that favor shade tolerant species close to the southern edge and shade intolerant species in locations that aren't shaded by trees at the southern edge (Chen, et al. 1992). A decrease in transpiration and interception of precipitation as compared to the surrounding undisturbed forest will increase the amount of soil moisture available (Ritter, et al. 2005). Solar radiation levels increase when the canopy is removed, most significantly on the north side of openings in the northern hemisphere, which increases PAR and soil temperatures (Canham 1988,de Chantal, et al. 2003). This leads to an increase in evaporation from the soil, decreasing the soil moisture. This can cause mortality in newly germinated seedlings (Noble and Alexander 1977). Another cause of increased evaporation is increased air flow due to lower resistance from trees (Bigelow and North 2012).

These factors that increase and decrease soil moisture in an opening lead to a high amount of variation within openings.

The influence of radiation and moisture availability on microsites changes in relation to the southern edge, creating patterns in natural regeneration within openings (York, et al. 2003,Diaci, et al. 2005,Gray and Spies 1998). Previous research has shown higher variation in tree growth on the southern side of group openings because solar radiation is intercepted by trees along the southern edge of openings in the northern hemisphere (York, et al. 2003). This solar interception along the southern edge increases variation in the southern half of openings significantly more than the northern half of openings. York, et al. (2003) also found there is no significant variation in tree growth from east to west in group openings. This is due to the fact that solar radiation is similar from east to west within openings, and leads to the conclusion that variation in microsites driven by solar radiation can be explained primarily by distance from the south edge of openings.

Engelmann spruce is well documented as a difficult species to regenerate (Schauer, et al. 1998,Smith 1955,Alexander and Shepperd 1984). Temperature and moisture levels during the germination and seedling life stages are the most influential factors for establishing regeneration (Noble and Alexander 1977). Newly germinated seedlings are likely to fail if the temperature falls outside the range of 0-25° C (Noble and Alexander 1977). Frost damage, dehydration, or heat girdling can kill seedlings outside of this range (Noble and Alexander 1977). Precipitation levels greater than one cm per week create favorable conditions for establishment, with adequate soil moisture (Alexander and Shepperd 1990). If these precipitation levels are reached and temperatures stay between 0-25° C, the associated soil moisture and soil temperature will be conducive to successful Engelmann spruce germination. Other causes of regeneration failure can include seed pathogens, frost heaving, and animal damage or consumption (Noble and Alexander 1977,Zhong and van der Kamp 1999).

Site preparation techniques such as scarification and slash retention can be used to create microsites with environmental conditions conducive to Engelmann spruce germination. Scarification is a mechanical disturbance of the soil surface used to enhance reforestation (Helms 1998). Water availability for seeds is substantially higher in mineral soil compared to the same depth in organic matter (Noble and Alexander 1977). Rocky Mountain spruce-fir forests humus depths are typically greater than 10 cm (Taylor, et al. 1991). Deep organic layers make site preparation necessary to reduce the depth to less than five cm and provide seeds with sufficient water availability. Mineral soil exposure is considered a necessity for successful Engelmann spruce germination (Alexander 1987). This can be accomplished with a mechanical harvest, as heavy equipment will provide adequate exposure of mineral soil in most cases (Alexander 1987). Pathogens that spread through organic matter have also been found to significantly decrease germination of Engelmann spruce (Zhong and van der Kamp 1999). The impact of these pathogens can be reduced by scarifying, which reduces the connectivity of organic matter and therefore reduces vectors for fungal pathogens.

While mineral soil exposure benefits germination success by increasing moisture availability for the seeds and reducing the risk of pathogens, it also increases the temperature and the water loss rate of the soil (Nyland 2002). Shading of the seedbed combats this temperature increase and moisture loss, and further increases regeneration success (Noble and Alexander 1977). This can be accomplished by retaining coarse woody debris when performing management activities. Coarse woody debris shades the seedbed, reducing radiation levels and the accompanying rise in temperature and moisture loss (Gray and Spies 1998,Alexander 1974).

Planting seedlings is an option when site preparation alone is not sufficient to overcome difficulties associated with naturally regenerating Engelmann spruce. Artificial regeneration has many advantages compared to natural regeneration. Planting allows silviculturists to control species, spacing, stocking, and timing of regeneration of a stand after disturbance. Seedlings have a much greater chance of survival if they have well developed roots before being subjected to outplanting (Alexander 1987). Planting can accelerate the establishment of an overstory while controlling cover type (Lajzerowicz, et al. 2006). Planting can also be used to establish regeneration in large openings where a seed source is not readily available due to the distance from residual trees. However, artificial regeneration is expensive, not always successful, and proper site preparation methods are crucial for artificial regeneration to succeed (Roe, et al. 1970,Parish and Antos 2005).

Regeneration failures in recent projects utilizing the group selection method have shown that more research is needed to successfully use this method to regenerate Engelmann spruce on the Uncompahgre Plateau (T. Gardiner, personal communication, December 4, 2014). Previous research identified conditions that improve Engelmann spruce regeneration success in the central Colorado Rocky Mountains (Noble and Alexander (1977). This work attempts to translate findings from Noble and Alexander (1977) to the Uncompahgre Plateau. Starting with the knowledge that scarification and shading are extremely beneficial, the next step is to identify opening sizes and slash retention levels that produce the highest success in regenerating Engelmann spruce.

We developed a project on the Uncompahgre Plateau to address these issues. We established a set of randomized and replicated plots in openings on the Uncompahgre Plateau to quantify the effect of distance from edge and coarse woody debris loading on germination rates and first year seedling survival of Engelmann spruce. Specifically, we strove to test these hypotheses:

1.) Engelmann spruce germination will increase with increasing coarse woody debris retention.
2.) Engelmann spruce germination will decrease with increasing distance from the southern edge of openings.
3.) Planted Engelmann spruce mortality will decrease with increasing coarse woody debris retention.
4.) Planted Engelmann spruce mortality will increase with increasing distance from the southern edge.
5.) Maximum daily temperature will not exceed 25°C where dead shade from coarse woody debris is present.

1.2 Methods

We answered our questions by sowing Engelmann spruce seeds and planting seedlings within a randomized, replicated set of site preparation treatments at varying distances from the edge of established openings. These openings are part of a 2013 patch clearcut treatment. Three similar openings were chosen for study. The study area is located on the Uncompahgre Plateau in western Colorado (**Error! Reference source not found.** & 2). It is at an elevation of 2800 m eters, with little to no slope (<10%). All three openings are within 500 meters of one another. The overstory is comprised of quaking aspen (*Populous tremuloides* Michx.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), subalpine fir (*Abies lasiocarpa* var. *lasiocarpa*), and Engelmann spruce. Average annual precipitation (1981-2010) is around 84 cm and mean temperature (1981-2010) is 4.4 °C.

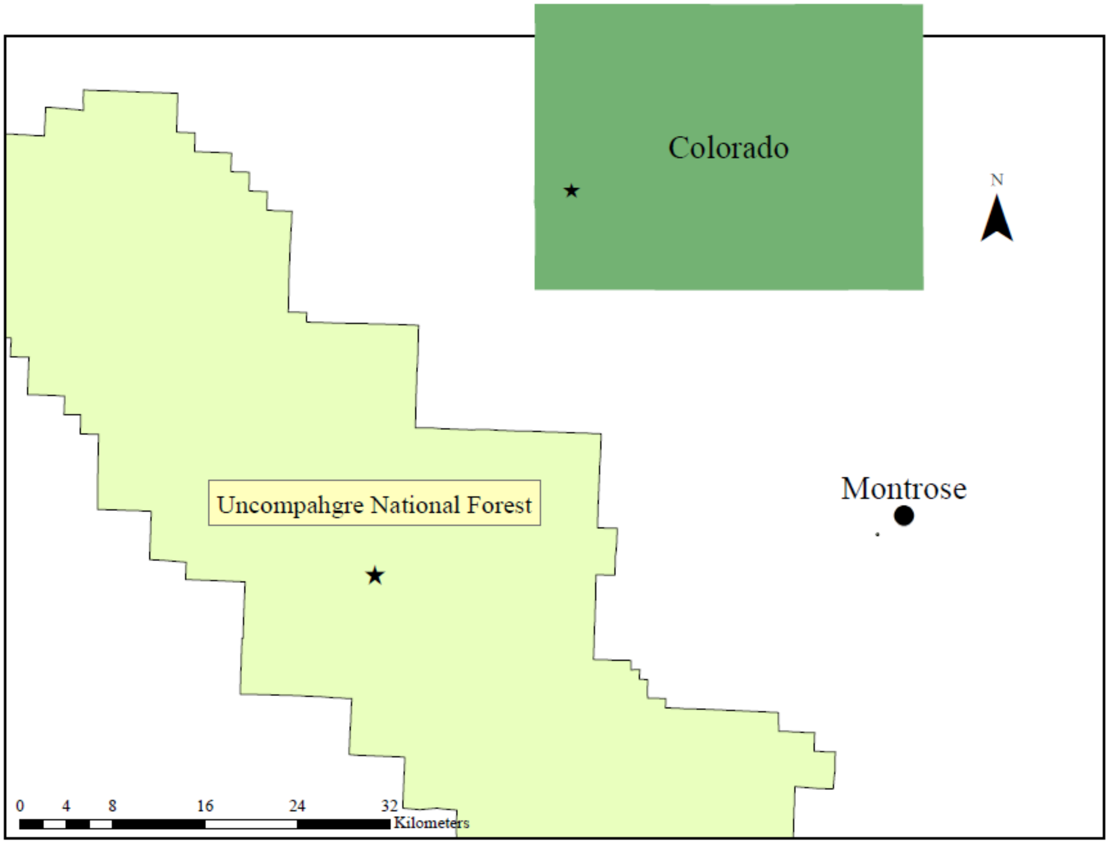

Figure 1: Map showing the location of the study sites on the Uncompahgre Plateau. The closest town is Montrose to the east. The study location is denoted with a star.

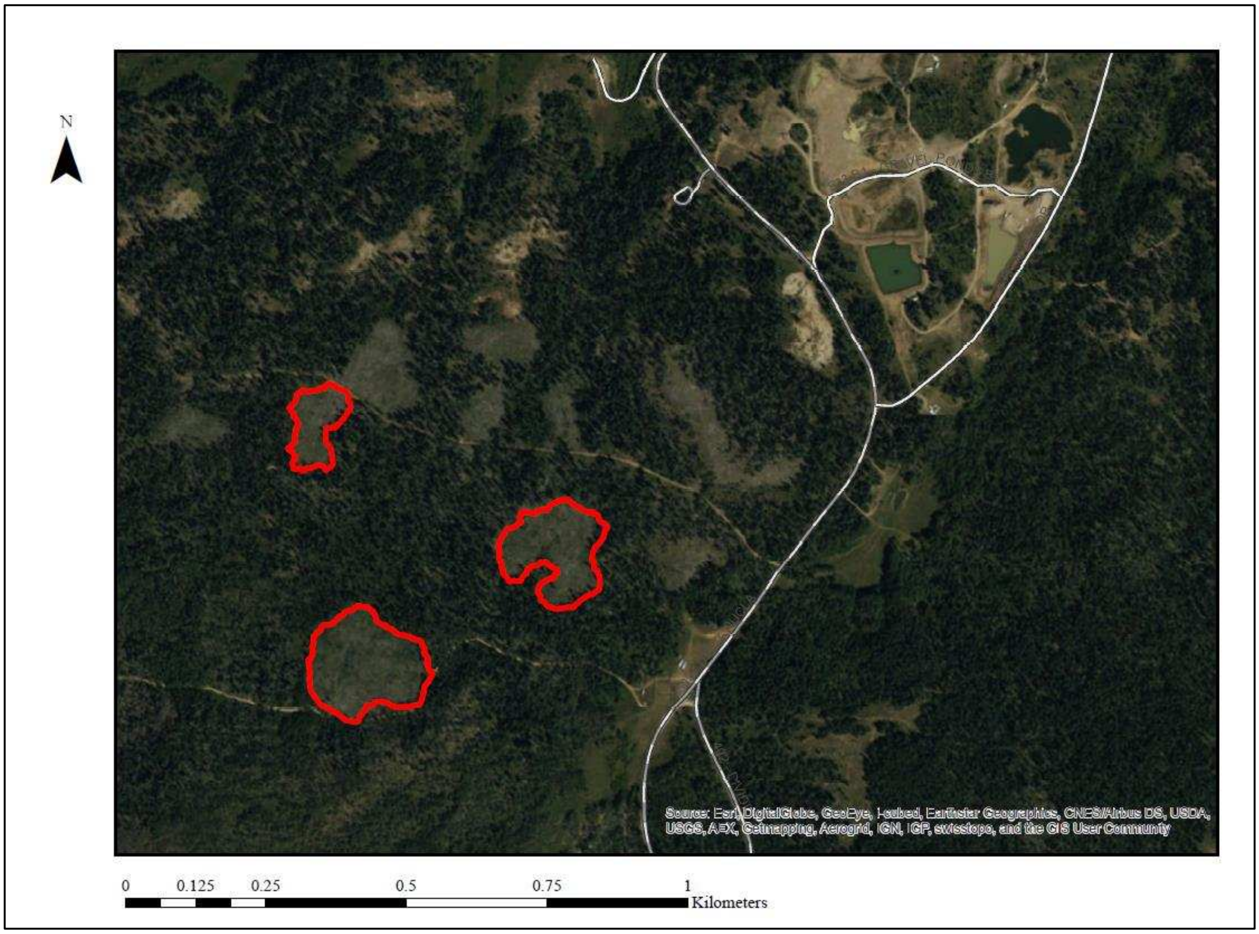

Figure 2: Image showing the location of the openings selected. They are just west of Delta-Nucla road, and south-west of the Columbine Campground.

Previous research has shown that coarse woody debris provides shade that increases germination rates of Engelmann spruce as well as other species such as Douglas-fir and Pacific Silver Fir (*Amies amablis)* (Gray and Spies 1998,Alexander and Shepperd 1990). Scarification exposes mineral soil, which also increases spruce germination success (Noble and Alexander 1977). All manipulative treatments in our experiment therefore included scarification by removing any coarse woody debris, litter and fine woody debris on the plot. This was to replicate the mineral soil exposure that would occur with harvesting.

The four treatments we evaluated were: no site preparation, scarification only with no coarse woody debris, scarification with low coarse woody debris loading, and scarification with high coarse woody debris loading. We scarified by removing all the loose coarse and fine woody debris and organic matter in the plot with hand tools. The no site preparation treatment did not alter the site, we left the treatment established by the United States Forest Service when the openings were created. This was a lop and scatter treatment that resulted in 31 metric tons ha^{-1} (14 tons ac^{-1}) of coarse woody debris, confirmed with a photo fuel load guide estimate (Ottmar, et al. 2000). The scarification only treatment received no additional treatment beyond scarification. The scarification with low coarse woody debris treatment consisted of 27 metric tons ha^{-1} (12 tons ac^{-1}) of coarse woody debris spread evenly across the plot. The scarification with high coarse woody debris treatment consisted of 36 metric tons ha^{-1} (16 tons ac^{-1}) of coarse woody debris spread evenly across the plot.

Each set of treatments was arranged in plots within openings along north-south oriented transects (Figure 3). Transects were placed 30 meters west and 30 meters east of the midpoint of each of the first two openings. One opening only had one transect because the opening was not wide enough for two transects. In this opening the transect was placed in the center. East-west centers were identified within the three openings using GIS polygons provided by the Uncompahgre National Forest.

The plots consist of a randomized complete block design with four 5 meter by 5 meter treatment blocks and a 5 meter by 5 meter control block placed side by side (Figure 4). Each of the blocks was split into two 2.5 meter by 5 meter sub-treatments. Sub-treatment blocks were randomly selected for either sowing seeds or planting seedlings (Figure 4). We sowed the equivalent of 135,000 seeds ha^{-1} to simulate a normal mast year (Noble and Alexander 1977). This equates to 6 grams, or approximately 170 seeds, per sub-treatment. Eight seedlings were planted in each sub-treatment at 1 meter spacing. One 2.5 by 5 meter sub-treatment in the control block was scarified and the other was untouched. We used these to control for natural regeneration on the site with and without scarification.

There is a minimum 1 meter buffer between blocks to mitigate effects of treatments on one another. If more than 20% of a block was unsuitable for seed germination (stumps/exposed rock), it was moved 3 meters east or west, shifting the plot away from the transect.

We sampled coarse woody debris in the openings using randomly located plots to determine the average distribution of piece sizes across three size classes: 5-10 cm, 10-15 cm, and 15-20 cm in diameter. This distribution was then used to distribute the two experimental levels of coarse woody debris loading among size classes. We used the specific gravity of spruce (0.34 g cm^{-3} [Hoadley 1990]) to convert fuel loadings into linear distances for each of the three size classes. Coarse woody debris smaller than 5 cm in diameter was not included in the manipulative plots. Coarse woody debris pieces were randomly oriented for the first low and high fuel loading treatments and then orientations were duplicated on all further plots.

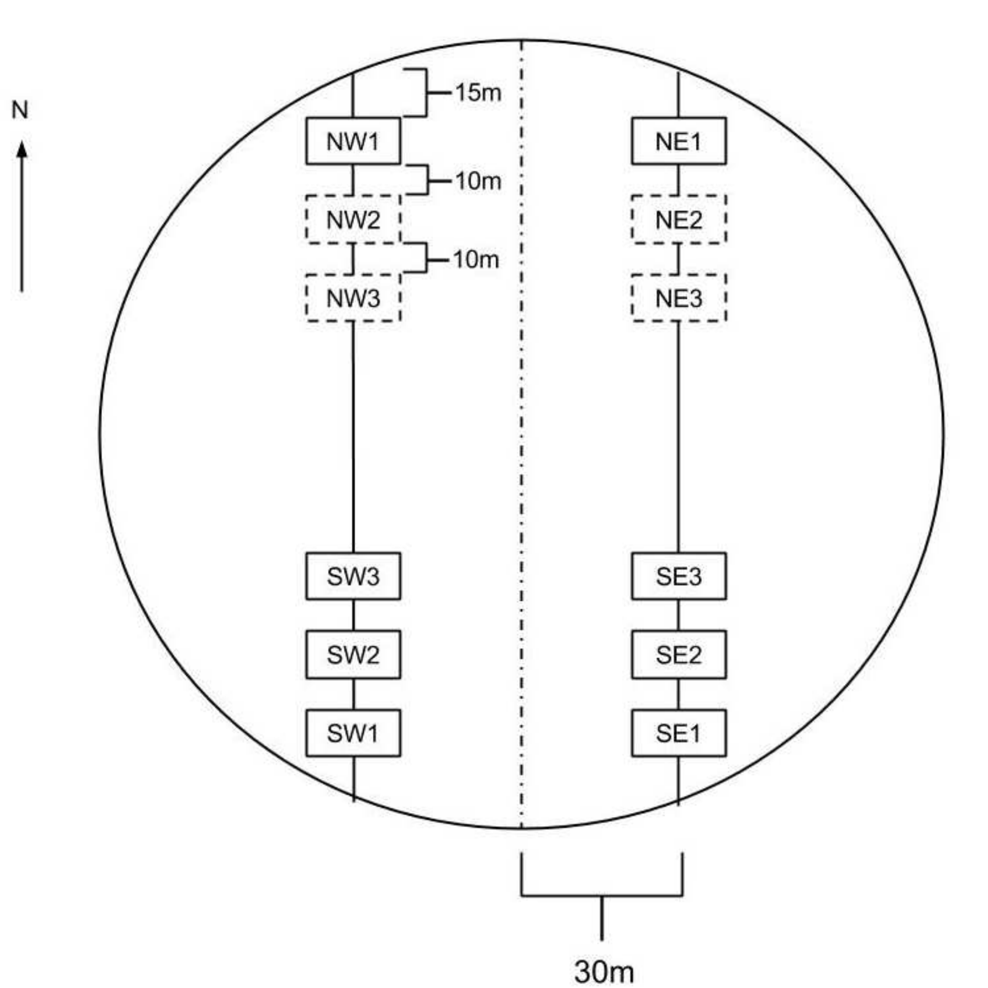

Figure 3: Diagram showing arrangement of plots along transects within openings. On each transect one of the two dotted plots was randomly chosen to increase sampling efficiency.

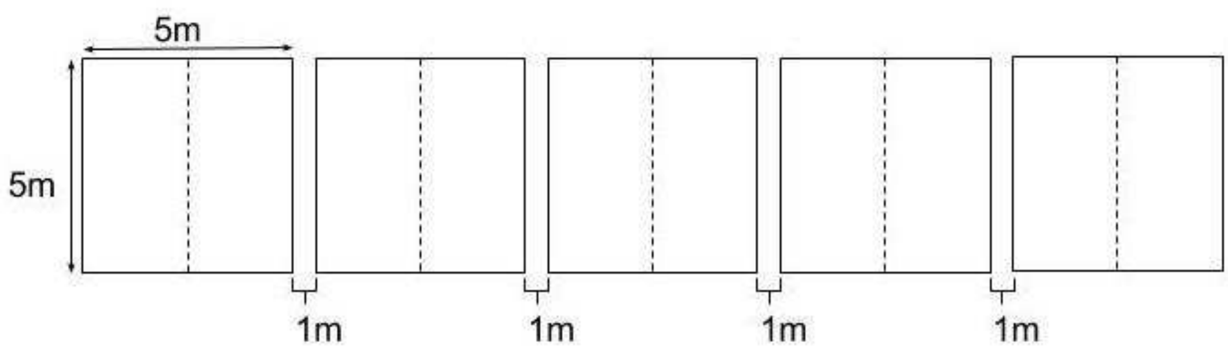

Figure 4: Arrangement of treatment blocks within plots. The four treatments and the control blocks were randomly assigned. Each sub-treatment was randomly selected for seeding or planting (manipulative treatments), or scarification (control).

We established five plots per transect. Three plots were located 15, 30, and 40 m (49, 98, and 131 ft) from the drip line on the southern edge of the opening. These distances correspond to the center of circular openings that are 0.07, 0.25, and 0.5 ha (0.17, 0.6, and 1.2 ac) in size. Given that the average height of surrounding trees was ~15 meters, these distances were 0.5, 1.0, and 1.5 tree lengths from the edge. Each treatment blocks distance to the drip line was measured individually to account for the variation in the edge of the opening from east to west. The individual distances were used for analysis. We also located one plot 15 m from the north drip line and another randomly at either 30 m or 40 m from the north drip line. Placing two plots instead of three on the north side of the opening increased sampling efficiency (Avery and Burkhart 2015).

We recorded temperature to quantify the effect of shading from edge trees and coarse woody debris on microsite temperatures. Temperature was recorded hourly throughout the summer using iButton temperature sensors (iButtonLink Whitewater, WI). One transect was randomly selected for measurement. On the north side of this transect, three plots were installed instead of two to account for all levels of distance sampled. A total of 24 sensors were installed. A sensor was placed on each of the six plots in four scenarios: on the north side of the largest log in the low coarse woody debris treatment (Shaded), 50 cm above the ground in the unseeded no treatment plot (Ambient Air), in the center of the unseeded scarified treatment (Scarified), and in the center of the no treatment plot (No Treatment). They were sheltered with PVC to prevent direct solar radiation (M. Smith, personal communication, April 28th, 2015). A nearby rain gauge at the US Department of Agriculture Natural Resources Conservation Service Snow Telemetry (SNOTEL) site, Columbine Pass, was used to obtain daily precipitation data (NRCS 2015).

Plots were established in late May and early June, 2015. We counted the number of germinate seedlings six times in each sub-plot about every two weeks throughout the growing season. Five times from July 1st through August 17th, and a sixth time on October 10th and 11th. This was to determine germination rates and survival over the first growing season. All of the counts were very similar, and analysis using change over the growing season did not alter results, so the average of the six counts were used for analysis. The height of each planted seedling was recorded at the onset of the study and re-measured at the end of the first growing season in mid-October. We also noted any mortality among planted seedlings at this time.

An analysis of variance (ANOVA) test was used to test the effect of treatment type on average germination per plot over the first growing season. Residual analysis showed that a square root transformation was required based on the Q-Q plot and the plot of residuals versus predicted mean. We estimated least squares means based on linear models for each pairwise comparison done during analysis. We performed a Tukey's honest significant difference test to correct for multiple comparison when performing pairwise comparisons. An analysis of covariance (ANCOVA) was used to analyze the effect of treatment type and distance from edge on germination per plot averaged across the first growing season. We used an ANCOVA since there is both a categorical and continuous predictor in the model. A square root transformation was used to manipulate the residuals in the germinate data to meet the assumptions of an ANOVA, correcting for the large number of zeros in the data (P. Turk, personal communication, August 26th, 2015). The interaction between distance from edge and treatment type was included in the analysis of both the north and south. An ANOVA was run to determine the influence of treatment type on maximum daily temperature. A least squares mean analysis was used to estimate means and to investigate pairwise differences between treatment types.

We also tested the effect of distance from edge and treatment type on planted seedling growth and survival. The first ANOVA model tested the influence of treatment type on the seedlings growth from planting until mid-October. Another model tested the influence of treatment type on mortality of seedlings. Seedlings that experienced mortality were eliminated from this model that evaluated the effect on growth. Then the plots were broken into north and south to include our distance from edge variable. Two ANCOVA's were run for both of these categories. These determined the significance of treatment type, distance from the edge, and the interaction between the two predictors first on mortality, then on change in height.

1.3 Results

1.3.1 Treatment Effects

An ANOVA showed that the average number of germinate seedlings significantly differed by treatment type ($p < 0.0001$, $\alpha = 0.05$ for all analysis [Table 1]). Pairwise differences between the treatments with germination were all significant save for between the high coarse woody debris and low coarse woody debris treatments, and the no coarse woody debris and unseeded treatments (Table 2). Summary statistics for the average number of germinates per plot and per hectare can be seen in Table 3, and are visually represented in Figure 5.

Table 1: ANOVA model results of average germination. The first model is for overall treatment type effect. The second and third show the effect of treatment, distance from edge, and the interaction between distance and treatment for plots on the south and north of openings. Significant differences are highlighted in bold.

Source	*df*	MSE	*F-value*	$p \geq F$
Overall				
Treatment	5	48.55	**53.30**	**<.0001**
South				
Treatment	5	8.60	**10.74**	**<.0001**
Distance (m)	1	5.15	**6.43**	**0.0134**
Distance x Treatment	5	0.73	0.92	0.4751
North				
Treatment	5	4.37	**3.73**	**0.0062**
Distance (m)	1	0.20	0.17	0.6828
Distance x Treatment	5	0.60	0.51	0.7664

Table 2: Pairwise comparisons between the least squares means estimates for germination by treatment. CWD is an abbreviation for coarse woody debris. Significant differences are highlighted in bold.

Treatment 1	Treatment 2	*t-value*	*Tukey's* $p \geq t$
High CWD Seeded	Low CWD Seeded	2.01	0.3396
High CWD Seeded	No Treatment Seeded	**5.52**	**<0.0001**
High CWD Seeded	Scarified Seeded	**9.57**	**<0.0001**
High CWD Seeded	Scarified Not Seeded	**12.03**	**<0.0001**
High CWD Seeded	No Treatment Not Seeded	**12.03**	**<0.0001**
Low CWD Seeded	No Treatment Seeded	**3.50**	**0.0081**
Low CWD Seeded	Scarified Seeded	**7.56**	**<0.0001**
Low CWD Seeded	Scarified Not Seeded	**10.02**	**<0.0001**
Low CWD Seeded	No Treatment Not Seeded	**10.02**	**<0.0001**
USFS Seeded	Scarified Seeded	**4.06**	**<0.0001**
USFS Seeded	Scarified Not Seeded	**6.52**	**<0.0001**
USFS Seeded	No Treatment Not Seeded	**6.52**	**<0.0001**
Scarified Seeded	Scarified Not Seeded	2.46	0.1435
Scarified Seeded	No Treatment Not Seeded	2.46	0.1435
Scarified Not Seeded	No Treatment Not Seeded	0.00	1

Table 3: Summary statistics for treatment types. Mean number of germinates per hectare, mean number of germinates per plot, standard deviation, and 95% confidence intervals are presented.

Treatment	Mean per Hectare	Mean	*S.D.*	*Lower 95% CI*	*Upper 95% CI*
High CWD	13992	17.49	12.05	12.40	22.57
Low CWD	10104	12.63	7.70	9.38	15.88
No CWD	1392	1.74	1.77	0.99	2.48
No Treatment	6216	7.77	10.35	3.40	12.14

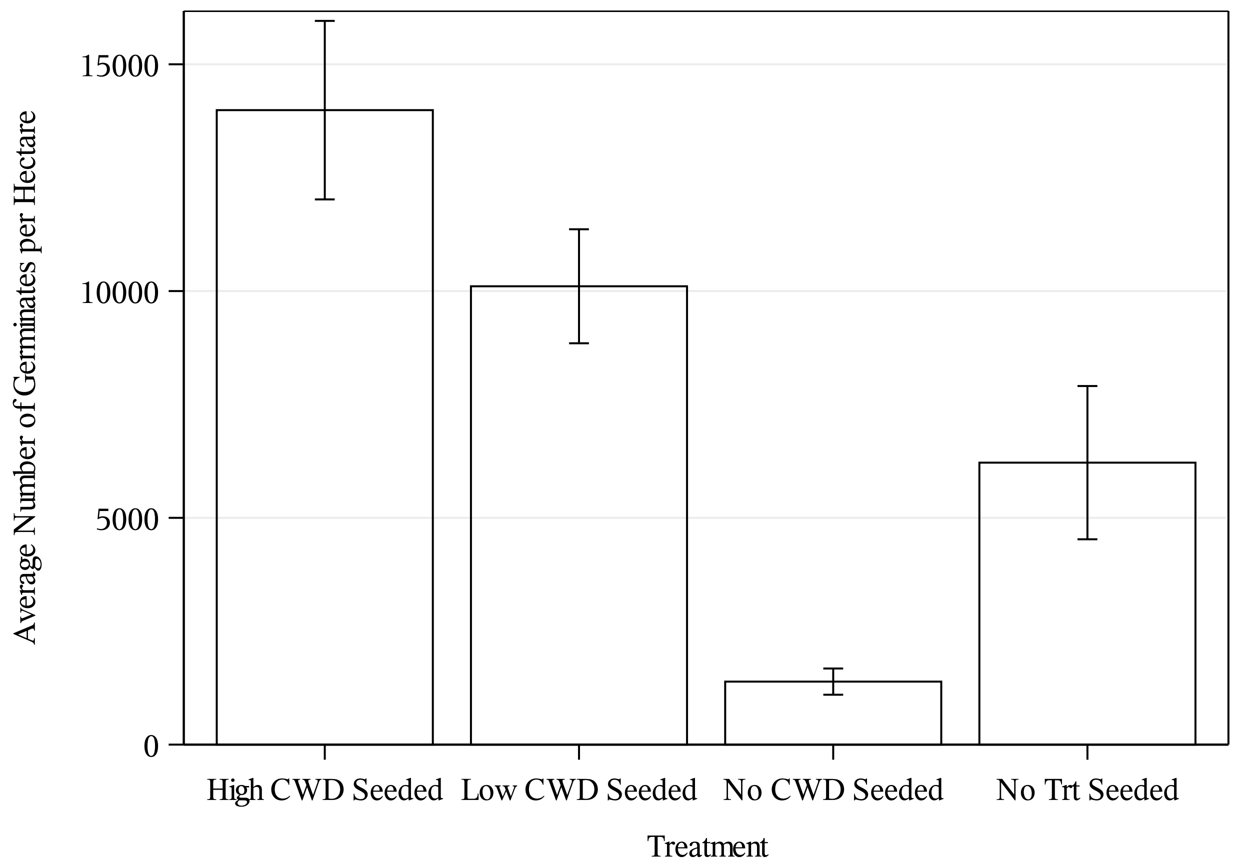

Figure 5: Average germination levels across the growing season by treatment. Unseeded plots were left out because they had no germination. Error bars represent standard error.

1.3.2 Distance from Edge

Distance from the south edge ($p = 0.0134$) and treatment ($p < 0.0001$) were significant predictors of germination (Table 1). There was no interaction between these variables in the model. Germination decreased as distance from the edge increased (Figure 6a). This model can be represented with the same slope since there is no interaction (Table 4).

Table 4: Slopes and intercepts for germination by treatment on the south side of openings. The slope is number of germinates per hectare per meter, from south to north. The intercept is number of germinates.

Treatment	Slope	Intercept
Overall	-215	
High CWD		12121
Low CWD		9279
No CWD		1442
No Treatment		4483

Treatment was a significant predictor of germination on the north ($p = 0.0062$), but distance from the north edge was not ($p = 0.6828$ [Figure 6b]). As with the south, there was no interaction in the model ($p = 0.7664$ [Table 1]).

To determine the maximum distance at which shade from trees at the southern edge of openings increased germination rate and seedling survival, we averaged values from plots on the north side of openings by treatment, and then determined the distance from the southern edge associated with equivalent values. These values were: 14,650 germinates ha^{-1} for High CWD, 10,2400 germinates ha^{-1} for Low CWD, 1,360 germinates ha^{-1} for Scarified, and 6,640 germinates ha^{-1} for No Treatment. This was calculated to be, on average, 23 m. Given the average height of trees in the surrounding forest was ~15 m, this equates to 1.5 tree lengths.

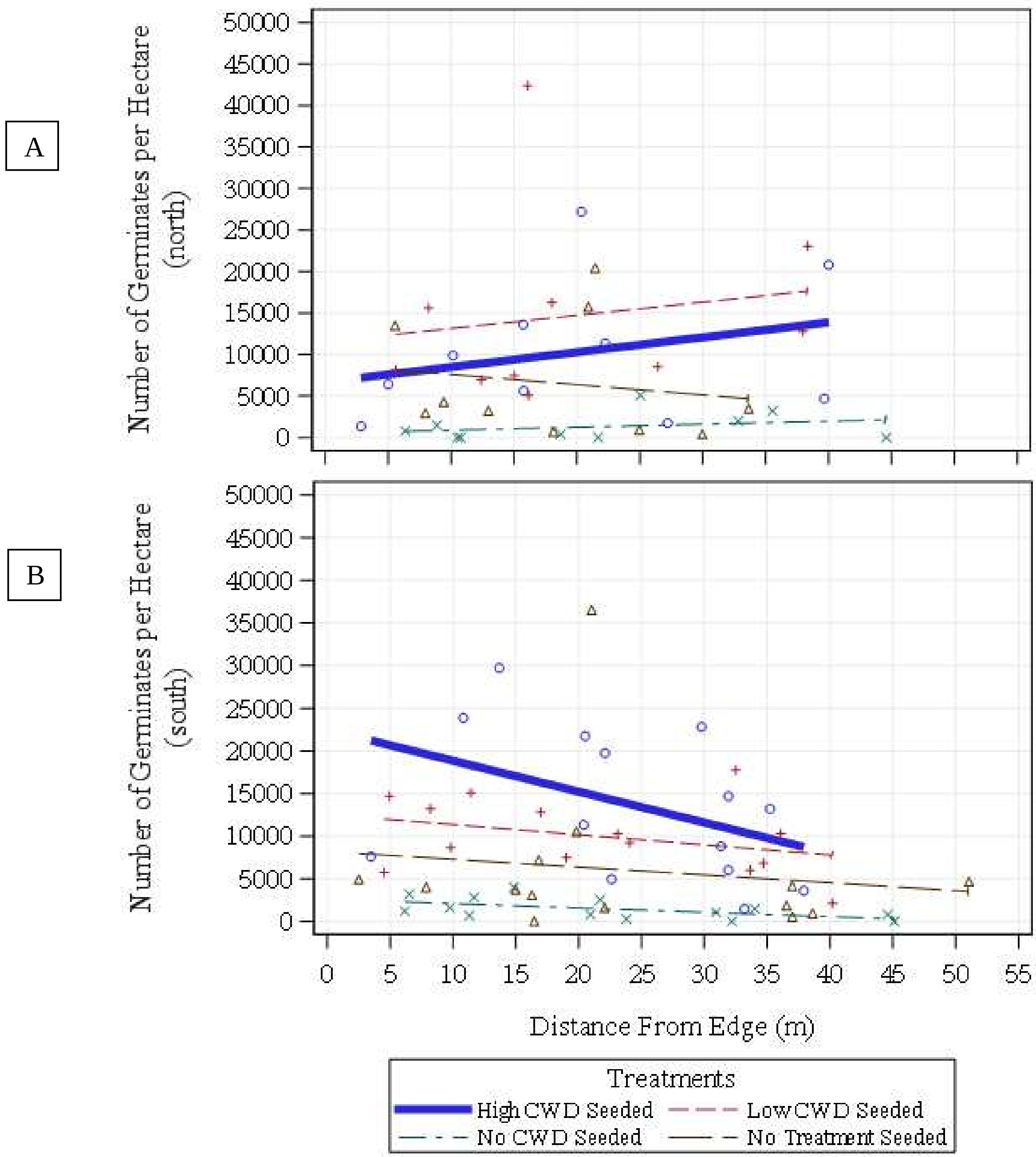

Figure 6: Number of germinates plotted over distance from edge. The north side (a) showed no correlation between germination and distance (p = 0.6828). The south side (b) showed a significant decrease in germination as distance increased (p = 0.0134). It is important to note that the distance is from each respective edge.

1.3.3 Environmental Factors

Maximum daily temperature was compared for the four different data logger placements. Shade provided a significantly lower daily maximum temperature as compared to the other three placements (Figure 7). The shaded placement reflected the effect of coarse woody debris. We used a least squares means analysis to estimate means for the maximum daily temperatures in the four scenarios. The mean maximum daily temperature for the shaded scenarios was 19.9°C. The means for the other placements were greater than 25°C (Table 5). Pairwise differences between each scenario were all significant (Table 6).

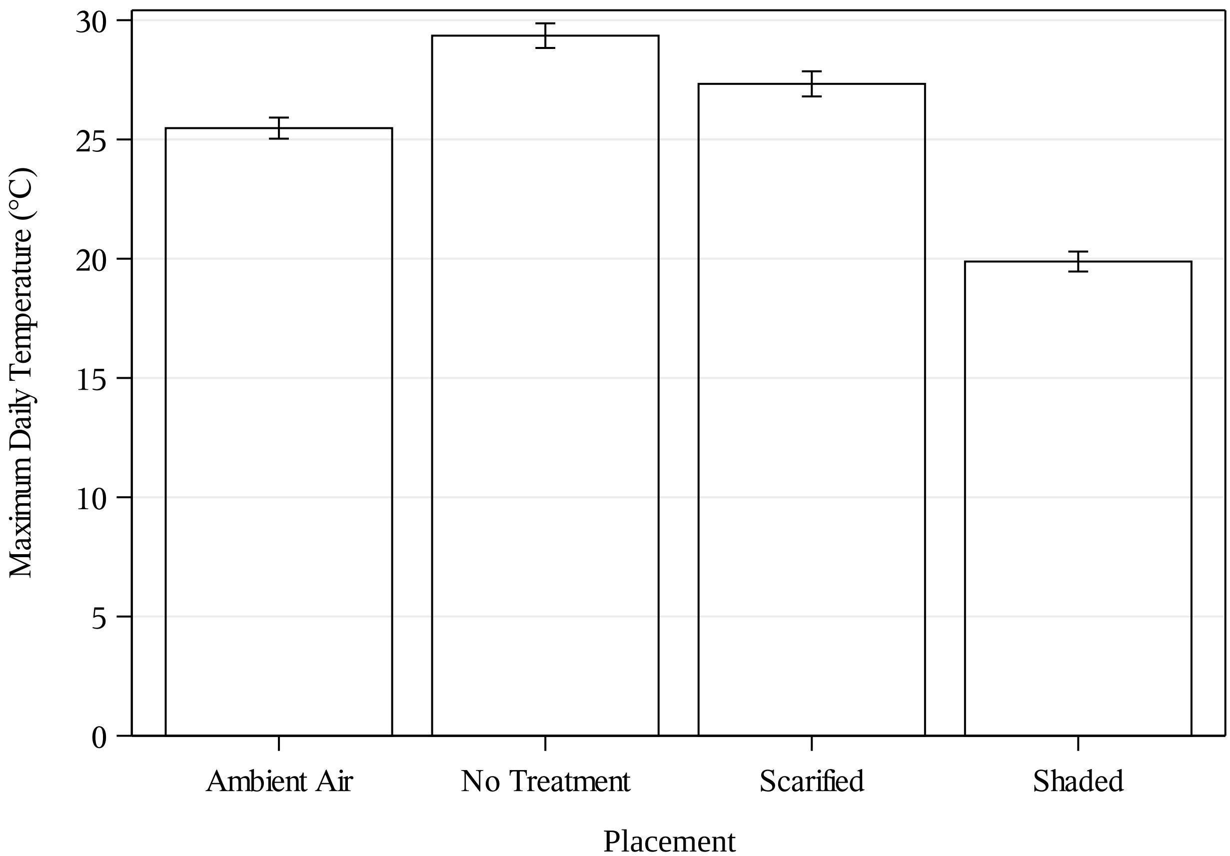

Figure 7: Average maximum daily temperature values for each temperature sensor placements. All treatments are significantly different each other. Error bars represent standard error.

Table 5: Summary statistics of daily maximum temperature for the four scenarios temperature loggers were placed in.

Scenario	Mean (°C)	*t-value*	$p \geq t$
Ambient Air	25.5	53.27	<0.0001
No Treatment	29.4	61.37	<0.0001
Scarified	27.3	57.15	<0.0001
Shaded	19.9	41.57	<0.0001

Table 6: Pairwise comparisons between the least squares means estimates for maximum daily temperature by scenario. Significant differences are highlighted in bold.

Scenario 1	Scenario 2	*t-value*	*Tukey's* $p \geq t$
Control	No Treatment	**-5.73**	**<.0001**
Control	Scarified	**-2.74**	**0.03**
Control	Shaded	**8.27**	**<.0001**
No Treatment	Scarified	**2.99**	**0.02**
No Treatment	Shaded	**14.00**	**<.0001**
Scarified	Shaded	**11.01**	**<.0001**

NRCS SNOTEL data was used to account for local precipitation during the study period. Over the course of the water year (October 1st 2014 - September 30th 2015) there was a total of 647.7mm of precipitation (USGS 2016). Weekly precipitation totals throughout the water year are presented with a 1 cm reference line in Figure 8.

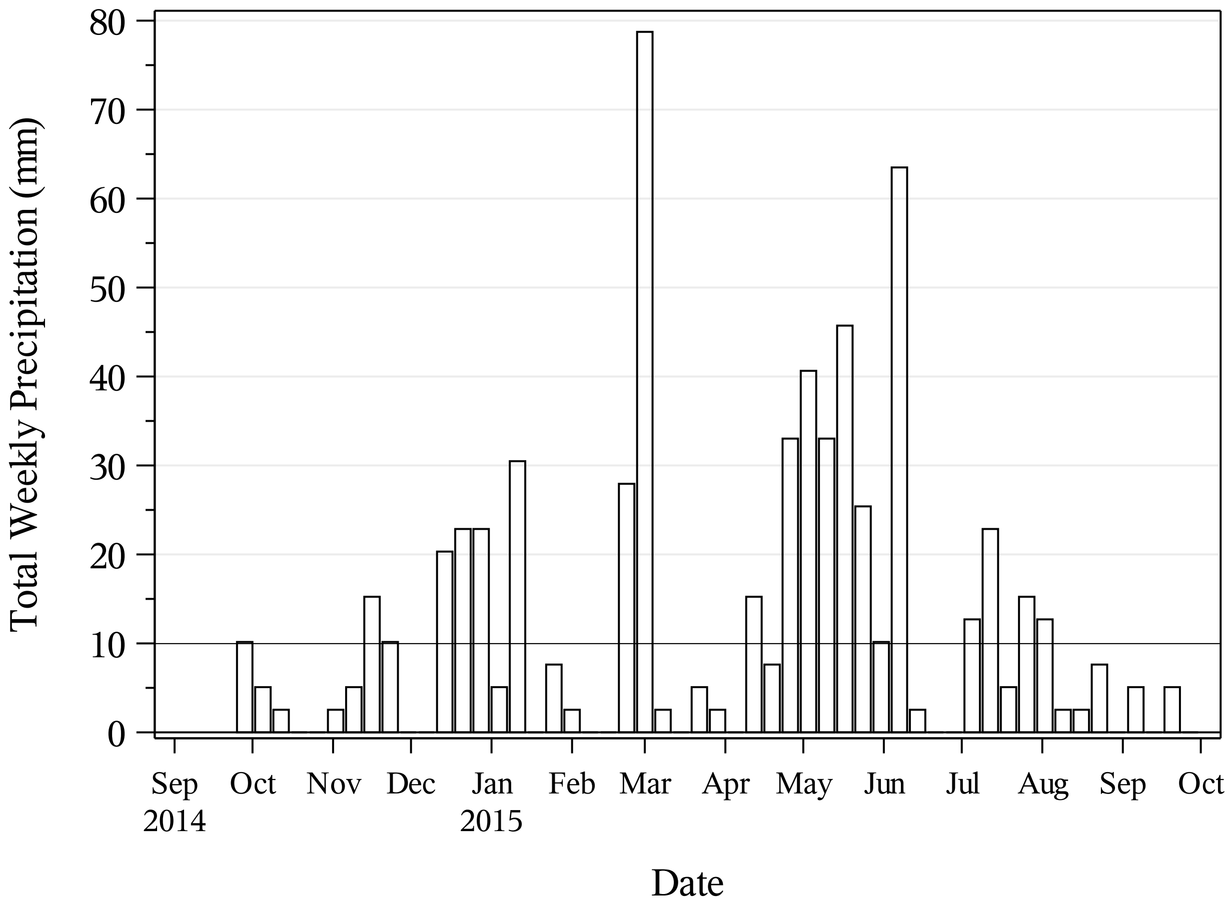

Figure 8: A time series showing total precipitation accumulation per week (mm) over the course of a water year. The solid line represents 1 cm of precipitation per week, which has been identified as a critical threshold for successful Engelmann spruce germination.

1.3.4 Planted Seedlings

We looked at both the change in height as well as mortality of seedlings over the course of the first summer. The first ANOVA model tested the effect of treatment type on the change in height of the planted seedlings. This was not significant ($p = 0.5675$). Next we looked instead at the effect of treatment type on the mortality of seedlings, which was significant ($p = 0.0162$). Looking at the north and south of openings sperately, we developed ANCOVA models for the effect of treatment type and distance from edge on both the change in height and mortality of planted seedlings. Distance from the north edge was not significant. Distance from the south edge had a significant effect on mortality (p = 0.0238 [Table 7]). Survival percentages ranged from 84-93% (Table 8).

Table 7: Results from ANOVA models for planted seedlings. Significant differences are highlighted in bold.

Source	Predictor	Response	*df*	*F-value*	$p \geq F$
Overall					
	Treatment	**Mortality**	**3**	**3.45**	**0.0162**
	Treatment	Height Change	3	0.68	0.5675
South					
	Treatment	Mortality	3	0.93	0.4266
	Distance (m)	**Mortality**	**1**	**5.14**	**0.0238**
	Distance x Treatment	Mortality	3	1.16	0.3257
	Treatment	Height Change	3	0.06	0.9809
	Distance (m)	Height Change	1	1.61	0.2046
	Distance x Treatment	Height Change	3	0.19	0.9054
North					
	Treatment	Mortality	3	2.33	0.0744
	Distance (m)	Mortality	1	2.64	0.1055
	Distance x Treatment	Mortality	3	0.35	0.7923
	Treatment	Height Change	3	0.80	0.4933
	Distance (m)	Height Change	1	0.11	0.1133
	Distance x Treatment	Height Change	3	0.85	0.4683

Table 8: Percent survival and standard deviation of planted seedlings by treatment type.

Treatment	1st Year Survival (%)	Standard Deviation
High CWD	89.5	30.70
Low CWD	93.0	25.60
No CWD	84.0	36.80
No Treatment	84.5	36.30

1.4 Discussion

Previous work has shown that Engelmann spruce is extremely difficult to regenerate (Alexander and Shepperd 1984). Our research provides detailed insights that can be used to help increase germination success using the group selection method. Required regeneration conditions for Engelmann spruce in the central Rocky Mountains have been researched for seed crop, ambient air temperature, precipitation, seedbed, and soil type requirements (Noble and Alexander 1977,Alexander 1987). The factors controlling conifer regeneration in openings has been a focus of research in the Pacific Northwest (Gray and Spies 1996), Sierran forests of California (York, et al. 2004), northwestern British Columbia (Coates 2000), and northern California (McDonald and Abbott 1994). Our work identifies how germination and seedling survival can be improved by manipulating slash retention and opening size using the group selection method on the Uncompahgre Plateau. This study showed that residual coarse woody debris substantially increased germination and seedling survival even in microsites shaded by trees at the edge of openings, and that beneficial sheltering effects of the southern edge of openings are limited to 1.5 tree lengths.

1.4.1 Treatment Effects

Our first research objective was to quantify the effect of different site preparation techniques on Engelmann spruce germination: coarse woody debris retention, and site preparation by scarification. The combination of scarification and both high and low coarse woody debris resulted in the greatest amount of germination out of any of our treatments. These treatments likely provided a higher percentage of microsites that are known to be beneficial for Engelmann spruce germination (Noble and Alexander 1977,Alexander and Shepperd 1984). While this result was not in itself startling, the large differences between the number of germinate seedlings in each of the treatments was. This work established a relationship between coarse woody debris loading and seedling establishment or survival of planted seedlings.

The number of germinate seedlings on the no treatment type was not intermediate between the high and low coarse woody debris treatments as one would expect based on the coarse woody debris amounts (Figure 5). Based on observations in the field and conversations with silvicultural staff on the Uncompahgre National Forest, we hypothesized that smaller numbers of germinate seedlings in the no treatment type were due to an excess of fine branches. Our experimental treatments consisted of only coarse woody debris larger than 5 cm, whereas fine woody debris present on the no treatment in places consisted of deep (> 10 cm) mats of fine branches. Microsites under these mats had little to no sunlight even if seeds were able to reach the soil. Another factor that could have influenced germination in this treatment type was the lack of recent scarification. While there was mineral soil exposure from machinery when the openings were created, organic matter has built up in the years since.

The shade provided by coarse woody debris provided a distinct advantage as compared to shade from live vegetation in this study. Scarification removed all of the coarse woody debris but did not suppress growth of grasses and forbs. Coarse woody debris is more effective in reducing maximum daily temperatures at the microsite due to the constant reduction in solar radiation (Helgerson 1989). This led to increased germination on plots with coarse woody debris (Figure 4). Live vegetation also competes for resources, reducing available moisture for newly germinated seedlings (Helgerson 1989).

There was no significant interaction between treatment type and distance from edge (Table 1). This leads to the interesting conclusion that coarse woody debris is beneficial for germination at all locations within an opening. So even at the highest levels of experimental shade, with the high coarse woody debris treatment along the southern edge, high temperatures and / or drying may still have been limiting factors for germination and seedling survival. This is similar to previous research that has found that the increase in temperature associated with direct solar radiation is the major limiting factor to Engelmann spruce germination (Ronco 1970).

1.4.2 Distance from Edge

Our second research objective was to determine the effect of shading from edge trees on Engelmann spruce germination. McDonald and Abbott (1994) found no change in ponderosa pine germination across openings of different size, but did find that growth rates correlated with opening size. Gray and Spies (1996) found that opening size influenced the quantity of regeneration, and that successful establishment was more common in the southern shaded portion of openings. York, et al. (2003) performed a highly controlled seedling growth experiment that demonstrated much greater growth rates in the northern portion of openings for six different species in a Sierran mixed conifer forest. What all of these studies have in common is that they documented variation in germination and / or growth along north-south gradients in openings. This heterogeneity shows that out study is necessary to fully understand how Engelmann spruce is impacted by opening size when using the group selection method.

In our study, the number of Engelmann spruce germinate seedlings was negatively correlated ($p = 0.0134$) with distance from the southern edge (Figure 6a). Germinate totals per hectare decreased by 214 for every additional meter from the south (Table 4). Presumably germinate seedling numbers were greater near the southern edge because they received more shade from edge trees. This effect disappeared by ~1.5 tree lengths, or ~23 m from the southern edge. This suggests the north-south dimension of openings should not exceed 1.5 tree lengths on the Uncompahgre Plateau if shade from edge trees is intended to increase germination and successful reestablishment of spruce. Small openings also have the advantage of receiving abundant natural seed fall from edge trees. Fifty percent of spruce seed that falls in openings lands within 30 meters of the edge (Alexander and Edminster 1983). The combination of seed-rain and shading in openings of this size will increase the potential for successful Engelmann spruce germination.

1.4.3 Environmental Factors

We investigated temperature conditions to better understand the mechanisms behind these treatment effects on germination. Previous work has shown that Engelmann spruce is extremely sensitive to temperature and moisture extremes (Alexander and Shepperd 1990). By placing iButton temperature logging sensors (iButtonLink Whitewater, WI) in varying microsites in our treatments we were able to empirically show the effect of coarse woody debris on temperature. Engelmann spruce seedlings succumb to drought and heat girdling at or above 25°C (Noble and Alexander 1977). Germination failures on un-shaded microsites can be attributed to this threshold being exceeded regularly throughout the growing season (Figure 7). Shaded microsites were significantly cooler, with maximum daily temperatures staying below this threshold throughout the growing season (Table 3). This helps explain the benefit of coarse woody debris. Higher fuel loading treatments in our project created more shaded microsites, leading to a higher success rate of germination. Our results coincide with others that Engelmann spruce germination is more successful with shade (Alexander and Shepperd 1984,Ronco 1970).

A local SNOTEL site was adjacent to the openings (NRCS). This provided detailed local precipitation data. Among the last 30 years, the 2015 growing season ranked as the 3rd driest. Precipitation totals and timing are most important during the first 6 weeks after germination (Noble and Alexander 1977). Amounts over 1 cm per week are favorable for successful establishment (Noble and Alexander 1977). Weekly precipitation was well above this threshold through May and into June, when germination was occurring (Figure 8). This was likely a benefit for establishment during the one season of this experiment. It also tells us that the likely driver of mortality in this study was temperature.

1.4.4 Planted Seedlings

The planted seedlings followed the same trends as the seed germination. Overall, treatment had a significant effect on mortality (Table 7). This shows that the coarse woody debris is beneficial in reducing mortality of planted seedlings. On the other hand, treatment was not a significant predictor of height change. On the southern plots, mortality increased as the distance from edge increased. Both of these significant results are similar to the response of the seed germinates. This shows that initial establishment conditions are also conducive to survival of established seedlings.

These results indicate that planting seedlings will benefit from coarse woody debris. The survival rate over one growing season is high, and supports the idea of artificially regenerating openings on the Uncompahgre Plateau if this holds up in future seasons (Table 8).

1.4.5 Future Questions

More work is needed to fully understand spruce germination in small openings created in group selection treatments. We controlled for seed pressure by scattering a measured amount of seed on each plot. In the future it would be beneficial to gain knowledge on seed dispersal into openings to better understand the regeneration patterns and rates within group selection.

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