Reforesting surface coal-mined land using Douglas-fir seedlings in Washington State

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DEDICATION

To my Mom and Dad, for all your support!

Introduction

The United States has abundant supplies of coal, and approximately 37 % of the electricity produced in the U.S. is generated by coal-fired power plants (USGS 2011). Surface mining is commonly used for extraction when the coal seams are relatively close to the earth's surface. Vegetation, soil, rock, and overlying deposits are removed and the coal is extracted from the ground. In geologic time, the process of extracting the coal is short when compared with the formation of the deposits and the reclamation of the land after removing the coal. In 2011, the U.S. produced just over 1 billion short tons of coal from surface and underground mines; nearly 70% of that came from surface coal mines (USEIA 2012). Some problems associated with surface coal-mined land are erosion, landslides, floods, water pollution, and destruction of fish and wildlife habitat (SMCRA 1977). Disturbed land may also pose hazards to life and property of the public, degrade the quality of life in local communities, and counteract government programs to conserve soil, water, and other natural resources.

In 1977, the U.S. legislature passed the Surface Mining Control and Reclamation Act (Surface Mining and Coal Reclamation Act, USC §1202, 1977) to regulate the environmental concerns related to surface mining. The federal law set forth requirements for reclaiming surface mines and also created the Office of Surface Mining, a federal agency that enforces those standards. In order to obtain a surface mining permit, a performance bond must be posted along with criteria dictating standards for reclaiming the land after mining. After meeting the requirements, the bond is released back to the mining company. This ensures the regulatory authority will have sufficient funds to reclaim the site if the mine fails to complete the plan approved in the permit (SMCRA 1977).

The passing of SMCRA had some unintended consequences to reforestation of mined lands. There are perceived increases in cost, difficulty in interpreting performance standards, and a longer time to bond release (Ashby 1991, Boyce 1999, Angel et al. 2009). One issue is that success standards for forestry are not based on productivity; bond release is based on numbers of surviving trees, without regard to their growth or long-term productivity (Torbert & Burger 2000). This is concerning because post-SMCRA sites might provide less conducive conditions for tree growth than those prior to SMCRA (Torbert & Burger 2000). Trees play an important role in soil building and contribute to long-term soil improvement during reclamation (Ashby 1991). Often, coal operators do not have a long-term commitment to the land; their goal is to mine and reclaim the land in a way that achieves bond release cost-effectively (Torbert & Burger 2000). Tree establishment is integrated with many other reclamation processes, and the needs of trees should be considered throughout the entire procedure so that a healthy, viable forest system may develop (Torbert & Burger 2000).

This project addresses methods for improving the reforestation of surface coal-mined land in the Pacific Northwest. Documenting that reclaimed mine land in this region has the potential to be productive timber land will benefit the mine's ability to resell the land and decrease time to performance bond release. The two case studies presented here investigate techniques for improving the performance of outplanted Douglas-fir seedlings at a surface coal mine in southwestern Washington State. The first chapter assesses pre-planting soil reclamation techniques, comparing the survival of bareroot and container Douglas-fir seedlings in two modified versions of the Forestry Reclamation Approach (FRA) and an industry standard technique. The second chapter evaluates the nutrient and growth response of the Douglas-fir seedlings to a post-planting fertilizer application.

Chapter 1: Assessing a modified Forestry Reclamation Approach using Douglas-fir seedlings

Introduction

Environmental and post-mining reclamation standards help reduce the detrimental impacts of overburden removal on the utility of the land. Surface mining causes land use problems such as landslides, erosion, flooding, loss of wildlife habitat, and pollution. The Surface Mining and Control Reclamation Act of 1977 (SMCRA) requires that mined land be restored "to a condition capable of supporting the uses which it was capable of supporting prior to any mining, or higher or better uses." One consequence of the act was to depress reforestation efforts at surface mines because of perceived increases in cost and risks, fear of misinterpreting the reforestation performance standards and longer bond-release waiting periods (Ashby 1991, Boyce 1999, Angel et al. 2009).

The Appalachian Region Reforestation Initiative (ARRI) formed as a result of decreased reforestation efforts during reclamation. The ARRI has advocated the Forestry Reclamation Approach (FRA), a method that has proven successful in planting tree species to reclaim surface coal mines in the Appalachian region of the eastern U.S. using hardwood tree species (Burger et al. 2005). The steps of FRA are: (1) create a suitable 1.2 m deep rooting medium for good tree growth comprised of topsoil, weathered sandstone, or the best available material; (2) loosely grade the topsoil or topsoil substitutes placed on the surface to create an uncompacted growth medium; (3) use native and noncompetitive ground covers that are compatible with growing trees; (4) plant two types of trees—early succession species for wildlife and soil stability, and commercially valuable crop trees; and (5) use proper tree planting techniques (Burger et al., 2005).

Currently, most active mining areas in the western U.S. consist of dry grassland and low shrubs (Boyce 1999). Although grasslands that are on a trajectory to follow a predictable pathway of succession to a forest fulfill SMCRA requirements, the post-mining forest capability on the native stands will likely be less than that prior to mining (Angel et al. 2009). Trees play an important role in soil building, and their use during reclamation contributes to long-term soil improvement (Ashby 1991). Suitable tree species develop deep root systems, improve drainage and aeration, and contribute to soil organic matter through leaf and branch litter (Ashby 1991). The loss of forestland after mining decreases ecosystem diversity and productivity, and improving the survival of trees on mined-lands will contribute to more productive land uses in the future.

The FRA has successfully been used to reforest areas of the eastern U.S., and with some modifications, the technique may improve tree seedling establishment at surface coalmines in the Pacific Northwest. Differences in climate, vegetation, and specific site resources prompt several changes to the FRA for its implementation in this study; the main modifications include planting only one tree species and using native understory covers. The historical practice at the study site is to grow only *Pseudotsuga menziesii* (Douglas-fir), and we maintained this approach since it is both an early seral and late successional species in the region. Douglas-fir is also a valuable timber species in the region; the dominant trees in productive stands near the study site can reach heights of 41 m over a 50-year period (Pringle 1990).

Reclamation in the area seeks to reestablish viable forestland after mining, and previous efforts have had mixed results. Soil compaction, understory vegetation and water stress may be limiting seedling establishment and performance (King 2010). We compared two reclamation methods that are modified versions of the FRA with the mine's standard reclamation technique. Survival of seedlings planted in the spring of 2010 was followed for three years in both bareroot and containerized Douglas-fir seedlings. The replaced overburden, understory vegetation, and weather were monitored to determine important factors in seedling establishment.

Methods

Site Description

The study site is located approximately 10 km northeast of the city of Centralia, Washington, USA. The site includes an open pit sub-bituminous coal mine and an active coal-burning power plant. It had been one of the largest coal mines in the state, producing an average of 4.3 millions tons of coal annually (Schasse 1998), until mining stopped in 2006. Efforts at reforesting the area have been ongoing since operations started in 1971.

The climate of the region has an average annual precipitation of 1195 mm, about 30% of which falls during the growing season, March through August. Mean temperatures range from a low of 4.5 °C in December to a high of 19.2 °C in August (National Climate Data Center, Centralia, WA). Soils in the area are primarily the Centralia Series or the Buckpeak Series, which are very deep, well drained Ultisols formed in weathered sandstone or siltstone (Evans and Fibich 1987, Pringle 1990). They are characterized by deep A horizons, up to 40 cm thick, and by clay-rich Bt horizons down to 150 cm. The region supports extensive coniferous forests, with Douglas-fir being the most valuable and common timber species; grand fir (*Abies grandis)*, western redcedar (*Thuja plicata)*, and western hemlock (*Tsuga heterophylla*) are also prevalent (Snavely et al. 1958).

Site preparation

During the summer of 2006, approximately 16-ha were re-graded for reclamation. After mining, the stockpiled overburden was mixed and replaced, containing fragments of coal and shells throughout. It was then ripped to depths of 60-75 cm, and a mix of fertilizer and understory seeds was applied. The seed mix has varied over time, but the following species have been applied for groundcover: alfalfa (*Medicago sativa*), alsike clover (*Trifolium hybridum*), bentgrass (*Agrostis castellana*), birdsfoot trefoil (*Lotus corniculatus*), annual ryegrass (*Lolium multiflorum*), orchardgrass (*Dactylis glomerata*), perennial ryegrass (*Lolium perenne*), red clover (*Trifolium pratense*), red fescue (*Festuca rubra*), white clover (*Trifolium repens*) (King 2010).

In the fall of 2009, three reclamation treatments were randomly assigned to twelve 1-ha plots (4 replicates each) on the previously graded land, surrounding a hill with varying aspects and slopes. Plot 4 was rotated 90 degrees in October of 2009 to avoid a runoff gully that had formed in the area, and preparation of this plot was not completed until one week prior to seedling planting.

The standard reclamation technique used at the site (Control) was compared with a Forestry Reclamation Approach modified for use in the Pacific Northwest (FRA) and a similarly modified Forestry Reclamation approach that also incorporated bottom ash from the on-site coal burning power plant into the replaced overburden (FRA+Ash). In the Control treatment, Douglas-fir seedlings were planted directly into the landscape. In the modified version of the FRA plots, overburden was placed in mounds on top of the re-graded land. Several other changes were implemented for use in Washington State: (1) only Douglas-fir was planted since it is considered both an early and late successional species and is also a commercially-valuable timber species in the region, (2) understory species native to Washington State were used, namely annual ryegrass (*Lolium multiflorum*) and sicklekeel lupine (*Lupinus albicaulis* Dougl.), and (3) the Centralia mine uses larger dump trucks, and if mounds were over four feet, they were pressed down slightly by a bulldozer. The FRA+Ash treatment used the same modifications as the FRA treatment, listed above, and also incorporated bottom ash from the on-site power plant. The bottom ash was applied at a calculated average depth of 2.5 cm over the 1 ha plots and mixed into the replaced overburden using caterpillars before mound placement by bull dozers. The bottom ash had a pH of 9.9 and contained 19300 mg kg^{-1} aluminum, although other metal concentrations were relatively low (King 2011).

In the spring of 2010, the split plots were hand-planted by professional tree planters. Half were planted with 1+1 bareroot Douglas-fir seedlings at 1200 trees per ha and the other half with p+0 “plug-15” Douglas-fir seedlings at 1700 trees per ha, with both types from local seed source. The 1+1 seedlings were grown for one year in an outdoor nursery bed, then lifted, graded, and transplanted back into the nursery and grown for an additional year. The p+0 “plug-15” seedlings were grown for one year in a small container in a greenhouse and then extracted. The analyses in this report are based on the plantation age of the seedlings.

Seedling survival and growth

Seedlings were surveyed in each measurement subplot at the end of the three growing seasons after planting (2010, 2011, and 2012). Seedlings were considered living if they had any green foliage on them. The total number of seedlings planted in each subplot is the sum of live trees and dead trees found in the subplots, and obvious missing seedlings (based on planting row spacing). There was evidence of elk browsing on some surviving seedlings, and some seedlings had been pulled out by elk, which contributed to dead seedlings. There were several seedlings with chlorotic foliage throughout the treatment plots.

The percentage of surviving trees in each plot after each growing season is a mean of the ratio of live trees to total planted trees in the three subplots. Since the seedlings were spaced approximately 2-3 m apart, we assumed that the different initial starting density for the two seedling types does not affect the proportion of surviving seedlings for either type.

Seedling annual height increment was measured at the end of the third growing season (2012) in each of the three subplots per split plot. In some cases where few seedlings survived, measurements were taken on seedlings adjacent to the subplots to obtain a minimum sample size of six. Since different numbers of seedlings were measured for height in each subplot due to varying survival, a weighted average of the seedling growth across the three subplots was calculated for each split plot unit.

Soil characteristics

Soils were sampled in each plot in late spring and early summer of 2010. Three sampling locations in each split plot were randomly located adjacent to each of the measurement plots and excavated to 50 cm. Separate bulk density and mineral samples were collected from the following depths: 0-5 cm, 5-15 cm, and 15-50 cm. Samples were stored at 3° C until chemical analysis. Soil analyses were performed in accordance with Methods of Soil Analysis unless stated otherwise (Page et al. 1982).

Bulk density samples were taken from each depth using a 137.4 cm^3 two-ring corer (in some cases where difficult, a 68.7 cm^3 core), and oven-dried at 105° C for 72 hours. Dry mass of the soil was used to calculate bulk density.

Soil chemical samples were prepared for analysis by air-drying for one week and subsequently sieving to 2 mm. Soil pH was measured using a Denver Instrument Model 220 pH meter in a 2 -to-1 ratio of de-ionized water to air-dried, sieved soil, kept at approximately 21° C and equilibrated for 30 minutes after stirring. Total carbon (C) and nitrogen (N) were analyzed using dry combustion with a Perkin Elmer 2400 CHN Analyzer. Other elements were analyzed using a Thermo Jarrell Ash ICAP model 61E spectrophotometer after acid digestion using the EPA Method 3050 (USEPA 1996).

Understory cover and species

Three replicate 20 m transects were used to measure understory cover in each whole plot. This was done after the growing season had ended, in September through October of the first and second growing seasons (2010 and 2011).

Percent understory cover was estimated using ocular assessment of cover over 1 m intervals. Additionally, a 1 m by 1 m grid was used to assess individual understory species cover. This was done at one random location within each subplot and averaged by whole-plot treatment. The values from each measurement subplot were averaged across the whole treatment plots.

Soil temperature and moisture

Soil temperature at 10 cm and soil moisture at 10 and 50 cm were recorded at noon and midnight at one location within each whole plot using Decagon data loggers connected to Decagon EC-5 moisture probes and a Decagon ECT temperature probe (Decagon Devices, Pullman, WA). This was done for two consecutive growing seasons after planting (2010 and

2011). Trend lines were added to the graphs by computing moving averages on the individual data points.

Experimental design

The experiment was laid out in a split plot model, with whole plot treatments in a completely randomized design. Each whole plot treatment area was 1 ha with a 20 m buffer surrounding two 40 m by 40 m split plots. Control, FRA, and FRA+Ash treatments were applied to 12 whole plots, making four replicates of each. Bareroot or containerized seedlings were then planted in each split plot and monitored for three consecutive years. For data collection, three 10 m by 10 m subplots were randomly located within each split-plot. These three measurement subplots were used to sample survival, height, soil properties, and understory vegetation. The quantities were averaged across each split-plot experimental unit before analysis.

Statistical Analysis

All statistical analyses were performed using R (R Statistical Software, version 2.14.0). A Type I error value of 0.10 was used for all tests. Tukey's HSD tests were used to determine where significant differences occurred in ANOVA models and 90% confidence intervals were produced for distinct means. We considered treatment as the whole plot factor and seedling type as the split plot factor; where repeated measures occurred, we considered the time of sampling as a split split-plot factor. In the case of understory cover, we left seedling type out of the model. For the third growing year height increment analysis, plot 10 was omitted from the analysis because there were no surviving seedlings to measure; consequently we used an unbalanced ANOVA with Type II sums of squares for the analysis.

Results and Discussion

Seedling survival and stocking

Seedling survival for all treatments in the first (2010), second (2011), and third (2012) growing seasons are displayed in Figure 1. Averaging over all treatments, the combined seedling survival was 46% after the first growing season, 39% after the second growing season, and 33% after the third growing season. Mean seedling survival differed by treatment ($p = 0.047$) and year ($p < 0.001$), with a significant seedling-year interaction ($p = 0.001$). The FRA+Ash plots had the highest survival in each of the three years after planting and the Control plots the lowest survival. Seedling survival decreased in each treatment across the three years, although it was not consistent across treatments. The difference between the FRA+Ash and the Control treatment was most pronounced after the first growing season and decreased in the subsequent years. There were no significant differences in survival between the bareroot and containerized Douglas-fir seedlings after any of the three growing seasons. However, by the third year, the bareroot seedlings had higher survival than the container seedlings in all three treatments.

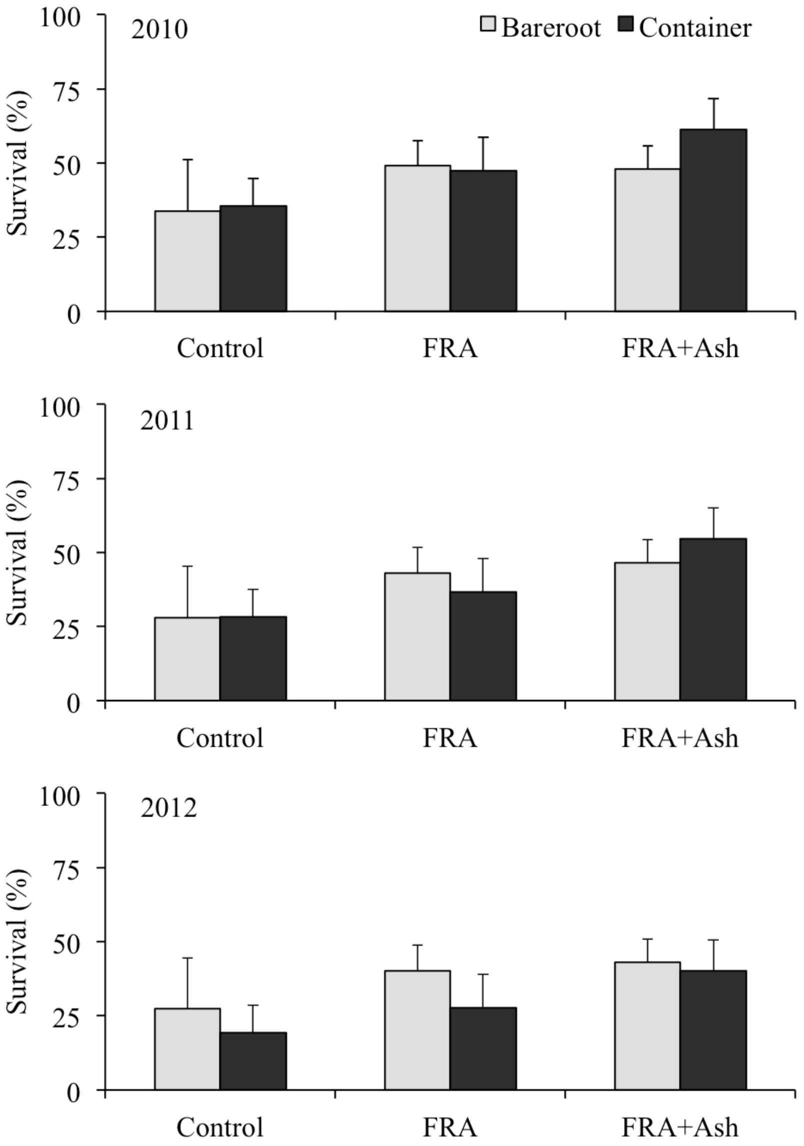

Figure 1. Mean survival with standard error after the first (2010), second (2011) and third (2012) growing seasons by reclamation treatment and seedling type with standard error. Control is the standard mine reclamation technique, FRA is the modified Forestry Reclamation Approach, and FRA+Ash is the modified Forestry Reclamation Approach with an addition of bottom ash from the on-site coal burning power plant. The seedlings are either bareroot or container Douglas-fir stock.

Washington State forest practices dictate that a harvested area is reforested when it contains an average of at least 470 trees per ha of “vigorous, undamaged” commercial species seedlings that have survived on site for at least one growing season (WAC 222-34-010). We calculated 90% confidence intervals for the population mean survival in each whole plot treatment area. Based on these results, we estimated the density of the treatment areas using the average density of the bareroot and containerized seedlings combined (1450 trees per ha). The stocking of the treatments (Table 1) provides a straightforward comparison with reclamation success compared to Washington State forest practices. All treatments meet the requirement of 470 trees per ha after the first growing season, with the FRA and FRA+Ash treatments exceeding standards and the Control treatment marginally acceptable. By the third year, the Control treatment has stocking levels below reforestation standards.

Table 1. Stocking of treatment plots after the first (2010), second (2011) and third growing seasons (2012) based on 90 % confidence intervals of mean survival and average initial planting density of bareroot and container Douglas-fir seedlings in the whole treatment area (1450 trees per ha). Control is the standard mine reclamation technique, FRA is the modified Forestry Reclamation Approach, and FRA+Ash is the modified Forestry Reclamation Approach with an addition of bottom ash from the on-site coal burning power plant.

Stocking			
Year	Treatment		
	Control	FRA	FRA+Ash
	--------------Trees per ha	--------------	
Initial	1450	1450	1450
2010	450 – 551	653 – 740	740 – 841
2011	363 – 450	537 – 624	682 – 783
2012	290 – 377	450 – 537	566 – 653

Seedling growth

During the third growing season after planting, the height increment of the seedlings ranged from 8 to 29 cm in the bareroot seedlings and from 11 to 18 cm in the container seedlings (Figure 2). Mean height increment across all treatments was 17 cm for bareroot seedlings and 15 cm for container seedlings. The main effect of treatment on seedling height increment was significant (p = 0.005), as well as the treatment-seedling interaction (p = 0.078). The FRA treatment had larger height increments than both the Control and FRA+Ash treatments. The two seedling types had similar height increments in the Control and FRA+Ash treatments, but in the FRA treatment, there was substantially more growth in the bareroot seedlings compared to the container seedlings.

During the initial period of establishment, seedlings continue to transpire which can result in physiological drought stress (Reitveld 1989). After transplanting, seedlings need to reestablish root-to-soil contact, resume water and nutrient uptake, and recover from any handling damage (Haase & Rose 1994). Seedlings can experience drought stress and reduced growth until established in a new environment; once the tree obtains favorable water status, shoot growth can proceed unchecked (Haase & Rose 1994). The response of a stressed seedling to transplant shock, which is probably due to moisture deficit, may be to allocate carbon to solutes for osmotic adjustment, further reducing available resources for growth (Morgan 1984**).** The seedlings may reduce growth and decrease bud production to lower their leaf production and area, which in turn decreases the transpirational area of new tissues (Morgan 1984).

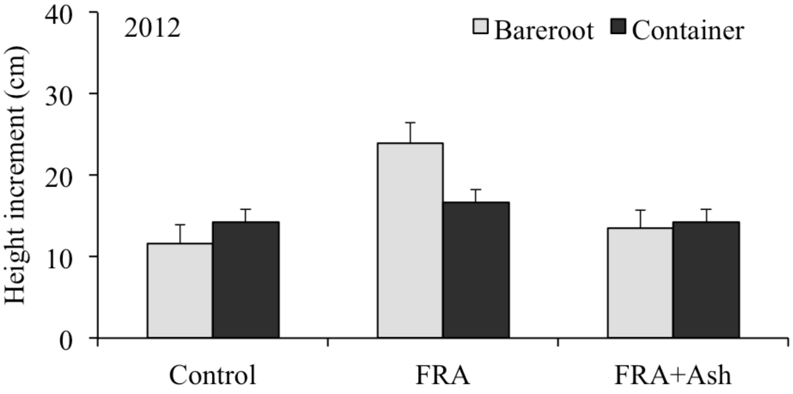

Figure 2. Mean height increment with standard error for the third growing season (2012). Control is the standard mine reclamation technique, FRA is the modified Forestry Reclamation Approach, and FRA+Ash is the modified Forestry Reclamation Approach with an addition of bottom ash from the on-site coal burning power plant. The seedlings are either bareroot or containerized Douglas-fir stock.

Soil characteristics

The bulk density ranged from 1.31 to 1.38 g cm^{-3} (Table 2) and did not vary significantly by treatment, but did increase with depth (King 2011). Compaction is often a concern during site preparation and may negatively impact survival and growth rates. Although it is clearly established that heavy equipment compacts mineral soil, the consequences to subsequent tree growth and stand yields are less predictable (Miller et al. 1996). Soil compaction can increase runoff and erosion and reduce root and shoot growth in plants. Low soil porosity inhibits the movement of air and water through soil (USDA NRCS, 2008). In clayey soils, bulk densities over 1.47 g cm^{-3} can restrict the root growth of plants, and the ideal bulk density for plant growth is under 1.10 g cm^{-3} (USDA NRCS, 2008). One method of reducing the likelihood of high bulk density and compaction is using practices that maintain or increase soil organic matter (USDA NRCS, 2008). Since the levels of current compaction are adequate for plant establishment, other factors may be of higher importance to evaluating the survival of trees at the site.

The individual soil pH measurements were highly variable, but overall, the treatments were slightly acidic and ranged from 6.0 to 6.4 (King 2011). Douglas-fir has optimal growth in mineral soils that range in pH from 5 to 8 (Brady and Weil, 2010). The high variability of soil pH measurements was likely due to the high rainfall in the region, calcium carbonate fossils in the soil, and the mixing of original soil horizons during overburden replacement. There are also a number of microsites in the area with poor drainage that hold water for much of the year. Mounding the replaced overburden in the FRA and FRA+Ash treatments likely increased the occurrence of these sites. The average levels of pH in this study were acceptable for Douglas-fir growth, although the range, from 2.4 to 8.0 indicates potential problems from acidity (King 2011). Some areas may have pH values detrimental to seedling survival. There are a variety of microsite types in the plots, including vastly different areas within individual plots. These are mainly combinations of grassland and swampland that are impacted by water flow and solar insolation. Some microsite differences may be a result of the topography created by mounding in the FRA and FRA+Ash treatments.

Table 2. Selected characteristics of the replaced overburden, averaged across all sampling depths, by treatment.

					Soil Characteristics				
Treatment	D_b	pH	C	N	P	K	S	Ca	Mg
	g cm^{-3}		------------------------------			μg g^{-1}		------------------------------	
Control	1.31	6.4	18200	600	700	2400	7900	11600	5900
FRA	1.31	6.3	29500	700	700	1600	5700	6700	5800
FRA+Ash	1.38	6.0	25400	900	500	1500	4500	9500	5100

Understory cover and species

The Control plots were seeded prior to determining the location of study plots. These areas had established dense understory cover by the time trees were planted; Control plots had a mean cover of 94% at the end of the first and second growing seasons (Table 3). The FRA and FRA+Ash plots were freshly graded and seeded just months (and in the case of plot 4, weeks) before planting. They had much lower understory cover after the first growing season. By the end of the second growing season, the understory had become well established on all treatment plots. In general, the understory vegetation was higher than seedling height after the first growing season but, by the end of the third season after planting, the tree seedlings began to overtake tall grasses and shrubs in the understory.

Table 3. Mean understory cover with standard error by treatment, after one and two growing seasons, with standard error of the mean. Control is the standard mine reclamation technique, FRA is the modified Forestry Reclamation Approach, and FRA+Ash is the modified Forestry Reclamation Approach with an addition of bottom ash from the on-site coal burning power plant.

Understory cover		
Treatment	Year	
	2010	2011
	------- % (SE) -------	
Control	94 (3)	94 (4)
FRA	49 (13)	74 (12)
FRA+Ash	58 (14)	86 (10)

There was a substantial amount of birdsfoot trefoil in the plots after the second growing season (Table 4). Birdsfoot trefoil (*Lotus corniculatus*) is a perennial herbaceous plant that is considered invasive in Washington State (Bush 2002). It encroached onto the FRA and FRA+Ash plots during the second growing season, which may have exacerbated interspecies competition in those plots as well. Low soil nitrogen could explain the presence of birdsfoot trefoil and lupine (*Lupinus albicaulis*), which are nitrogen-fixing species and would be consistent with its ability to adapt to disturbed sites. In some areas the grasses occur in high abundance, especially in the dryer microsites, such as the south-facing aspects and upper portions of the hill. The unseeded plants generally covered only a small portion of the treatment areas.

A well-established understory cover aids in organic matter accumulation and can improve soil structure in the surface horizon, however it also plays a role in competing with seedlings during establishment. The reclaimed sites were dominated by habitat generalists, which may have inhibited tree growth and establishment by competing for site resources, especially water, which is a principle-limiting factor of Douglas-fir seedling growth (Khan et al. 1996). Early establishment of understory cover in Douglas-fir plantations can decrease seedling growth because of competition for soil moisture during the dry summer months (Dinger & Rose 2009).

Less competitive understory species might provide similar erosion control benefits in the first year, but not compete as heavily with native species or tree establishment (Torbert & Burger 2000). Results from our study indicate that it is also important to synchronize the planting of tree seedlings and the establishment of an understory cover to minimize simultaneous competition for the site's water resources.

Table 4. Mean abundance of some understory species with standard error by treatment and year. Control is the standard mine reclamation technique, FRA is the modified Forestry Reclamation Approach, and FRA+Ash is the modified Forestry Reclamation Approach with an addition of bottom ash from the on-site coal burning power plant. In some cases, species were not found in the treatment area (NF = not found).

Understory species						
Species	Treatment by year					
	Control		FRA		FRA+Ash	
	2010	2011	2010	2011	2010	2011
	---------------------------- % (SE) ----------------------------					
Lupinus albicaulis	3 (2)	2 (1)	5 (4)	4 (3)	2 (1)	1 (0)
Lotus corniculatus	54 (12)	55 (9)	20 (4)	42 (6)	35 (7)	60 (9)
Lolium multiflorum	9 (3)	5 (3)	10 (3)	3 (2)	7 (3)	3 (1)
Trifolium pratense	NF	2 (0)	NF	1 (1)	NF	1 (1)
Other Graminoids	6 (2)	17 (4)	4 (0)	8 (1)	9 (5)	6 (4)
Unseeded plants	11 (3)	9 (4)	10 (1)	10 (6)	6 (1)	6 (2)

Precipitation

Precipitation for each month from the start of mining in 1971 through the third growing season (2012) was measured at the mine. Precipitation for the first three growing seasons after planting (2010, 2011, and 2012) was compared with the previous thirty-year average 1980-2009 (Table 5). We calculated the mean and standard deviation for each month over the past 30 years and standardized the monthly precipitation for the two growing seasons against the climatic average. The growing season in the Pacific Northwest for conifers is approximately March through August.

Table 5. Monthly precipitation for first three growing seasons after planting (2010, 2011, and 2012), including average from 1980-2009 from data collected at the mine.

Precipitation												
Year	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	cm											
1980-2009	18	12	13	10	7	5	2	3	5	11	21	18
2010	16	12	14	12	14	10	1	1	12	14	12	18
2011	17	11	23	15	11	3	2	0	2	9	21	9
2012	17	17	24	13	7	6	2	0	0	19	25	28

The first season after planting had above average precipitation for most of the year, with relative deficits during July, August, and November (Figure 3). The second season after planting had several wet months early in the year, but a prolonged drought with seven straight months of below-average rainfall starting in June. The region underwent a substantial period without rainfall during the third growing season; July through September was especially dry, with 2 cm of precipitation on record.

The relatively dry months that occurred during the growing seasons after planting contributed to moisture stress in the seedlings. The seedlings had little time to establish prior to two relatively dry months in July and August in the first season after planting. Additionally, stress in the first year from transplanting the seedlings can inhibit their ability to take advantage of soil water (Newton & Preest, 1988). That pressure carried over to the second and third years, which provided even less favorable water conditions during the growing season.

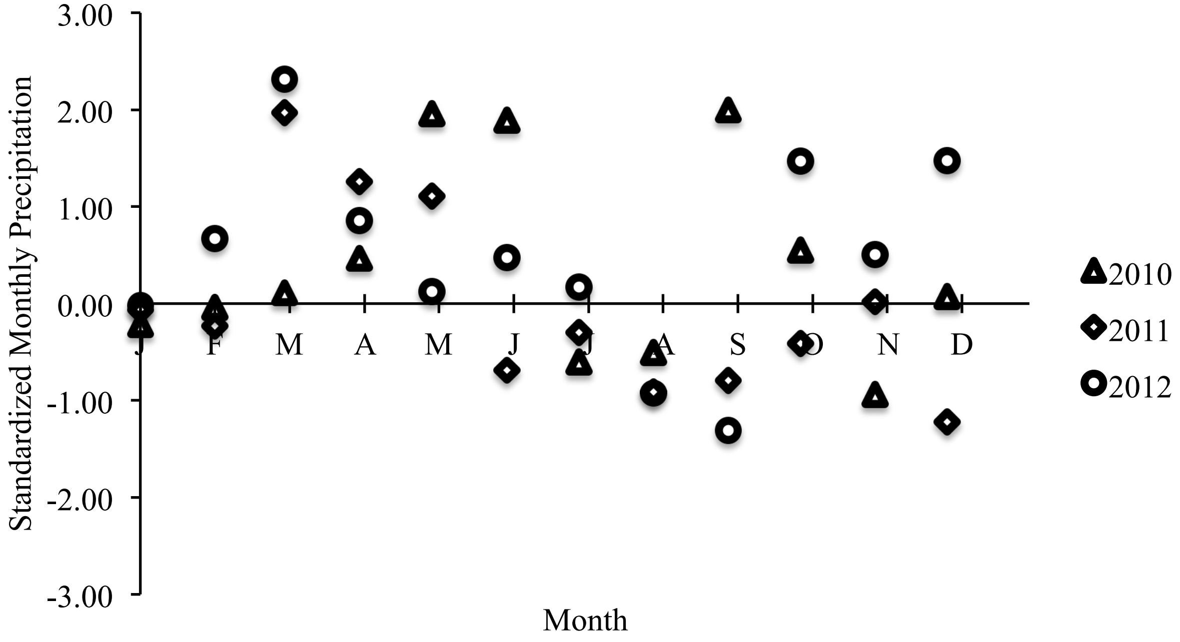

Figure 3. Standardized monthly precipitation for the three growing seasons (2010, 2011, and 2012), based on the climatic average (1980-2009) from data collected at the mine.

Soil temperature and moisture

The soils show a strong link between temperature and moisture and the general climatic variability of the region. Hot/dry summers and cool/wet winters drive the overall trends in temperature and moisture dry-down towards the end of the growing season that drives seedlings to dormancy (Figure 4).

Soil temperature at 10 cm was similar in all treatments during the first growing season, and it peaked around 20˚ C between July and September. The soil moisture at 10 cm showed a corresponding dry-down in all treatments during this same time. The soils decreased in volumetric water content from about 0.4 $m^3\ m^{-3}$ to about 0.2 $m^3\ m^{-3}$. The FRA+Ash treatment maintained the highest moisture content over this period, with the FRA treatment having the lowest moisture content. At 50 cm. the FRA+Ash dried down to about 0.3m^3 m^{-3}, while the Control and FRA treatments dipped to about 0.2 m^3 m^{-3}.

In the second growing season, the Control treatment had the highest temperatures, followed by FRA+Ash and then FRA. Soil moisture similarly decreased during that period. The Control treatment maintained higher moisture levels late in the growing season compared to the FRA and FRA+Ash treatments. The FRA and FRA+Ash treatments dropped to near 0.2 m^3 m^{-3} at 10 cm, with the Control treatment slightly higher. At 50 cm, the Control and FRA+Ash treatments decreased from around 0.4 m^3 m^{-3} at the start of the growing season to nearly 0.2 m^3 m^{-3} at the end of the growing season. The FRA treatment dropped abruptly to 0.2 m^3 m^{-3} in July and held steady through the rest of the growing season.

The original soils that constituted the replaced overburden in this study were high in clay content, so the seedlings may have been at a disadvantage to access what water supply did exist over the summer months. The plots dry considerably towards the end of the growing season, and although there was still moisture retained at 50 cm depth, it may have been bound so tightly to the clay it was not available for plant use.

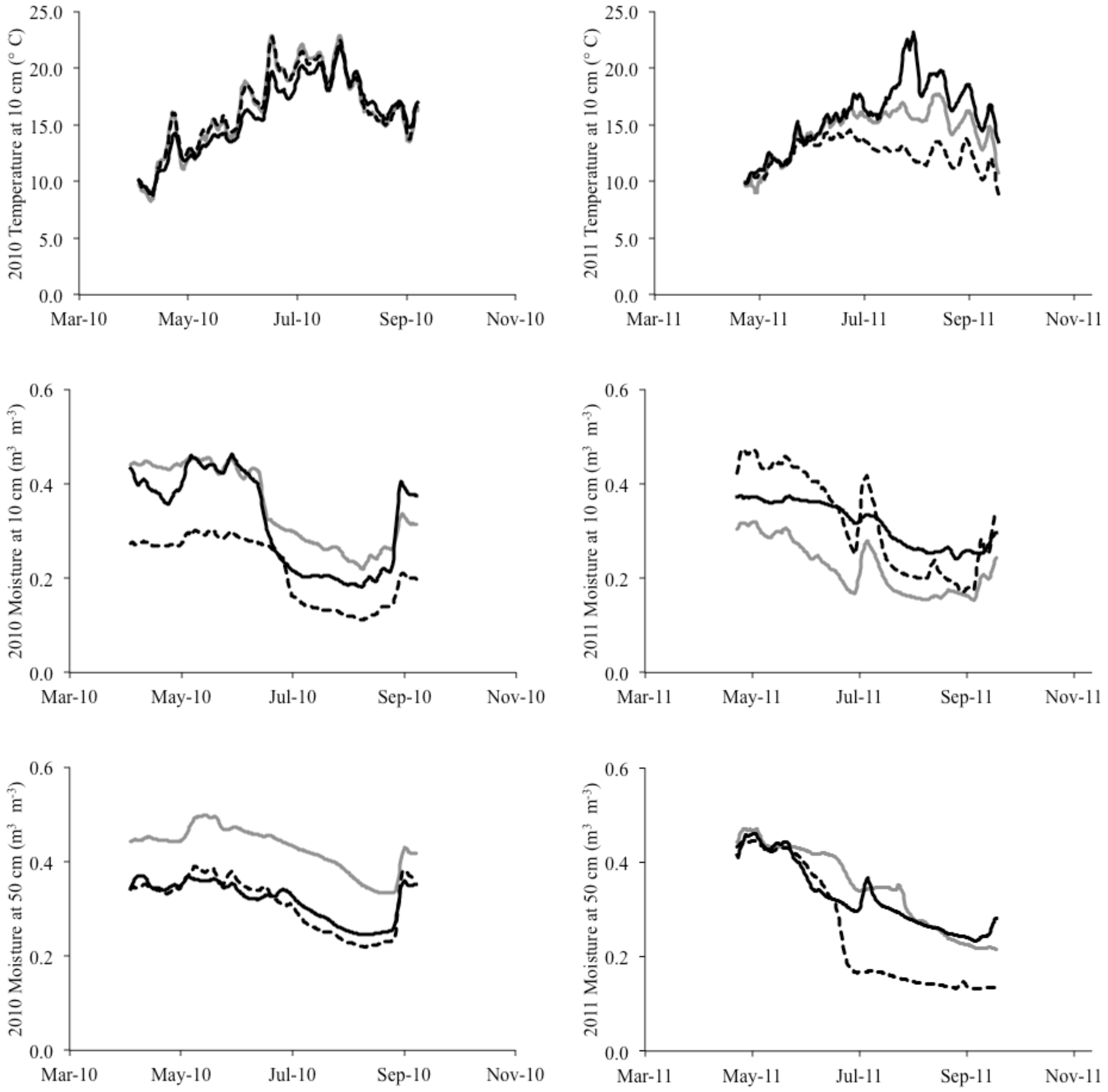

Figure 4. Soil temperature at 10 cm, and soil moisture at 10 cm and 50 cm for the first (2010) and second (2011) growing seasons. Control (solid black line) is the standard mine reclamation technique, FRA (dashed black line) is the modified Forestry Reclamation Approach, and FRA+Ash (solid grey line) is the modified Forestry Reclamation Approach with an addition of bottom ash from the on-site coal burning power plant.

Conclusions

All of the treatments met Washington State forest practices for reforestation after the first year. While seedling survival in the FRA and FRA+Ash treatments was higher than the Control treatment after the first year, they dropped considerably by the third season. The difference in survival between the treatments was much less pronounced by the third growing season, where overall survival was 33%. We found no difference in survival between the bareroot and container seedlings throughout the course of the study, although the trend suggests the possibility of higher survival in the bareroot stock over the long term. Stocking levels were adequate in all three treatments after the first growing season, but by the third season after planting, the Control treatment no longer met Washington State reforestation standards.

An adequate root system and water supply is essential to seedling survival and growth. In our study, the replaced overburden, understory competition and annual weather provided difficult conditions for seedling survival in the first few years after planting. These factors likely affected seedling access to water in the first few seasons after planting, which in turn led to desiccation and death. The results indicate that the overall trends in seedling survival were mainly driven by the weather, competition from understory cover, and differences in soil attributes.

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Chapter 2: Post-planting fertilization of Douglas-fir seedlings during surface coal mine reclamation

Introduction

Surface mine reclamation in the United States is governed by the Surface Mining Control and Reclamation Act of 1977 (SMCRA), a piece of legislation that addresses environmental problems associated with coal mining. It ensures that mined areas are restored so that the land is at least as productive as before mining. One unintended consequence of SMCRA was to discourage reforestation of mined-lands because of perceived increase in costs, difficulty of interpreting performance standards, and longer time to bond-release (Ashby 1991, Boyce 1999, Angel et al. 2009). Trees play an important role in long-term soil improvement (Ashby 1991), but there are a number of problems associated with reestablishing forest on mined land.

Mine soil properties are a primary concern for long-term site productivity of land reclaimed to forest (Bussler et al. 1984). Mined soils can be greatly different from un-mined land and potentially limit plant establishment (Davis & Jacobs 2004). Two major concerns for tree productivity are compaction of replaced overburden and competition from understory cover (Torbert & Burger 2000). Compaction from heavy equipment during the re-grading process reduces soil porosity, hinders root growth and limits water-holding capacity (Cleveland & Kjelgren 1994). Additionally, grasses and legumes that are seeded to reduce erosion during reclamation compete with tree seedlings for what water is available, along with light and nutrients (Ashby 1991). Reforestation focuses on providing suitable conditions for the establishment and growth of tree seedlings.

The Forestry Reclamation Approach (FRA) arose from numerous studies on reforestation since the passing of SMCRA and was developed for reclaiming mountaintop mines in the Appalachian region. The steps of FRA are: (1) create a suitable 1.2-m-deep rooting medium for good tree growth comprised of topsoil, weathered sandstone, or the best available material; (2) loosely grade the topsoil or topsoil substitutes placed on the surface to create an uncompacted growth medium; (3) use native and noncompetitive ground covers that are compatible with growing trees; (4) plant two types of trees—early succession species for wildlife and soil stability, and commercially valuable crop trees; and (5) use proper tree planting techniques (Burger et al., 2005). The FRA has been successful in planting hardwood tree seedlings on surface coal mines in the eastern U.S. (Burger et al. 2005).

Seedlings must reestablish root to soil contact after planting in order to resume water and nutrient uptake (Haase & Rose 1994, Grossnickle 2005). During this time, seedlings may experience water stress because they continue to transpire while reestablishing soil contact after planting (Rietveld 1989). Seedlings use stored reserves for initial growth and cannot exploit nutrients in the soil until they develop new roots (van den Driessche 1991b). This can lead to planting check, a reduction in growth due to stress after planting. Fertilizing Douglas-fir (*Pseudotsuga menziesii*) seedlings at the time of planting may increase seedling height growth (Arnott & Brett 1973), but the cost of reducing planting check in relation to the benefits gained has been questioned (Smith et al. 1966).

A well-developed root system allows seedlings to establish a proper water balance and to respond to site conditions; once seedlings are linked with the site hydrologic cycle, they may begin the establishment phase (Grossnickle 2005). Planting stress may be overcome with the proper combination of physiological and morphological attributes, and root growth ability to respond to site conditions (Grossnickle 2005). Nitrogen is commonly identified as a limiting nutrient for plant growth on coal spoils in the eastern USA (Haghiri & Sutton 1982, Roberts et al. 1988, Schoenholtz & Burger 1984). In the Pacific Northwest, nitrogen fertilizers frequently increase the growth of Douglas-fir since the rate of nitrogen turnover in the soil is frequently inadequate to meet tree requirements (Miller & Fight 1979). Nitrogen fertilizers are often applied to overburden to promote the establishment of vegetation (Schoenholtz et al. 1992).

The objective of this study was to assess whether the addition of fertilizer to individual trees after planting would improve Douglas-fir seedling establishment at a surface coal mine reclamation site. Previous research on the success of reforestation at the site found mixed results with the standard reclamation technique and two modified FRA treatments (Miller 2013). There were observations of chlorotic foliage, indicating that nutrient deficiencies may limit seedling performance at the site. Therefore, outplanted bareroot and container Douglas-fir seedlings were fertilized to determine the effects of post-planting fertilization on newly planted seedlings as well as seedlings that had survived on site for several growing seasons.

Methods

Study area

The study area, which includes an open pit coal mine and a coal-burning power plant, was located approximately 10 km northeast of Centralia, WA. The mine opened in 1971 and was one of Washington State's largest coal producers until operations ended in 2006. The climate in the region has an average annual precipitation of 1200 mm, with about 30% of it falling during the growing season, March through August. Mean monthly temperatures range from a low of 4.5 °C in December to a high of 19.2 °C in August (National Climate Data Center, 1981-2010).

Soils in the area are primarily of the Centralia Series or the Buckpeak Series. They are very deep, well drained Ultisols formed in weathered sandstone or siltstone and characterized by deep A horizons, up to 40 cm thick, and by clay-rich B horizons down to 150 cm (Evans and Fibich 1987, Pringle 1990). The region supports extensive coniferous forests, and Douglas-fir is the most valuable and common timber species. Grand fir (*Abies grandis*), western redcedar (*Thuja plicata*), and western hemlock (*Tsuga heterophylla*) are also prevalent (Snavely et al. 1958).

Site preparation and experimental design

In the summer of 2006, a 16 ha reclamation area of the mine was re-graded and prepared for installation of plots for the study. Stockpiled overburden was mixed with caterpillars, replaced on the site, and ripped to depths of 60-75 cm. The area was seeded with the mine's standard understory species mix. In the fall of 2009, twelve plots were situated around a hill with varying aspects and slopes. Each whole plot treatment area was 1 ha with a 20 m buffer surrounding two 40 m by 40 m split plots. The three reclamation treatments were randomly assigned to the twelve plots, making four replicates of each.

In the Control (Control) treatment, Douglas-fir seedlings were planted directly into the re-graded overburden. In the modified FRA treatment (FRA), stockpiled overburden was mounded over the re-graded area using the methods outlined in the FRA with three specific modifications: (1) used only Douglas-fir, both an early seral and late successional species, (2) used understory species native to Washington state, namely annual ryegrass (*Lolium multiflorum*) and sicklekeel lupine (*Lupinus albicaulis* Dougl.), and (3) used larger dump trucks that required leveling when mounds exceeded four feet. The FRA+Ash treatment (FRA+Ash) used the same modifications as the FRA treatment and also incorporated bottom ash, a byproduct of the coal-burning process, at an average depth of 2.5 cm in the plots.

Overall, the chemical and physical properties of the replaced overburden are suitable for the growth of Douglas-fir seedlings (King 2011). The range of some important soil properties across the three treatments are as follows: soil pH from 6.0 – 6.4, bulk density from 1.31 – 1.38 g cm^{-3}, electrical conductivity from 1.58 – 1.82 dS m^{-1}, and total extractable nitrogen from 0.010 – 0.016 mg g^{-1}. Bulk density and electrical conductivity did not vary across treatments, but did increase with depth. Soil pH did not vary by treatment or depth, but was highly variable within the treatment plots (King 2011).

In the spring of 2010, after the plots were installed, 1+1 bareroot and 1+0 “plug-15” containerized Douglas-fir seedlings were planted at 1200 trees per ha and 1700 trees per ha, respectively, in split plots nested within each whole plot treatment area. The 1+1 seedlings were grown for one year in an outdoor nursery bed, then lifted, graded, and transplanted back into the nursery and grown for an additional year. The p+0 “plug-15” seedlings were grown for one year in a small container in a greenhouse and then extracted. Three subplots (10 m by 10 m) were randomly located within each split plot for measurements.

Measurements

Two growing seasons after the installation of the study plots, in the fall of 2011, twenty current-year foliage samples were collected from an upper lateral branch on three random trees within each of the three subplots. We used a random number generator to provide azimuth headings and, from the center of the subplot, sampled the nearest seedling just outside the subplot. Samples were combined within each split plot before analysis. Needles were dried in a

65 °C oven for three days and then ground with a mortar and pestle. Foliar nitrogen was analyzed using dry combustion with a Perkin Elmer 2400 CHN/O Analyzer. Other elements were determined using a Thermo Jarrell Ash ICAP model 61E spectrophotometer after acid digestion using EPA Method 3050 (USEPA 1996).

In the spring of 2012, new bareroot and container Douglas-fir seedlings were planted in each plot to replace dead or missing seedlings. Twelve 1+1 bareroot and twelve 1+0 container seedlings were planted in each respective split plot, for a total of 24 new seedlings per each of the 12 plots. After one growing season, six of the new seedlings were randomly selected to fertilize and six marked for later measurement. At the same time, we also randomly selected six older seedlings (planted in spring of 2010) to fertilize and six for control. Overall, we planted and fertilized 6 new bareroot seedlings, 6 new container seedlings, 6 old bareroot seedlings, and 6 old container seedlings in each plot, for a total of 288 seedlings. The same number of corresponding seedling types were not fertilized and marked for analysis.

At the start of the growing season in 2012, we applied 16-16-16 N-P-K fertilizer (at 220 kg ha^{-1}) and $CaSO_4$ (at 100 and 82.5 kg ha^{-1}, respectively) to individual seedlings. The fertilizer was applied to the surface in a circular area with a 30 cm radius (approximately 1:1 ratio of distance to crown width) around the seedlings to minimize fertilizer application to understory vegetation. In the fall of 2012, one growing season after fertilizer application, foliage of the seedlings in both the fertilized and unfertilized sets was analyzed using the same methods as previously described. Samples were composited within each split plot for analysis.

Seedling survival during the 2012 growing season was defined as the proportion of living seedlings counted in the fall of 2012 compared with those marked at the time of fertilizer application in the spring of 2012. Seedlings were considered dead if they had no live foliage on them, or if missing. There was evidence of desiccation and elk browsing that contributed to mortality during the growing season.

Statistical analysis

The experiment was laid out in a split plot design, with whole plot treatments in a completely randomized design. Treatment (Control, FRA and FRA+Ash) was considered the whole-plot effect and seedling type the split-plot effect. For samples taken after the fertilizer application, a split split-plot factor was added to test for differences between the fertilized and unfertilized seedlings. The seedlings planted in 2012 had high rates of mortality and reduced the replication enough to prevent statistical analysis between treatment groups.

All statistical analyses were performed using R (R Statistical Software, version 2.14.0). A Type I error value of 0.10 was used for all tests. Tukey's HSD tests were used to determine where significant differences occurred in ANOVA models and 90 % confidence intervals were produced for distinct means.

Results

Foliar nitrogen

After two plantation years, foliar nitrogen was low in the Control and FRA+Ash treatments (Table 1). Foliar nitrogen may be considered deficient when less than 1.25% – 1.30%, as given by Walker and Gessel (1991) and Ballard and Carter (1991), respectively. Nitrogen concentrations ranged from 0.9 – 1.4 %, and the average level across all treatments and seedling types was 1.2 %. There were no effects from treatment or seedling type on foliar nitrogen. The container seedlings had higher nitrogen in all treatments, and the FRA treatment had the highest foliar nitrogen concentrations. The FRA treatment did not appear to have deficient foliar nitrogen concentrations.

Three seasons after planting, seedlings had nitrogen contents ranging from 1.2% – 1.6%. There was a significant difference in nitrogen content between the fertilized and unfertilized seedlings ($p = 0.074$). Foliar nitrogen averaged 1.3 % in the unfertilized seedlings compared to 1.4% in the fertilized seedlings. There was a significant treatment-seedling interaction ($p = 0.027$). The container seedlings in the FRA+Ash treatment had the highest foliar nitrogen concentration.

The newly planted seedlings, sampled after one growing season in the field, had deficient nitrogen levels across almost all treatment combinations. The average foliar nitrogen concentration was 1.0%, at the low end of the deficiency levels. In some cases, bareroot seedlings had higher nitrogen than the container seedlings. The fertilized seedlings had higher foliar nitrogen concentrations than the unfertilized seedlings, although statistical tests were not performed because of insufficient data. There were lower nitrogen concentrations in the newly planted seedlings than the seedlings that had survived on site for at least two growing seasons.

Table 1. Seedling foliar nitrogen by plantation age and seedling type for each reclamation treatment. Fertilizer was applied at the start of the growing season and foliage collected at the end of the growing season. Control is the standard mine reclamation technique, FRA is the modified Forestry Reclamation Approach, and FRA+Ash is the modified Forestry Reclamation Approach with an addition of bottom ash from the on-site coal burning power plant. The seedlings are either bareroot or container Douglas-fir stock, and are unfertilized (No-F) or fertilized (Fert). Seedlings planted in 2010 had complete mortality across several Control and FRA plots, and statistical analyses were not completed. Deficiency levels given by Ballard and Carter (1986) are considered the range for slight to moderate deficiency in Douglas-fir, whereas Walker and Gessel (1991) provide a single value for the level at which deficiency symptoms appear in Douglas-fir seedlings.

Nitrogen

Plantation Age	Seedling	Treatment					
		Control		FRA		FRA+Ash	
		No-F	Fert	No -F	Fert	No-F	Fert
		% (SE)					
2	Bareroot	0.9 (0.10)		1.3 (0.09)		1.0 (0.15)	
	Container	1.1 (0.14)		1.4 (0.12)		1.4 (0.29)	
3	Bareroot	1.2 (0.04)	1.3 (0.03)	1.4 (0.03)	1.5 (0.06)	1.2 (0.14)	1.5 (0.18)
	Container	1.3 (0.07)	1.3 (0.08)	1.3 (0.11)	1.3 (0.14)	1.4 (0.16)	1.6 (0.09)
1	Bareroot	0.9 (0.05)	1.1 (0.13)	1.0 (0.16)	1.1 (0.05)	1.0 (0.10)	1.2 (0.13)
	Container	0.7 (NA)	1.3 (NA)	1.0 (0.21)	1.5 (NA)	0.7 (0.03)	1.1 (0.10)

Deficiency range	1.05 – 1.30 %	(Ballard & Carter 1986)
Deficiency threshold	1.25 %	(Walker & Gessel 1991)

Foliar phosphorus

After two plantation seasons, foliar phosphorus concentrations were similar across all treatment groups and near deficiency levels (Table 2). Foliar phosphorus may be considered deficient when below 1000 – 1600 μg g^{-1} (Ballard & Carter 1986, Walker & Gessel 1991). There were no significant differences between treatments or seedling types, and the overall average foliar concentration of phosphorous was 1400 μg g^{-1}.

After three growing seasons, seedlings had phosphorus levels at the lower end of the deficiency thresholds. There was a significant effect from fertilizer on the foliar concentration of phosphorus ($p = 0.008$), where the unfertilized seedlings had an average of 1000 $\mu g\ g^{-1}$ phosphorus and the fertilized seedlings 1100 $\mu g\ g^{-1}$ phosphorus. Overall, the differences from fertilizer were minimal. The container seedlings were at least as high in phosphorus as the bareroot seedlings across all treatments, although differences were not significant.

For the new seedlings sampled after one growing season in 2012, foliar phosphorus concentrations were deficient in all except the fertilized container seedlings in the FRA treatment. Foliar phosphorus ranged from 700 – 1600 $\mu g\ g^{-1}$, with the highest concentration found in the fertilized FRA container seedlings. In some cases, the bareroot seedlings had higher phosphorus content than the container stock. The seedlings showed mixed response to the application of fertilizer, with increases in some cases and slight decreases in others. The seedlings that had survived on site for at least two growing seasons had higher foliar phosphorus concentrations than the newly planted seedlings.

Table 2. Seedling foliar phosphorus by plantation age and seedling type for each reclamation treatment. Fertilizer was applied at the start of the growing season and foliage collected at the end of the growing season. Control is the standard mine reclamation technique, FRA is the modified Forestry Reclamation Approach, and FRA+Ash is the modified Forestry Reclamation Approach with an addition of bottom ash from the on-site coal burning power plant. The seedlings are either bareroot or container Douglas-fir stock, and are unfertilized (No-F) or fertilized (Fert). Seedlings planted in 2010 had complete mortality across several Control and FRA plots, and statistical analyses were not completed. Deficiency levels given by Ballard and Carter (1986) are considered the range for slight to moderate deficiency in Douglas-fir, whereas Walker and Gessel (1991) provide a single value for the level at which deficiency symptoms appear in Douglas-fir seedlings.

Phosphorous							
Plantation Age	Seedling	Treatment					
		Control		FRA		FRA+Ash	
		No-F	Fert	No-F	Fert	No-F	Fert
		---- $\mu g\ g^{-1}$ (SE) ----					
2	Bareroot	1200 (150)		1500 (100)		1300 (130)	
	Container	1400 (120)		1500 (210)		1300 (270)	
3	Bareroot	1100 (50)	1000 (70)	1000 (80)	900 (50)	1000 (10)	1000 (90)
	Container	1300 (120)	1100 (50)	1100 (80)	900 (40)	1100 (120)	1000 (80)
1	Bareroot	800 (30)	1000 (60)	1000 (110)	900 (120)	900 (50)	800 (40)
	Container	800 (NA)	900 (NA)	800 (70)	1600 (NA)	700 (50)	1000 (40)

Deficiency range	800-1000 $\mu g\ g^{-1}$	(Ballard & Carter 1986)
Deficiency threshold	1600 $\mu g\ g^{-1}$	(Walker & Gessel 1991)

Foliar potassium

After two plantation seasons, foliar potassium levels (Table 3) were below deficiency thresholds in all treatment and seedling groups. Foliar potassium concentrations are deficient at levels below 6000 and 7000 $\mu g\ g^{-1}$, according to Walker and Gessel (1991) and Ballard and Carter (1986), respectively. The samples ranged from 4500 – 5600 $\mu g\ g^{-1}$, with an overall average foliar concentration of potassium of 5000 $\mu g\ g^{-1}$. There were no significant differences between the treatments or seedling types, but the container seedlings showed higher concentrations in all treatments.

After three growing seasons, seedlings had potassium concentrations that ranged from 6400 – 7700 µg g^{-1}. There was a significant treatment-fertilizer interaction ($p = 0.057$) but no clear trends in potassium with either treatment or fertilizer overall. Foliar potassium increased after fertilization in the FRA treatment and decreased in the Control and FRA+Ash treatments. The unfertilized container seedlings in the FRA+Ash treatment had the highest levels. Several groups had concentrations closer to deficiencies, but overall, the samples did not appear to be deficient. Container seedlings had higher potassium concentrations in all treatment groups.

The new seedlings planted in 2012 had a wide range of foliar potassium concentrations, from 4500 – 8600 µg g^{-1}. Three of the treatment groups had levels above the thresholds for deficiency. Foliar potassium was higher in the container seedlings compared to the bareroot seedlings across all treatments. In most cases, fertilized seedlings had higher foliar potassium concentrations; the fertilized FRA+Ash container seedlings had the highest levels overall.

Table 3. Seedling foliar potassium by plantation age and seedling type for each reclamation treatment. Fertilizer was applied at the start of the growing season and foliage collected at the end of the growing season. Control is the standard mine reclamation technique, FRA is the modified Forestry Reclamation Approach, and FRA+Ash is the modified Forestry Reclamation Approach with an addition of bottom ash from the on-site coal burning power plant. The seedlings are either bareroot or container Douglas-fir stock, and are unfertilized (No-F) or fertilized (Fert). Seedlings planted in 2010 had complete mortality across several Control and FRA plots, and statistical analyses were not completed. Deficiency levels given by Ballard and Carter (1986) are considered the range for slight to moderate deficiency in Douglas-fir, whereas Walker and Gessel (1991) provide a single value for the level at which deficiency symptoms appear in Douglas-fir seedlings.

Potassium							
Plantation Age	Seedling	Treatment					
		Control		FRA		FRA+Ash	
		No-F	Fert	No-F	Fert	No-F	Fert
		µg g^{-1} (SE)					
2	Bareroot	4500 (410)		4800 (370)		4700 (200)	
	Container	5200 (700)		5600 (810)		5200 (620)	
3	Bareroot	6500 (110)	6500 (450)	6600 (330)	7000 (360)	6800 (440)	6400 (200)
	Container	7100 (440)	7000 (240)	6700 (170)	7100 (270)	7700 (540)	6800 (850)
1	Bareroot	4500 (400)	4900 (730)	5100 (340)	5300 (880)	6000 (420)	4800 (530)
	Container	6100 (NA)	6500 (NA)	7400 (650)	7700 (NA)	6100 (1060)	8600 (3390)

Deficiency range	3500-7500 µg g^{-1}	(Ballard & Carter 1986)
Deficiency threshold	6000 µg g^{-1}	(Walker & Gessel 1991)

Foliar sulfur

After the second plantation season, seedling foliar sulfur (Table 4) was low in all treatments and stock types, ranging from 1600 – 2800 µg g^{-1}. Foliar sulfur concentrations below 3500 µg g^{-1} are considered deficient by Walker and Gessel (1991). The sulfur content differed significantly between seedling types ($p = 0.033$), with the bareroot seedlings having an average of 1700 µg g^{-1} compared to 2500 µg g^{-1} for the container seedlings.

After the third growing season, seedlings had sulfur concentrations between 1300 – 2100 μg g^{-1}, and were deficient in all treatment combinations. There were significant effects from both seedling type and treatment-seedling interaction ($p = 0.030$, 0.086, respectively). In all but one instance, the container seedlings had higher sulfur content than the bareroot seedlings. The container seedlings in the FRA plot had especially high sulfur content compared to the bareroot stock. There was no change in foliar sulfur with respect to the application of fertilizer.

The seedlings planted in 2012 and sampled after one growing season had a wide range of sulfur concentrations, from 1500 – 4100 μg g^{-1}. Two of the twelve samples were above the threshold considered deficient. The container seedlings had higher foliar sulfur in all cases except one, where they were the same. The highest concentrations were found in the fertilized FRA container seedling group. There was no clear trend from fertilization, with some groups showing increased levels of foliar sulfur and some showing decreased levels. The newly planted seedlings had higher foliar sulfur concentrations than the seedlings that had survived on site for at least two seasons.

Table 4. Seedling foliar sulfur by plantation age and seedling type for each reclamation treatment. Fertilizer was applied at the start of the growing season and foliage collected at the end of the growing season. Control is the standard mine reclamation technique, FRA is the modified Forestry Reclamation Approach, and FRA+Ash is the modified Forestry Reclamation Approach with an addition of bottom ash from the on-site coal burning power plant. The seedlings are either bareroot or container Douglas-fir stock, and are unfertilized (No-F) or fertilized (Fert). Seedlings planted in 2010 had complete mortality across several Control and FRA plots, and statistical analyses were not completed. Deficiency levels given by Ballard and Carter (1986) are considered the range for slight to moderate deficiency in Douglas-fir, whereas Walker and Gessel (1991) provide a single value for the level at which deficiency symptoms appear in Douglas-fir seedlings.

		Sulfur					
Plantation Age	Seedling	Treatment					
		Control		FRA		FRA+Ash	
		No-F	Fert	No-F	Fert	No-F	Fert
		---------- $\mu g\ g^{-1}$ (SE) ----------					
2	Bareroot	1700 (310)		1800 (90)		1600 (160)	
	Container	2200 (360)		2800 (600)		2600 (550)	
3	Bareroot	1500 (100)	1600 (130)	1300 (100)	1400 (200)	1600 (230)	1400 (170)
	Container	1600 (60)	1400 (190)	2000 (200)	2100 (130)	1800 (340)	1700 (490)
1	Bareroot	2200 (150)	1500 (240)	1800 (140)	1700 (100)	2100 (350)	1700 (500)
	Container	3300 (NA)	2300 (NA)	3700 (950)	4100 (NA)	2100 (560)	3000 (1650)

Deficiency range	NA	(Ballard & Carter 1986)
Deficiency threshold	3500 $\mu g\ g^{-1}$	(Walker & Gessel 1991)

Foliar calcium

After two growing seasons, foliar calcium concentration (Table 5) was below deficiency levels for all treatment and seedling types. The foliar calcium deficiency levels given by Ballard and Carter (1986) and Walker and Gessel (1991) are 2000 and 2500 $\mu g\ g^{-1}$, respectively. The samples ranged from 1400 – 2400 $\mu g\ g^{-1}$, with the container seedlings having higher foliar calcium in all treatments. The difference between seedling types was significant ($p = 0.035$), with the bareroot seedlings having an average of 1700 µg g^{-1} versus 2200 µg g^{-1} for the container seedlings.

After the third growing season, seedlings had deficient levels of foliar calcium in all treatment groups, ranging from 1600 – 2200 µg g^{-1}. There were significant effects of treatment-fertilizer interaction ($p = 0.054$) and treatment-seedling-fertilizer interaction ($p = 0.025$). Seedlings in the FRA+Ash treatment had increased foliar calcium after fertilization, whereas the Control and FRA treatments showed mixed results. The fertilized FRA+Ash container seedlings had the highest foliar calcium concentration.

The seedlings planted in 2012 ranged in foliar calcium concentration from 1300 – 3100 µg g^{-1} with the majority of the treatment groups under the deficiency threshold. There did not appear to be much difference in foliar calcium between the seedling types, as bareroot seedlings were higher than container under some conditions, and reversed under others. The fertilized FRA+Ash container seedlings had the highest concentration of calcium. There was a mixed response to fertilizer among the treatment groups.

Table 5. Seedling foliar calcium by plantation age and seedling type for each reclamation treatment. Fertilizer was applied at the start of the growing season and foliage collected at the end of the growing season. Control is the standard mine reclamation technique, FRA is the modified Forestry Reclamation Approach, and FRA+Ash is the modified Forestry Reclamation Approach with an addition of bottom ash from the on-site coal burning power plant. The seedlings are either bareroot or container Douglas-fir stock, and are unfertilized (No-F) or fertilized (Fert). Seedlings planted in 2010 had complete mortality across several Control and FRA plots, and statistical analyses were not completed. Deficiency levels given by Ballard and Carter (1986) are considered the range for slight to moderate deficiency in Douglas-fir, whereas Walker and Gessel (1991) provide a single value for the level at which deficiency symptoms appear in Douglas-fir seedlings.

Calcium							
Plantation Age	Seedling	Treatment					
		Control		FRA		FRA+Ash	
		No-F	Fert	No-F	Fert	No-F	Fert
		------ $\mu g\ g^{-1}$ (SE) ------					
2	Bareroot	1400 (110)		2100 (290)		1600 (250)	
	Container	2100 (430)		2200 (110)		2400 (120)	
3	Bareroot	1600 (190)	1900 (80)	2000 (280)	1700 (150)	1700 (150)	1900 (250)
	Container	2000 (60)	1600 (150)	1800 (220)	1900 (140)	1800 (30)	2200 (100)
1	Bareroot	2000 (630)	1600 (130)	1500 (240)	2500 (190)	2100 (250)	2000 (50)
	Container	2800 (NA)	1300 (NA)	2000 (100)	2700 (NA)	1700 (110)	3100 (20)

Deficiency range	1500-2000 $\mu g\ g^{-1}$	(Ballard & Carter 1986)
Deficiency threshold	2500 $\mu g\ g^{-1}$	(Walker & Gessel 1991)

Foliar magnesium

Seedling foliar magnesium (Table 6) ranged from 1100 – 1300 $\mu g\ g^{-1}$ in the samples taken two growing seasons after planting, and were marginally deficient. Concentrations of foliar magnesium below 1000 and 1700 $\mu g\ g^{-}1$ are considered deficient by Ballard and Carter (1986) and Walker and Gessel (1991), respectively. There were no significant differences in foliar magnesium between treatment or seedling types, and the average magnesium content was 1200 $\mu g\ g^{-1}$. No magnesium fertilizer was applied.

After three plantation years, seedling foliar magnesium ranged from 700 – 1000 µg g^{-1}, deficient in all treatment and seedling combinations. There was a significant treatment-seedling-fertilizer interaction ($p = 0.007$), indicating that, although the fertilizer did not contain magnesium, the application of other nutrients affected foliar magnesium concentrations. The fertilized container seedlings in the Control treatment had the lowest magnesium concentration. However, the main effect of fertilizer on magnesium concentration was not significant and showed mixed responses. Several treatment groups had higher magnesium concentrations in the bareroot seedlings compared to the container stock.

The seedlings sampled in 2012, one growing season after planting, had magnesium concentrations ranging from 700 – 2000 µg g^{-1}. Most of the samples were under deficiency thresholds. In most cases, the container seedlings had higher magnesium concentrations than the bareroot seedlings.

Table 6. Seedling foliar magnesium by plantation age and seedling type for each reclamation treatment. Fertilizer was applied at the start of the growing season and foliage collected at the end of the growing season. Control is the standard mine reclamation technique, FRA is the modified Forestry Reclamation Approach, and FRA+Ash is the modified Forestry Reclamation Approach with an addition of bottom ash from the on-site coal burning power plant. The seedlings are either bareroot or container Douglas-fir stock, and are unfertilized (No-F) or fertilized (Fert). Seedlings planted in 2010 had complete mortality across several Control and FRA plots, and statistical analyses were not completed. Deficiency levels given by Ballard and Carter (1986) are considered the range for slight to moderate deficiency in Douglas-fir, whereas Walker and Gessel (1991) provide a single value for the level at which deficiency symptoms appear in Douglas-fir seedlings.

Magnesium							
Plantation Age	Seedling	Treatment					
		Control		FRA		FRA+Ash	
		No-F	Fert	No-F	Fert	No-F	Fert
		---------- $\mu g\ g^{-1}$ (SE) ----------					
2	Bareroot	1100 (100)		1200 (120)		1100 (50)	
	Container	1100 (90)		1300 (80)		1300 (90)	
3	Bareroot	1000 (70)	1000 (90)	1000 (80)	800 (70)	900 (40)	1000 (60)
	Container	1000 (60)	700 (50)	800 (50)	900 (70)	900 (20)	900 (50)
1	Bareroot	1100 (390)	900 (70)	1000 (100)	1200 (170)	1200 (120)	1100 (30)
	Container	1400 (NA)	700 (NA)	1500 (120)	2000 (NA)	1100 (70)	1300 (390)

Deficiency range	600-1000 $\mu g\ g^{-1}$	(Ballard & Carter 1986)
Deficiency threshold	1700 $\mu g\ g^{-1}$	(Walker & Gessel 1991)

Seedling growth

The annual height increment during the third growing season for the seedlings planted in 2010 ranged from 13 – 26.3 cm (Figure 1). The overall average growth was 14.8 cm, and there was a significant effect from reclamation treatment (p = 0.027). The seedlings in the FRA treatment had higher growth than both the Control and FRA+Ash treatments. There were no significant differences by seedling type or fertilizer application.

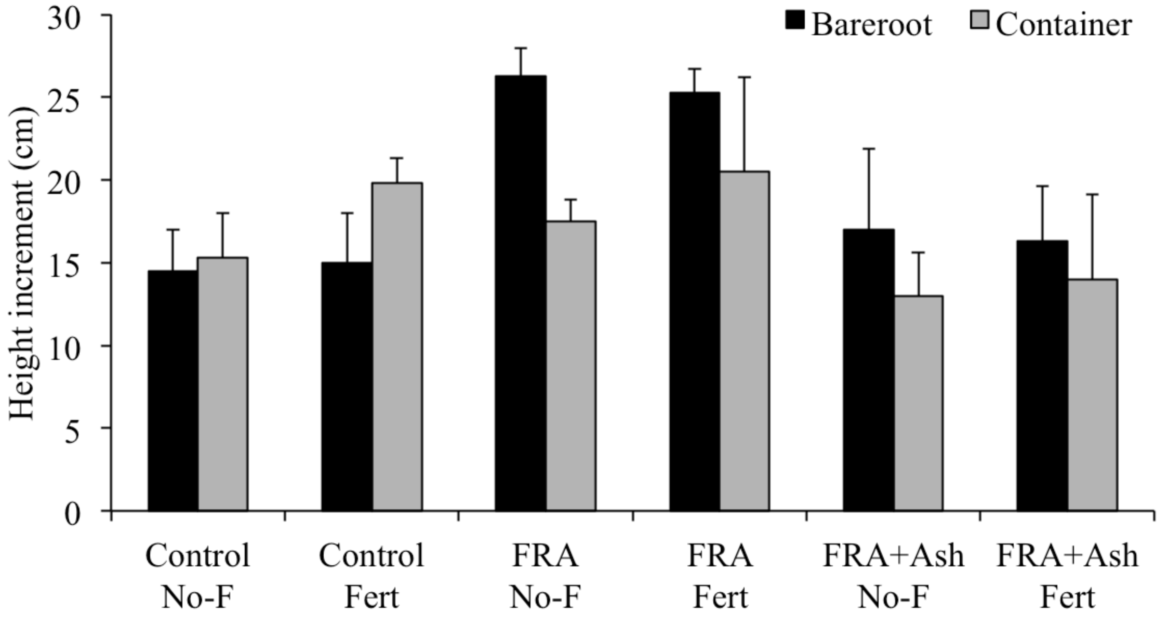

Figure 1. Mean seedling height increment with standard error during the third growing season for the seedlings planted in 2010. Fertilizer was applied at the start of the growing season and foliage collection at the end of the growing season. Control is the standard mine reclamation technique, FRA is the modified Forestry Reclamation Approach, and FRA+Ash is the modified Forestry Reclamation Approach with an addition of bottom ash from the on-site coal burning power plant. The seedlings are either bareroot or container Douglas-fir stock, and are unfertilized (No-F) or fertilized (Fert).

Seedling survival

In the third plantation year, 58% – 88% of the seedlings marked for sampling survived at the end of the growing season, with an average of 71% (Table 7). Generally, the bareroot seedlings had higher survival than the container seedlings. There was lower carryover of surviving seedlings in the fertilized groups compared to the unfertilized groups.

The seedling survival measurements taken at the end of the 2012 growing season showed high rates of mortality among the newly planted seedlings. For the seedlings planted in the spring of 2012, the average survival through the first growing season in the field was 24%. Survival was almost always higher in the bareroot seedlings compared to the container stock across all treatment groups. Fertilized seedlings had lower rates of survival than the unfertilized groups in many cases.

Table 7. Mean seedling survival with standard error following one growing season (2012), when fertilizer application occurred. Fertilizer was applied at the start of the growing season and survival measured during foliage collected at the end of the growing season. Control is the standard mine reclamation technique, FRA is the modified Forestry Reclamation Approach, and FRA+Ash is the modified Forestry Reclamation Approach with an addition of bottom ash from the on-site coal burning power plant. The seedlings are either bareroot or container Douglas-fir stock, and are unfertilized (No-F) or fertilized (Fert).

Survival following one growing season (2012)

Plantation Age	Seedling	Treatment					
		Control		FRA		FRA+Ash	
		No-F	Fert	No-F	Fert	No-F	Fert
		------------------------------- % (SE) -------------------------------					
1	Bareroot	13 (8)	38 (13)	29 (4)	13 (8)	54 (17)	50 (18)
	Container	4 (4)	4 (4)	29 (4)	4 (4)	33 (18)	17 (12)
3	Bareroot	88 (13)	79 (13)	88 (8)	75 (11)	79 (8)	58 (5)
	Container	63 (8)	63 (4)	58 (5)	79 (4)	79 (8)	46 (10)

Precipitation

Precipitation during 2012 was compared with the thirty-year average 1980-2009 using data collected at the mine since 1971 (Table 8). We calculated the mean and standard deviation for each month over the 30-year period and standardized the monthly precipitation for the two growing seasons against their corresponding climatic averages. The growing season in the Pacific Northwest for conifers is approximately March through August.

Table 8. Monthly precipitation for 2012, including average from 1980-2009 from data collected at the mine.

	Precipitation											
Year	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	------- cm -------											
1980-2009	18	12	13	10	7	5	2	3	5	11	21	18
2012	17	17	24	13	7	6	2	0	0	19	25	28

The region underwent a substantial drought at the end of the growing season in 2012. July through September was especially dry, with 2 cm of precipitation on record. When the new seedlings were planted in the spring, there was relatively high precipitation compared to the climatic average (Figure 2). Between July and seedling sampling in the fall, there was extremely little rainfall.

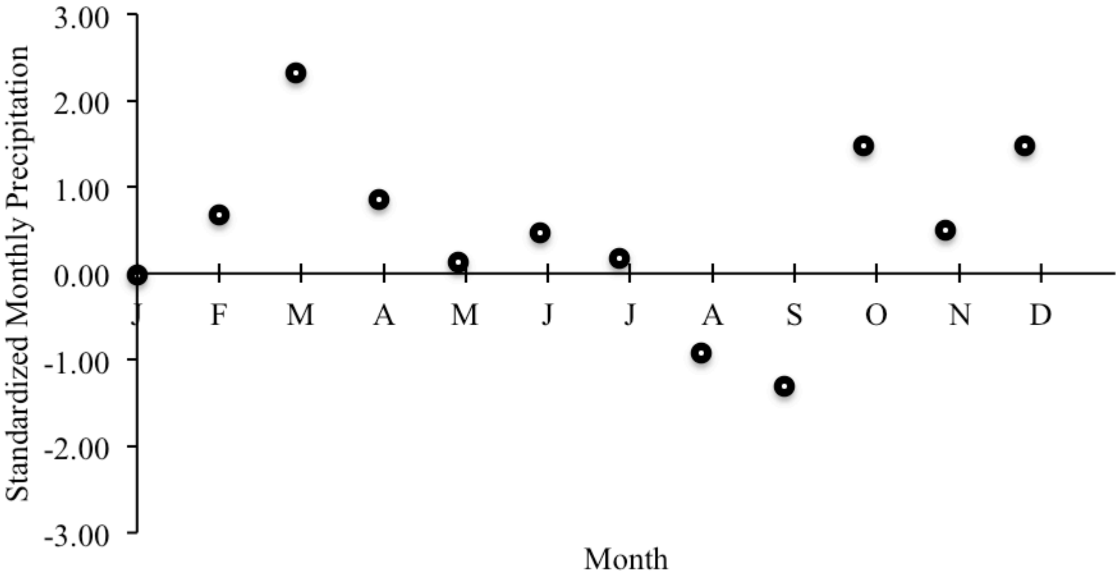

Figure 2. Standardized monthly precipitation for 2012 based on the climatic average (1980-2009) from data collected at the mine.

Discussion

The prolonged drought during our study had a large effect on our results, with many of the newly planted seedlings dying from desiccation in the first year. Additionally, the treatment plots were more heavily covered with understory species at the time of re-planting than the initial site conditions (Miller et al. 2013). The combined effects of drought and understory competition appeared to be the main limitations to seedling establishment. There was no indication that the fertilizer applications improved seedling survival in the first year after planting under these conditions. This agrees with previous studies that have found fertilizing seedlings at the time of planting can impact seedling survival (Roth & Newton 1996, Brockley 1998). Jacobs et al. (2004) suggest that fertilization might limit the need for root expansion when nutrients are readily available by decreasing the need for new root growth to extract soil nutrients. However, Friend et al. (1990) find that Douglas-fir seedlings showed increased root proliferation in high nitrogen microenvironments when subjected to limited nitrogen resources overall. Restrictions to root growth may lead to lower drought tolerance in the seedlings. Additionally, the increased competition from the fertilized understory might contribute to soil water depletion and water stress in the seedlings (Roth & Newton 1996).

Although Douglas-fir has shown a response in growth after fertilization during the first year after planting (van den Driessche 1988), the potential response was likely masked by the drought in our study. Seedlings need adequate soil moisture to show positive responses to fertilization. Warm, dry weather after planting can have a negative impact on seedling survival (Brockley 1988). Under such conditions, seedlings may experience increased water stress and decreased drought tolerance. Many natural resource managers are reluctant to fertilize at planting either because of cost efficiency or concerns over impacts on seedling survival (Walker 2005).

The higher survival of the bareroot seedlings relative to the container was likely due to the fact that the bareroot seedlings had bigger root systems at planting. A study by van den Driessche (1991a) found a small correlation between seedling size and height after planting, with the difference becoming more pronounced after several years. Grossnickle (2005) suggests that seedlings with larger root systems may be able to avoid planting stress better due to a superior ability to take up water.

The increased foliar nitrogen concentrations after fertilization are in accordance with previous studies of outplanted seedlings. A study by van den Driessche (1988) found slightly higher foliar nitrogen concentrations in fertilized Douglas-fir seedlings than in control seedlings in the first year after planting with larger responses showing up three to four years after planting. Roth and Newton (1996) found that fertilized seedlings had increased nitrogen concentration in the first year after planting. We found a slight increase in phosphorus concentrations, which Roth and Newton (1996) did not see. Walker (2005) found increased foliar phosphorus in juvenile Jeffrey pine after fertilizing, with calcium and sulfur being reduced. We found no response to calcium or sulfur and a mixed response to potassium. There was adequate precipitation to allow for nutrient uptake early in the growing season, but the extreme drought during August and September impacted the effectiveness of fertilization. Furthermore, the newly planted seedlings likely experienced delayed access to the added nutrients while reestablishing root to soil contact.

Conclusions

Managers must weight the cost of fertilizing with the response in seedling performance. In this study, the application of fertilizer happened before an extremely dry growing season. The lack of precipitation, combined with the heavy understory cover, served as strong impediments to seedling survival. The results make it difficult to gauge the potential response of the seedlings during a year without such water limitations. Overall, the results indicate that initial performance of planted seedlings is strongly determined by variations in weather and amount of understory cover. Poor seedling nutrient status may lead to long-term consequences in tree growth, but the most immediate cause of seedling mortality appeared to be desiccation, likely due to the exacerbating effects of drought and competition with understory vegetation. Browsing from elk and deer also contributed to seedling damage during the first years after planting.

Many seedlings were deficient in foliar nutrient concentrations after outplanting. Although survival was often higher in the bareroot seedlings compared to the container seedlings, container seedlings generally fared better for foliar nutrient concentrations. The general responses of seedling foliar nutrient concentrations to fertilization were: increased nitrogen, slightly increased phosphorus, mixed potassium response, and no change in calcium or sulfur. Although we did not fertilize with magnesium, there was some indication the nutrients applied affected seedling foliar magnesium. Seedlings response to the fertilizer application may become more pronounced in subsequent years, especially if there is more rainfall throughout the growing season.

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Conclusions

The main obstructions to seedling establishment during the first several seasons after outplanting of Douglas-fir seedlings appeared to be heavy understory competition and a lack of precipitation during the growing season. The Control plots had the lowest seedling survival and highest understory cover throughout the study. By the third year, however, differences in survival and understory cover were less pronounced between treatments. The understory likely competed for site resources, especially utilizing any available water during the growing season. This seemed to have a considerable impact during the first growing season after planting in the Control treatments. There was no difference in survival between the bareroot and container seedlings in any year, although container seedling survival decreased more over the three growing seasons. The clayey texture of the soils also impacted the hydrology of the site, as evident by myriad cracks during the dry season and saturation during the wet season. Along with elk and deer browsing during the first planting year, relatively low precipitation during the growing season and heavy understory competition were common impediments to seedling establishment.

Seedling foliar nutrients measured during the second growing season showed deficient foliar nitrogen and phosphorus concentrations. An application of fertilizer to seedlings during the third growing season had small affects on seedling foliar nitrogen and phosphorus. The outcome of fertilization on newly planted seedlings was not clear due to extensive seedling mortality over the growing season. Again, heavy understory cover and a lack of precipitation during the growing season confounded the results. There was no indication that fertilization reduced seedling tolerance of understory competition and drought. Additionally, fertilizing at the time of planting is not recommended during drought conditions. However, these results may not be indicative of the potential seedling response to post-planting fertilization during a non-drought year.

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