OSM Applied ScienceFinal Report

Project: **Development of a Modified Forest Reclamation Approach to Establish Coniferous Forest Plantations in the Pacific Northwest**

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INTRODUCTION

Under SMCRA, the reclamation goals for mined land are to “protect society and the environment from the adverse effects of surface coal mining operations” and to “assure that surface coal mining operations are so conducted as to protect the environment.” Thus, reclamation was completed to ensure land stability, minimize erosion and maintain water quality with the hope of returning land to its original capability. These reclamation measures included extensive regrading and planting with continuous grass cover to ensure erosion control (Torbert and Burger 2000, Ashby 1991). In the Appalachian region much of the reclaimed land was designated for grazing, wildlife habitat or unmanaged forest land, however little of this land was actively managed after reclamation and either persisted in aggressive and often invasive grasses or it became low-value forests. While the goals of assuring land stability and limiting erosion were often accomplished, compaction by excessive machinery operation and competition from grasses limited forest growth and restricted the economic value of the land (Casselman et al. 2006). This does not return the land to its original level of capability, which is clearly the ultimate goal.

In 2005, the Office of Surface Mining adopted a new approach in the Appalachian States called the Forest Reclamation Approach (FRA) of the Appalachian Regional Reforestation Initiative (ARRI) (Angel et al. 2005). The ARRI differs from previous reclamation methods in that it focuses on minimizing soil compaction as a critical part of developing productive forests on reclamation lands. The FRA has five basic steps: 1) create a suitable rooting medium for good tree growth that is no less than 4 feet deep and is comprised of topsoil, weathered sandstone and/or the best available material, 2) loosely grade the topsoil or topsoil substitute established in Step 1 to create a non-compacted growth medium, 3) use ground covers that are compatible with growing trees, 4) plant two types of trees-early successional species for wildlife and soil stability and commercially valuable crop trees, and 5) use proper tree planting techniques (Burger et al. 2005).

The methodology of FRA has been tested with research in the Appalachian region and has been shown to be highly effective (Angel et al. 2005, Burger et al. 2005). In particular, avoiding soil compaction allows trees to root more extensively in the new soil material. Providing a suitable substrate for tree growth, regardless of the origin of the material, is clearly more important than meeting specific requirements of previous regulations. The flexibility in the five steps of FRA for meeting final forest growth goals has often been shown to be a more economical way for coal operators to meet regulatory compliance in the region where it has been studied. On the other hand, techniques that include extensive ground preparation and grading with machinery, though often more costly, have not been as successful as the FRA in reestablishing good forest growth (Rodrigue et al. 2002).

Adoption of FRA is growing in the Appalachian coal-mining region, and it seems clear that the basic methodology of FRA might also be proven in other regions that support both coal mining and productive forests. Some coal-mining regions of the U.S. do not naturally support productive forestland (i.e. parts of Montana and Wyoming), but the coal mines around Centralia, Washington previously supported some of the most productive coniferous forests in the world. For instance, the state of Washington has ranked second only to Oregon in U.S. lumber productivity for several decades. It is estimated that 30% of U.S. softwood lumber currently comes from these two states alone (Howard, 2003). This high productivity is a result of numerous factors, including tree genetics and site factors such as soil and climate. Reclamation of coal mine land in this productive timber region should attempt to restore highly productive growth.

Soils in the Centralia mine area were predominantly fine-loamy, mixed, superactive, mesic Xeric Palehumults developed in residuum and colluvium of weathered sandstone, siltstone and shale (Soil Survey Staff 1987). The mine area is still surrounded by patches of the two prevalent soil series, the Centralia loam and Buckpeak silt loam. These two soil types are both productive forest soils with deep A horizons with 3-8% organic matter, deep Bt horizons and a site index of 135 (135ft height growth at 50 years). These soils are some of the most productive forest soils mapped in LewisCounty. Ideally, effective reclamation would return soils to this level of productivity.

Since the climate of the region continues to support highly-productive forests, and productive forestland surrounds the mining site, the Centralia mine area is a perfect test ground for the application of region-specific FRA techniques for restoring soil productivity. Clearly, the Appalachian region differs from the Pacific Northwest and the Centralia mine site in many ways that impact tree growth. The climate of Centralia, Washington, for instance, is maritime, with cool, rainy winters and warm, dry summers. The average annual total precipitation is 48.9 inches per year. The regional climate of the FRA sites in the Appalachian region vary, but are characterized by cool to cold winters and warm or hot summers with a more even distribution of precipitation. For example, the average annual precipitation at Blacksburg, Virginia is 42.6 inches per year, very similar to Centralia at 48.9 inches. However, July has the highest annual precipitation in Blacksburg with 4.2 inches and December the lowest with 2.9 inches, whereas Centralia has the highest in December with 7.6 inches and lowest in July with 0.9 inches (SERCC, 2008; WRCC 2008).

These climatic differences have major impacts on when and how forests can be established and how they grow. The evergreen coniferous forests of the PNW largely escaped being decimated during the Pleistocene glaciation, and now dominate the region's forests. Coniferous traits offer advantages in the PNW climate since photosynthesis and nutrient uptake and storage can occur during the relatively warm and wet fall and winter months, while high demand for water during the warm, dry summer limits photosynthesis. Northwestern deciduous tree species, which have no green foliage during the late fall and winter, are more limited since much of the time period that they carry foliage is dry, limiting photosynthesis. In both cases, dry summers can result in difficulty in establishment of tree seedlings.

Succession of Appalachian vs. PNW forests is also often different. Douglas-fir seedlings often establish strongly after disturbance and can dominate early succession and continue to dominate a site's biomass for hundreds of years. The long life and vigor of Douglas-fir trees assures that most forests of the PNW do not reach the climax forest stages that Appalachian forests often do before disturbance renews the cycle. It is possible, for instance, because of the unique characteristics of the region's forests, that Douglas-fir might be planted initially, without the need for multiple, successional species of trees.

This research tested a modified version of the Forest Reclamation Approach (FRA) that has been successfully used in the Appalachian region for reforestation following surface coal mining operations. The overall objective of the project was to reestablish Douglas-fir plantations on reclaimed land that would approach productivity of the original forested lands.

The original FRA has five basic steps: 1) create a suitable rooting medium for good tree growth that is no less than 4 feet deep and comprised of topsoil, weathered sandstone or best available material, 2) loosely grade the topsoil or topsoil substitute established in Step 1 to create a non-compacted growth medium, 3) use ground covers that are compatible with growing trees, 4) plant two types of trees – nurse trees and commercial crop trees, and 5) use proper tree planting techniques. Modifications to the FRA that were investigated are intended to adapt it to western Washington's climate and coniferous ecosystem. This project modified but basically applies this method to coniferous western forests. Three treatments were examined, the modified FRA, the modified FRA with an amendment of bottom ash, and the standard reclamation approach used at the Centralia TransAlta Mine. In addition to examining current reclamation treatments, past reclamation efforts will be examined using a chronosequence approach. The overall goal of the project is to determine the effectiveness of a modified FRA approach for coniferous western forest ecosystems.

MATERIALS AND METHODS

Site Description

The Centralia Mine Site is located approximately 10 km northeast of the city of Centralia, WA in Lewis and Thurston County. Centralia is located within the southern Puget Sound Lowlands and receives approximately 114 cm of annual rainfall (WRCC, 2010). Of this, 30 cm (28 percent) of the precipitation falls between April and September (Evans &Fibich, 1987). Weather in this area is mild with warm summers, light precipitation, and occasional hot days; winters are cool with frequent rainfall and occasional snow and freezing temperatures. The annual maximum and minimum air temperatures are 16.6°C and 5.4°C, respectively. Logging and farming were the major industries in the area since settlement, and revenues from timber cutting in Lewis County were often higher than those of any other county in Washington (Evans &Fibich, 1987). Historically, undisturbed soils in the area were primarily the Centralia Series or Buckpeak Series, which are productive soils for forests

TransAlta Centralia Mining, LLC purchased the Centralia Mine in May of 2000. The mine is a sub-bituminous surface coalmine, and commercial operations began on-site in 1971. The mine supplied coal to TransAlta's Centralia Coal Plant until November 2006, when active mining operations ended and TransAlta began to focus on reclamation of the entire mine site (TransAlta, 2009). As a result of halting mining operations, the Centralia Coal Plant, which supplies ten percent of Washington State's power, currently burns coal delivered by train from the Powder River Basin, a region encompassing southeastern Montana and northeastern Wyoming (TransAlta, 2011).

The study site is located within the boundaries of the Centralia Mine. It is referred to as the Pit 7 spoils, in an area known as the 570 lift (Section 4, Township 14 North, Range 1 West). The Centralia Mine encompasses 5,666 hectares, with the boundaries of the study site encompassing 16 hectares. A map of the study site is shown in Figure 1. The plots are located on all aspects of a hill, the peak of which is located in the center of the site. Slopes vary across the site, ranging from approximately 3 to 12%. The site has been revegetated with grasses and herbaceous plants.

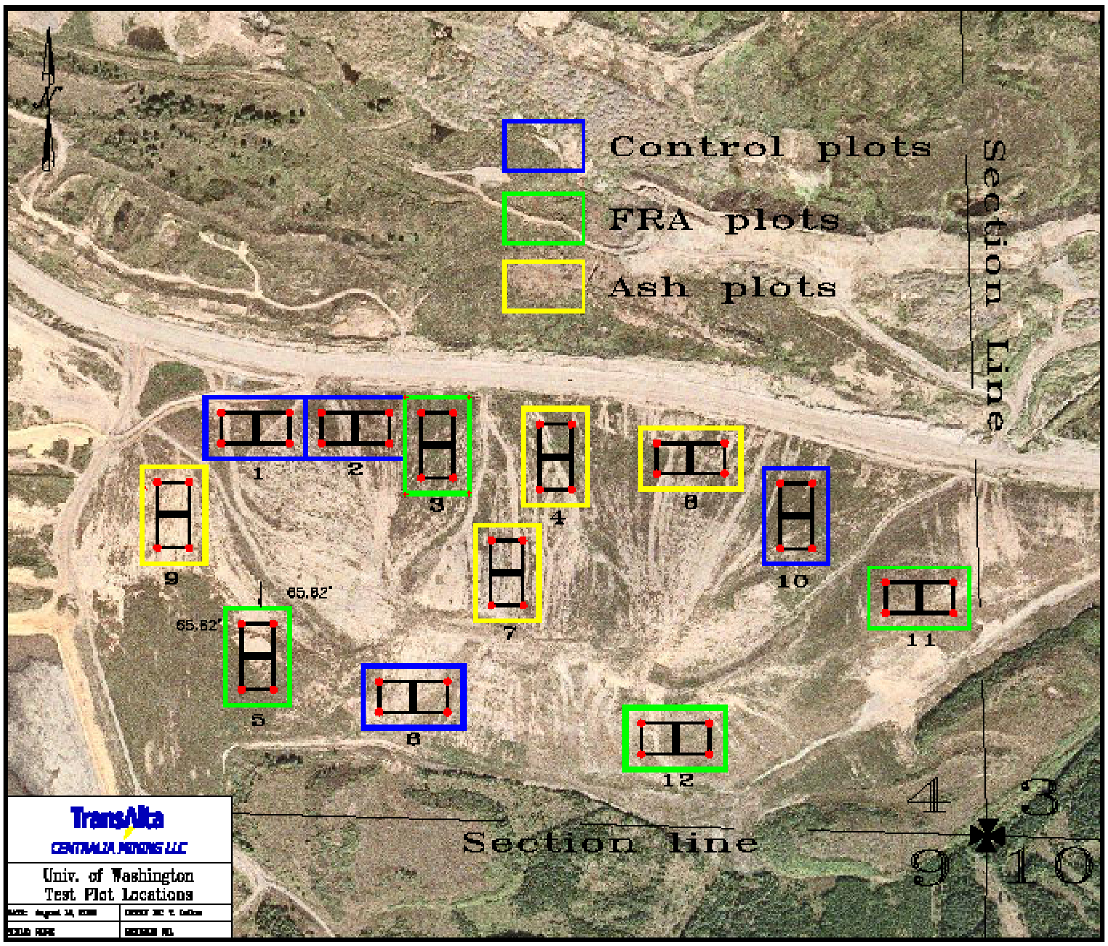

Figure 1. Map of the research site, located on TransAlta Centralia Mine Lift 570 near Centralia, Washington. Control plots are outlined in blue, FRA in green and FRA+ash in yellow.

Study Site Preparation

The spoils near the study site were re-graded to their current configuration during the summer of 2006 with D-7 and D-10 Caterpillar bulldozers. Caterpillar 235 excavators were also used to help mix material (T. LeDuc, personal communication, 2010). Twelve treatment plots were established randomly within the boundaries of the study site. During September and October of 2009, three site preparation treatments were randomly assigned to plots. Treatments consist of: a Control, a modified FRA (referred to as FRA in this study), and FRA+ash (modified FRA plus application of bottom ash).

Control plots were prepared using the standard reclamation grading practice historically used at the Centralia mine. Stockpiled soil or waste overburden was applied using the equipment described above. Ripping, a standard preparation method on-site, loosens pre-existing compaction for planting and was completed with small-to-medium size D5 to D7 class dozers. The ripper blades were 61-75cm and spacing was 10 feet or approximately 300 cm.

The modified FRA treatment is based on the FRA's five basic steps with slight modifications:

1. Create a suitable rooting medium for good tree growth that is no less than four feet deep and comprised of topsoil, weathered sandstone or the best available material (no modifications to original method, best available material or subsurface soil was used rather than topsoil).
2. Loosely grade the topsoil established in Step 1 to create a non-compacted growth medium. <u>Modification:</u> Due to larger dump trucks available on-site than those used in the Appalachian region, if soil mounds produced are too high they will be slightly pressed with the front of the dozers to obtain four-foot mounds.
3. Use ground covers including annual rye grass and lupine (*LupinusalbicaulisDougl.)* that are compatible with growing trees. <u>Modification:</u> Groundcover species listed above are native to Washington State, however control plots were seeded with the standard reclamation mix prior to the start of this project.
4. Plant two types of trees – early successional species for wildlife and soil stability, and commercially valuable crop trees. <u>Modification</u>: Plant only Douglas-fir as it is both an early successional species and a commercially valuable species in the region.
5. Use proper tree planting techniques (no modifications to the original method).

The FRA+ash treatments followed the same procedure as listed above for the FRA treatment. However, bottom ash was incorporated as part of the rooting medium. The ash is a byproduct of the coal-burning process and was collected from the Centralia Coal Plant. Characteristics of the ash are listed in Table 1. To apply bottom ash on each FRA+ash plot, 30-yard articulating dump trucks were used. A total of 254 m^3 (an average depth of 2.54 cm mixed in over the 1 hectare site) was dumped and spread on the plots during grading with the dozers mentioned. In October of 2009, it was decided to rotate FRA+ash Plot 4 to avoid a runoff gully through the plot area. Actual construction of this plot included a 90 degree rotation and was not completed until one week prior to seedling planting in March of 2010.

Table 1. Bottom ash pH, and total concentrations of some elements. Data from Columbia Analytical Services, INC Analytical Report, completed 12 Sept. 2008.

Characteristic	Value
pH	9.87
Sulfate	491 mg Kg^{-1}
Nitrite + Nitrate Nitrogen	1 mg Kg^{-1}
Total Phosphorus	121 mg Kg^{-1}
Potassium	2150 mg Kg^{-1}
Manganese	172 mg Kg^{-1}
Nickel	9.9 mg Kg^{-1}
Aluminum	19300 mg Kg^{-1}
Cadmium	.09 mg Kg^{-1}
Calcium	18700 mg Kg^{-1}
Copper	15.8 mg Kg^{-1}
Lead	2.04 mg Kg^{-1}
Zinc	15.2 mg Kg^{-1}

Experimental Design

Plots were surveyed using a GPS, meter tape and a compass to ensure plot area accuracy. Each treatment plot is 1 hectare with a 20 m treatment buffer encompassing two 40 m x 40 m measurement plots. Within each treatment plot, standard 1+1 stock type Douglas-fir seedlings (bare root) were planted in one of two measurement plots. In the second plot, "plug 15" Douglas-fir seedlings (containerized) from the Washington State Department of Natural Resources Webster Nursery were planted (R. Harrison, personal communication, 2011). Figure 2.3 provides a schematic of the plot setup. Following plot installation, seedling planting spots were established with pin flags to ensure consistent density of the container seedlings. Container seedlings were planted at a density of 1800 trees per hectare (729 trees per acre), and bare root seedlings were planted at a density of 1200 trees per hectare (485 trees per acre). Three 10m x 10m subplots were randomly located within each seedling plot for seedling vegetation measurements within each of the twelve 1 hectare treatment plots.

Soil

Sampling

Three soil sampling locations within each treatment plot were randomly located adjacent to three of the vegetation subplots. All pits were excavated to a depth of 50cm. Mineral samples were collected for chemical analyses from the following depths: 0-5cm, 5-15cm and 15-50cm, for a total of 108 samples (twelve plots, three soil sample locations within each plot, three depths per location). Bulk density samples (D_b) were also taken from each depth using a bulk density corer (two-ring method) for a total of 108 samples. Samples were stored at 3°C until chemical analysis. Plots were sampled in late spring and early summer of 2010.

Classification

In the spring of 2010, a soil pit was excavated to classify the soils near Plot 1. The soil was described using the USDA Soil Taxonomy sheet. The soil was keyed as TypicEndoaquent using the 2010 Keys to Soil Taxonomy (Soil Survey Staff, 2010). This is primarily due to aquic conditions present in the upper 50cm of the profile. The profile can be seen in Figure 2, with the profile description is Table 2. The soil was on a North-facing slope (0-5%) at the bottom of a side slope. The parent material was determined to be mine overburden, but remnants of old clay from the previous soil and fragments of fossil shells and saprolite were evident throughout the profile. Due to the variability of the site and differences in observed soil water saturation, it is likely that a profile excavated from a position higher up the hill would classify as a HaplicXerarent. This is due to fragments of diagnostic horizons (former A and Bt horizons), the xeric moisture regime, and a lack of other distinguishing key characteristics.

Soil Analysis

Soil chemical samples were prepared for analysis by air-drying for one week and subsequently sieving samples to 2mm. Unless stated otherwise, soil analyses were performed in accordance with Methods of Soil Analysis (Page et al, 1982). With the exception of cation exchange capacity (CEC), and percent base saturation (%BS), samples from each depth of each subplot were analyzed on the <2mm fraction individually. For CEC and %BS analysis, samples were composited by treatment plot but remained separated by depth for a total of 36 samples, plus quality control replicates. Moisture correction for air-dried samples was determined and used if air-dry moisture content exceeded 3 %.

Figure 2. A soil profile excavated on Plot 1 classified as a TypicEndoaquent. The parent material is mine overburden. The soils have formed on a North-facing slope (0-5%). There are mottles and evidence of gleying throughout the profile as well as fragments of clay formed in older soil, fossils of shells, and saprolite.

Table 2. Profile description of a soil from Plot 1 used for classification. The parent material was determined to be overburden. Soil is located on a North-facing side-slope of approximately 0-5% slope. Evidence of clay from older soil, saprolite, coal excavation remnants and the presence of fossil shells occur as fragments throughout the profile. Soil was classified as a TypicEndoaquent.

Horizon	Depth	Description
^A	0-14 cm	Dark brown (10YR 3/3) clay loam, 7% light brownish gray (10YR 6/2) mottles and very dark brown (10 YR 2/2) mottles; firm medium blocky structure; many fine roots; neutral (pH 6.6); clear, smooth boundary.
^C1	14-35 cm	Very dark grayish brown (10YR 3/2) clay loam, 10% brownish yellow (10 YR 6/8) and very dark brown (10YR 2/2) mottles; firm medium blocky structure; presence of crumbling saprolite; neutral (pH 6.5); clear, smooth boundary.
^Cg2	35-48 cm	Dark brown (10YR 3/3) clay loam; 10% yellow (10YR 7/8) and very dark brown (10YR 2/2) mottles; firm; medium course blocky structure; presence of crumbling saprolite; strongly acidic (pH 5.4); clear, smooth boundary.
^Cg3	48-57+ cm	50 % dark brown (10YR 3/3) clay loam, 50 % very dark brown (10YR2/2),with 10% yellow (10 YR 7/8) mottles; firm; medium Sub-angular blocky structure; presence of crumbling saprolite; strongly acidic (pH 5.9).

Bulk Density

Bulk density of the samples was determined by using a 137.4 cm^3 corer to collect samples and oven-drying samples at 105°C for 72 hours. A few samples were collected using a 68.7 cm^3 core due to sampling difficulty. Dry weight was recorded and data was entered into the standard bulk density equation.

pH and Electrical Conductivity

Soil pH was measured in the lab using a Denver Instrument Model 220 pH meter. Samples were prepared using a 2ml-to-1g ratio of de-ionized water to air-dried, sieved soils. After allowing 30 minutes for samples to equilibrate after stirring, the pH was recorded. These samples were kept at approximately 21°C. Electrical conductivity (EC) was measured using the same samples as prepared for pH. After pH was recorded, the samples were allowed to settle 12 hours before EC of the solution was measured. An Orion Conductivity Salinity Meter Model 140 was used to collect measurements of EC.

Acid-Base Neutralization Potential

The soil neutralization potential was determined using the EPA-SOBEK method (Sobek, 1978). As no ascarite tube was available to store carbon dioxide-free water, the method was slightly modified by preparing multiple batches of water to limit contamination by carbon dioxide. Samples were acidified using 0.1 N HCl and titrated using 0.1N NaOH if the effervescent rating was determined to be none or slight, and samples with moderate or strong effervescent ratings were acidified with .5 N HCl and titrated with .5 N NaOH. The inflection point of titration was identified when the solution (at approximately 21° C) reached pH = 7, measured using a Denver Instrument Model 220 pH meter.

Total Organic Carbon and Nitrogen

Total Organic Carbon (TOC) and Total Organic Nitrogen (TON) were analyzed using a Perkin Elmer 2400 Series II CHNS/O Analyzer. Grinding samples less than or equal to 1mm with a mortar and pestle ensured homogeneity of the samples (approximately 20-50 mg per capsule). Four blank samples and four acentanilide K-factor calibration standards and periodic soil samples of known CHN content were run to ensure quality control.

Extractable Nitrogen

Extractable Nitrogen (ammonium and nitrate) was measured using a KCl extraction. Ratios of 10ml of 2M KCl-to-1g of sieved soil were prepared in 250 ml wide-mouth bottles and placed on a mechanical shaker for 1 hour. Samples were subsequently filtered through Whatman ® 42 filter circles and solutions were analyzed using a Perstorp Analytical Auto Analyzer for $N\text{-}NH_4^+$ and $N\text{-}NO_3^-$ concentrations.

Total Metal Analysis

Acid digestion of soil samples for total metals was performed using the EPA Method 3050 (US EPA, 1996). Approximately 20 ml of solution was filtered using Whatman ® 42 filter circles and stored in a refrigerator at 3°C prior to ICP analysis. A Thermo Jarrell Ash ICAP model 61E spectrophotometer was used to determine solution metal concentrations.

Cation Exchange Capacity and Base Saturation

Cation exchange capacity (CEC) and base saturation (%BS) were determined by removing all cations from their exchange sites into solution. First, 50 ml of 1M NH_4Cl (ammonium chloride) was added to 5.0 g of air-dried soil in extraction tubes that contained filter paper. The tubes were assembled in a Centurion mechanical extractor and set for an extraction period of twelve hours. The leachate was collected, diluted to volume, and analyzed using the Thermo Jarrell ICAP model 61E spectrophotometer. To remove free NH_4Cl from the soil samples, 50 ml of ethanol was added to each extraction tube and set for an extraction period of three hours. The leachate from this extraction was discarded. To analyze for the NH_4 in the solution and determine the CEC, 50 ml of 1M KCl (potassium chloride) was added to each extraction tube and set for an extraction period of twelve hours. This leachate was collected, brought to volume, and analyzed using an autoanalyzer to obtain CEC concentrations. The %BS was calculated using concentrations of Ca^{2+}, Mg^{2+}, K^+ and Na^+ from step one relative to the total CEC.

Erosion and Infiltration

As all plots are located on varying slopes, surface erosion of each treatment plot (1 ha) was estimated along the lower edge of each plot. Three 5m long sections along the lower edge of each plot were randomly selected. Within each section any visibly eroded soil was noted, and the shape of the eroded area was sketched as rectangular or triangular. For triangular erosion areas, rhombic sections were measured for width, length and vertical depth to estimate the volume of soil eroded from the surface. Eroded rills that formed varied in size, from small, shallow rills to somewhat large gullies, and therefore several depths, widths and lengths were measured within each eroded area. The start and end point of each eroded soil section was determined to be where the depth of the rill was level with the soil surface. If there was no visual evidence of erosion within the randomly selected section along the lower edge of the treatment plot, then erosion within that 5m section was considered to be zero. Measurements were completed during the winter of 2010, and are a first-year estimate of plot erosion after initial plot installation.

Total erosion rate (Mg ha^{-1} yr^{-1}) of each treatment plot was estimated by multiplying the average erosion (cm^3/m) by the total length (125 m or 80 m, depending on plot orientation) of the lower edge of each plot and by the average plot bulk density. It was assumed that no eroded soil entered the plot from above (no upslope erosion was evident). Slope angles of each plot were also determined by using aclinometer.

Vertical infiltration rate was determined in the field using a double ring infiltrometer with an inner ring diameter of 20.5 cm and outer ring diameter of 26.5 cm. A total of 400 ml and 200 ml of water was supplied to the inner ring and outer ring, respectively, which resulted in identical initial levels within the rings. Infiltration rate was then calculated from the rate of fall of the water level (the change in depth) inside the inner ring within 45 minutes and expressed as cm min^{-1}(Page *et al.* 1982). Infiltration rate measurements were done only once in May 2011, for comparisons among treatments.

Soil Moisture and Temperature

To monitor the dynamics of soil temperature and moisture, a Decagon EC-5 Moisture probe was installed at 10cm and 50cm below the soil surface, and one Decagon ECT temperature probe was installed at 10cm below the soil surface for each treatment plot. For this study, data was collected from April 2010 to October 2011 at 12-hour intervals using an Em50 Decagon data logger installed in each treatment plot at a randomly selected location within the buffer area of each plot. Average daily soil temperature and moisture were calculated later for data analysis purposes. Daily air temperature and precipitation data was also monitored at the Centralia Mine weather station.

Soil water characteristic curves were determined to relate water content to water availability. Soil cores (68.7 cm^3) were randomly collected within 10cm below the soil surface at three different plots for each type of treatment, resulting in a total of nine soil cores. Soils were completely saturated within two days after returning from the mine, weighed for saturated water content and inserted into a pressure chamber. Total dry weight of each soil core was determined after samples were oven-dried at 105°C for two days, following completion of the pressure chamber experiment. Tensions of 0.4, 0.5, 1, 5, 7.25, 10 and 15 bar were used, with 1, 5 and 15 bar pressure plates and a pressure chamber to develop soil water characteristic curves. Soil water tensions in bars were then converted to MPa.

It was necessary to make some assumptions about how water availability affected seedling survival due to the large variability in soil moisture found across treatment plots. To compare relative availability of soil water at the study site, an approximate number of days when water was not a limiting factor for tree growth was determined. The concept is a simplification of the growing degree-days used in meteorology in most agricultural systems to describe the timing of biological processes, and therefore, will be referred to as water-days (McMaster and Wilhelm 1997). April 15th was chosen as the beginning of the growing season as this was the earliest point at which soil moisture data became available.Soils are also generally not yet depleted in water due to the high rainfall in April and low evapotranspiration demand of early Spring conditions. To determine wilting point and water saturation of the soils at the mine site, soil water content at -1.5 MPa and -0.05 MPa were determined using the soil water characteristic curves (Lopushinsky 1991). We choose a soil dry-down/plant shutdown date, when soil moisture first dropped to its wilting point (using -1.5MPa as the wilting point) and remained there for at least 10 consecutive days in summer, for each treatment (at 10 cm depth: FRA+ash: August 19th, FRA: July 17th, Control: July 11th). The total number of days when soil moisture was above wilting point, between these dates, was counted. These are the days during which, seedlings are likely to be least limited in growth.

Vegetation Measurements

Tree survival was measured after the first and second growing season by counting all surviving trees within all six subplots (three per tree type) per plot. Seedling height growth was measured following the second growing season. All missing trees were assumed to be dead. Total percent ground cover was measured using 20 meter transects, with ocular measures of cover in one-meter intervals. Three transects per plot were performed with values averaged per plot. Additionally, understory species cover was measured within three 1-m^2 plots within each treatment plot.

Statistical Analyses

Statistical analyses were performed using the computer program R (The R Foundation for Statistical Computing, Version 2.8.0, 2008). A one-way ANOVA was used to test for mean differences. Survival rate were compared across treatment groups using split-plot factor: seedling stock types; erosion rate and percent ground cover were compared using whole-plot factor:treatment types. Differences were determined to be significant at $p = 0.10$.

RESULTS AND DISCUSSION

Seedling Survival and Growth

Figure 3 shows overall seedling survival from years 1 and year 2 by treatment type. Overall, seedling survival was lowest with the control treatment. Some additional seedlings were lost during the second year, but overall survival remained similar by treatment, and the FRA+Ash treatment continued to perform better than either FRA or control treatments. Table 3 shows statistical results for survival; only treatment was found to be significantly different with no effect of seedling type or interaction between treatment and seedling type. There was a slightly higher survival with the FRA+Ash treatment. The containerized seedlings show slightly greater survival with the FRA+Ash treatment, but there was nosignificant difference in survival by seedling types (Figure 4).Ideally survival would be near 80%, but no treatment met this level. The survival of containerized seedlings in the FRA+ash treatment is near what would be acceptable for reforestation within Washington State (if survival rates do not drop). Some mortality was evident from elk damage. There was evidence of seedlings being torn from the ground and discarded. Other causes of mortality were not clear, but could be due to poor soil conditions.

In addition to survival, we measured seedling height growth by treatment and seedling type (Figure 5). Growth was somewhat better for both the FRA and FRA+Ash treatments compared to the controls. Additionally, height growth was better with the bare root seedlings than with the containerized seedlings. Height growth in year 2 is probably still be influenced by nursery carryover, but may be showing some indications of treatment effects.

Seedling foliar analysis shows that all seedlings from all treatments are deficient in all nutrients that were measured (Table 4). These widespread nutrient deficiencies can mean that either all nutrients in the soil are deficient, or the low soil oxygen levels are preventing adequate root metabolism and there is insufficient energy for nutrient uptake.

Table 3. Results of split-plot ANOVA for treatment and seedling type.

Df	Sum Sq	Mean Sq	Fobs	Fcrit	P	Ho	Result	
Treatment	2	2026	1012.9	6.890	4.256	0.015	No treatment effect	Reject
Treatment:Plot	9	1323	147.0					
Seedling	1	4	4.2	0.008	5.117	0.929	No seedling effect	Accept
Treatment:Seedling	2	163	81.3	0.161	4.256	0.854	No interaction effect	Accept
Treatment:Plot:Seedling	9	4539	504.					

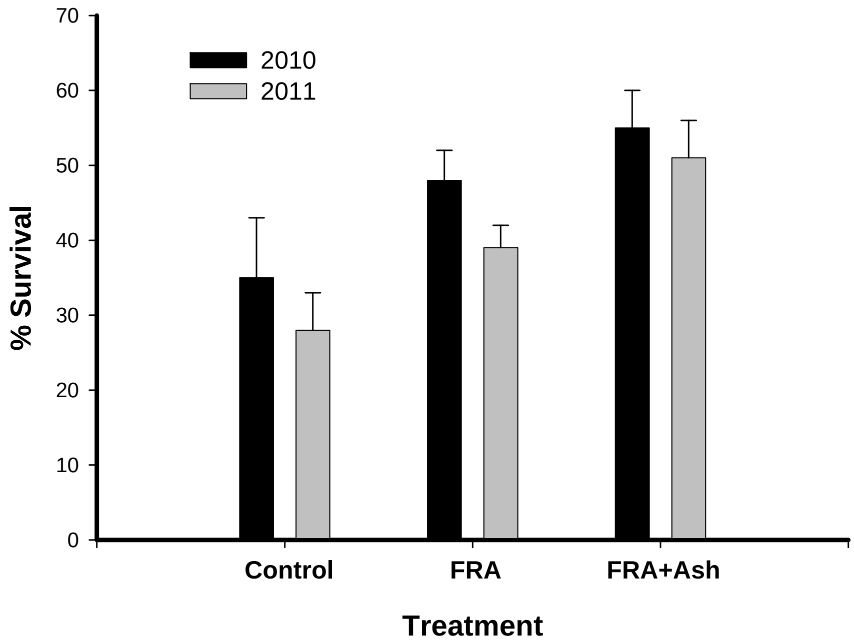

Figure 3.Overall Douglas-fir seedling survival for the first and second year following installation of treatments. Treatments include: Control, Forest Reclamation Approach (FRA), and Forest Reclamation Approach with bottom ash (FRA+Ash).

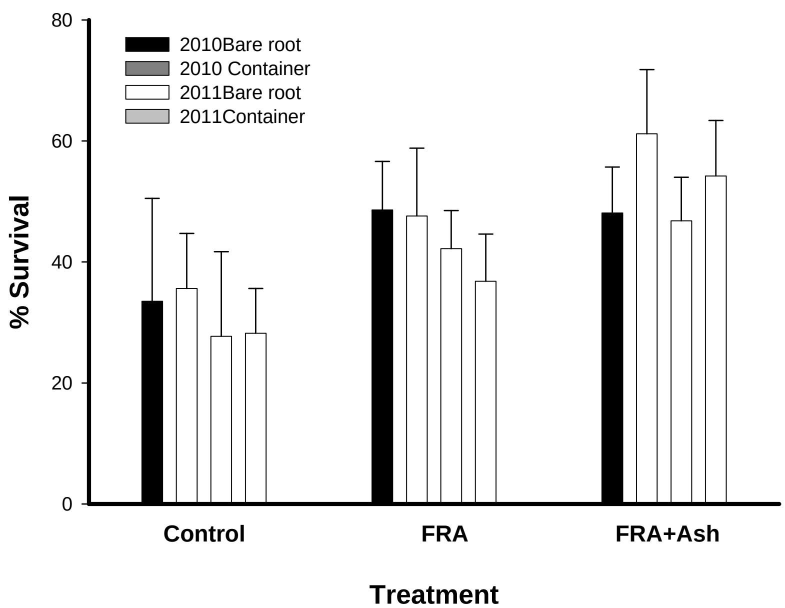

Figure 4.Douglas-fir seedling survival for the first and second year following installation of treatments and planting of bare root and containerized seedlings. Treatments include: Control, Forest Reclamation Approach (FRA), and Forest Reclamation Approach with bottom ash (FRA+Ash).

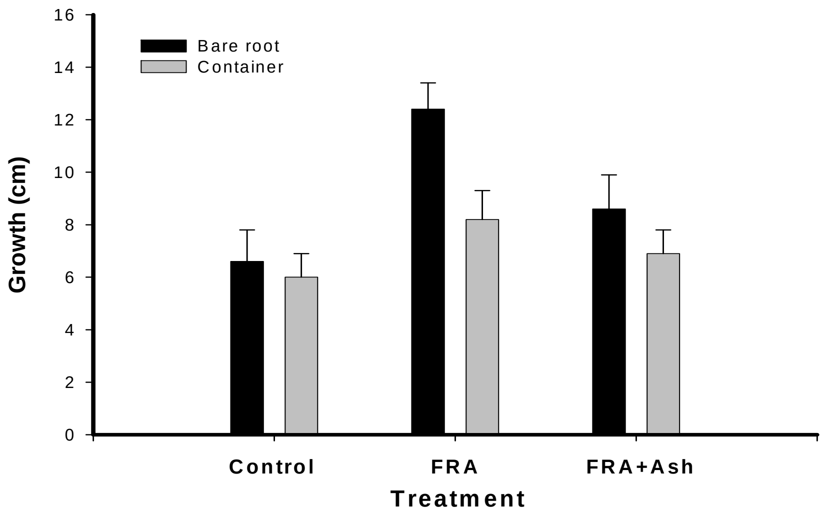

Figure 5.Douglas-fir seedling height growthof bare root and containerized seedlings after the second season (2011) following installation of treatments and planting. Treatments include: Control, Forest Reclamation Approach (FRA), and Forest Reclamation Approach with bottom ash (FRA+Ash).

Table 1. Foliar concentrations of nitrogen, calcium, magnesium, potassium, phosphorus and sulfur in Douglas-fir seedlings by treatment and seedling type. Foliar samples were collected in fall of 2011 after the second growing season.

		Control	**FRA**	**FRA+Ash**	**Deficiency Level***
N	Bare root	0.86	1.28	1.02	1.25
	Container	1.12	1.36	1.37	
Ca	Bare root	0.14	0.21	0.16	0.25
	Container	0.21	0.22	0.24	
Mg	Bare root	0.11	0.12	0.11	0.17
	Container	0.11	0.13	0.13	
K	Bare root	0.45	0.48	0.47	0.6
	Container	0.51	0.56	0.52	
P	Bare root	0.12	0.15	0.13	0.16
	Container	0.14	0.15	0.13	
S	Bare root	0.17	0.18	0.16	0.35
	Container	0.22	0.28	0.26	

*Walker, R.B. and W.P. Gessel. 1991. Mineral deficiencies of coastal northwest conifers. Inst. of For. Res. Contrib. No. 70. Seattle, Wa.

Soil Physical andChemical Properties

Figures 3 shows soil bulk density by treatment and soil depth. There is an increase in bulk density with all treatments by depth. Surprisingly, bulk density is lowest in the control treatment in the top 5 cm. This may be due to more understory vegetation and roots as vegetation was present in these plots longer than in the other treatments. Overall, soil bulk density levels are not low but not high enough to be of concern in any treatment at this time.

Soil pH varied widely within treatments but there were no large differences in average pH by treatment or by soil depth (Figure 7). A few individual samples had verya low pH (~pH 3) but these occurred in all treatments and at varying depths. Some were also extremely high (greater than 7). This variability in pH is likely due to the very mixed materials within the soil such as fossils and coal fragments and suggests that there may be microsites within the soil that have a pH that is not favorable for Douglas-fir.

Figures 8 and 9 shows total soil carbon and nitrogen concentrations by depth. Soil carbon concentrations are within the normal range for forest soils, even in the control soils which are somewhat lower in carbon than either FRA or FRA+Ash. Total soil nitrogen concentration is also within the normal range for northwest forest soils, and is even somewhat higher than typical at depth. There is no pattern either of decreasing soil carbon or soil nitrogen with depth as would be expected in a forest soil. The fact that the parent materials are mixed overburden including remnant fragments of the original soil scattered throughout the profile and the heavy clay texture may explain the relatively high concentration of C and N and the fact that they remain high with depth. Overall, there does not appear to be a lack of either carbon or nitrogen in any treatment soil.

Electrical conductivity (EC) of soil solutions were low overall and showed little variation by treatment (Figure 10). There was a large increase in conductivity by depth which suggests leaching of the upper horizons. The high rainfall of the Pacific Northwest is undoubtedly removal ions from the surface soil to lower in the soil profile, but even at depth, EC is not likely to be a concern for growth of Douglas-fir.

Soil Moisture and Temperature, and Soil Water Days

The total precipitation at the Centralia TransAlta mine site for the 2010 water year (October 1 through September 30) was 140 cm (55 in), which is slightly above the average annual rainfall for this area of western Washington, 137 cm. For the first growing season (April 1 – November 30, 2010), the accumulated precipitation was 74 cm, which is above average rainfall for this period, and may have increased the difficulties of initial seedling survival, as the soil was waterlogged in spring.

Figure 11 shows the average soil temperature at 10cm depth by treatment (along with volumetric soil water content at 10 and 50cm). There is a suggestion of higher soil temperatures with both the FRA and FRA+Ash treatments. This is probably due to the lower percent ground cover present in these plots. Although soil temperatures are slightly lower with the controls and closer to soil temperatures better for Douglas-fir, the additional competition from the abundant understory vegetation is undoubtedly a problem for seedlings. Soil temperatures were lower with both FRA and FRA+Ash in year 2 most likely from the additional understory vegetation.

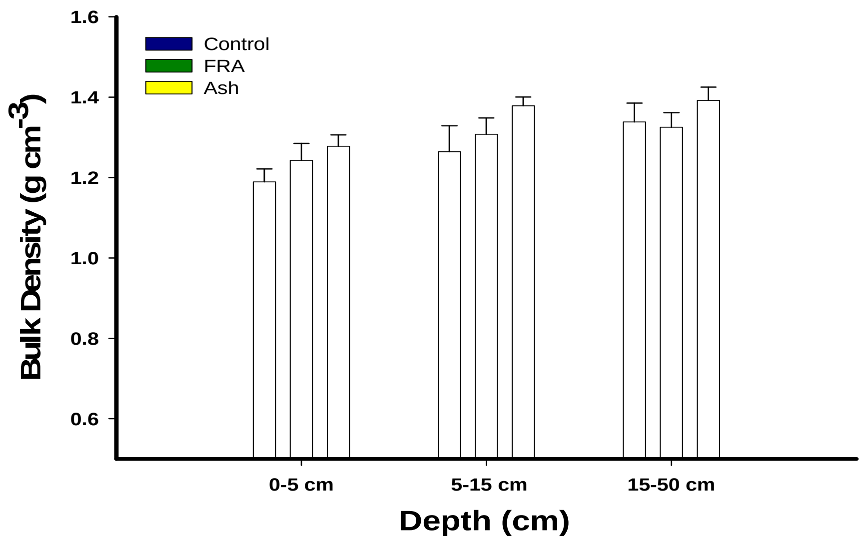

Figure 6. Soil bulk density by soil depth and by treatment.

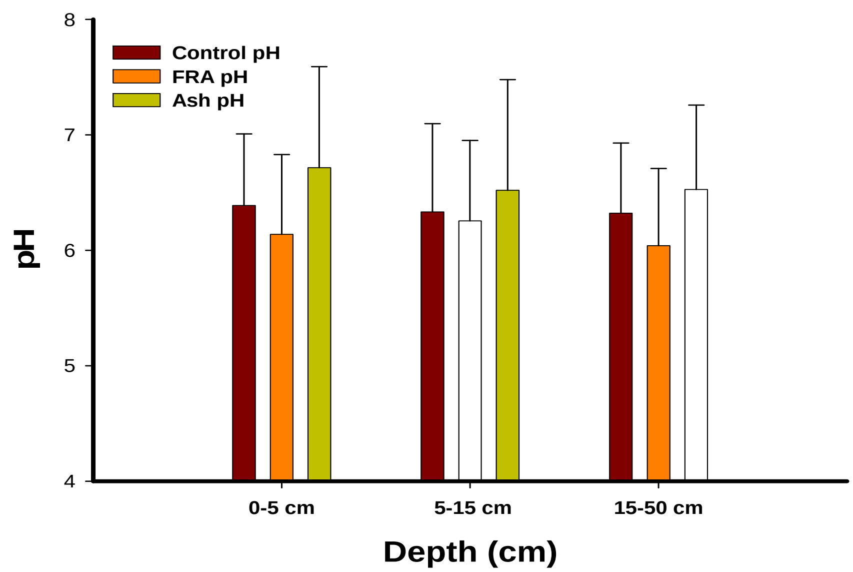

Figure 7. Soil pH by soil depth and by treatment.

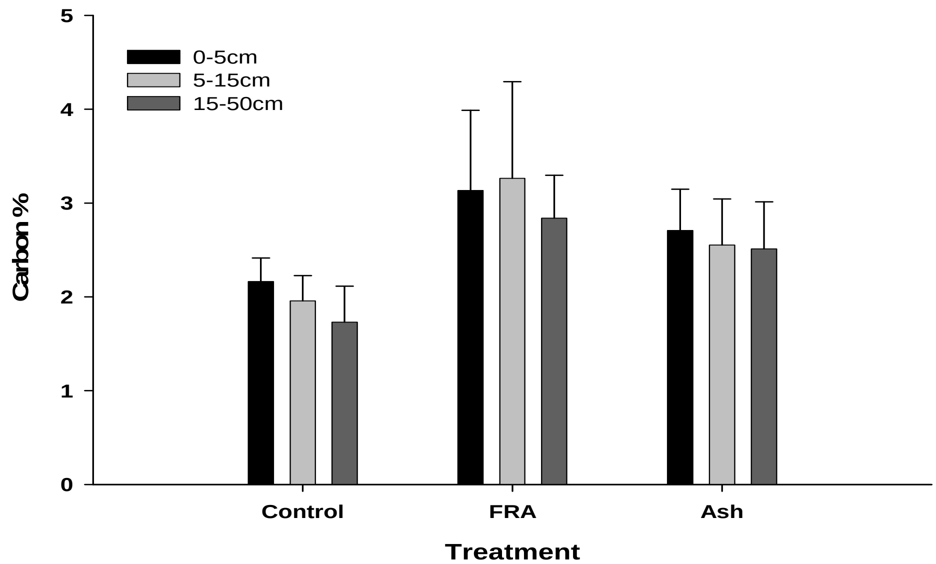

Figure 8. Preliminary soil carbon concentrations by treatment (control, FRA and FRA+Ash) and by soil depth with SE bars.

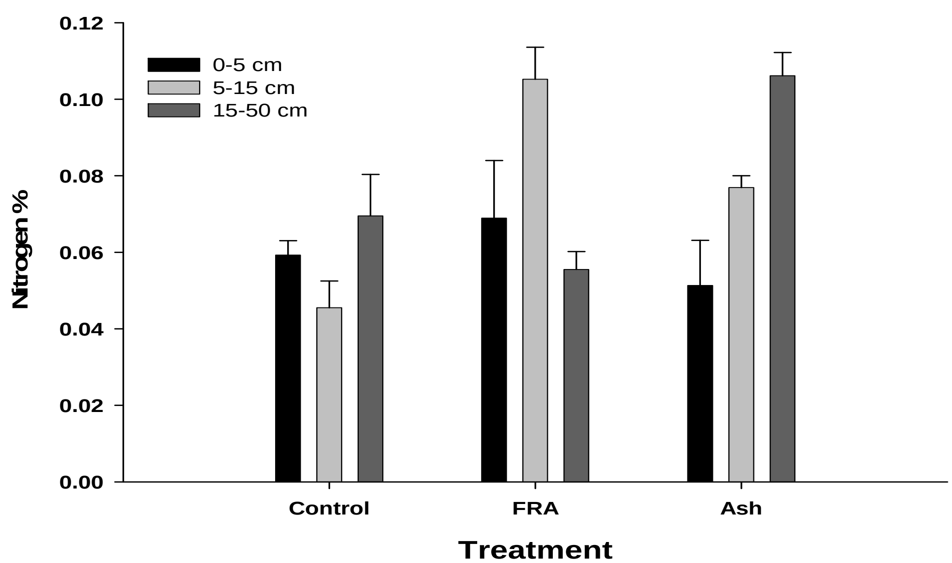

Figure 9. Preliminary soil nitrogen concentrations by treatment (control, FRA and FRA+Ash) and by soil depth with SE bars.

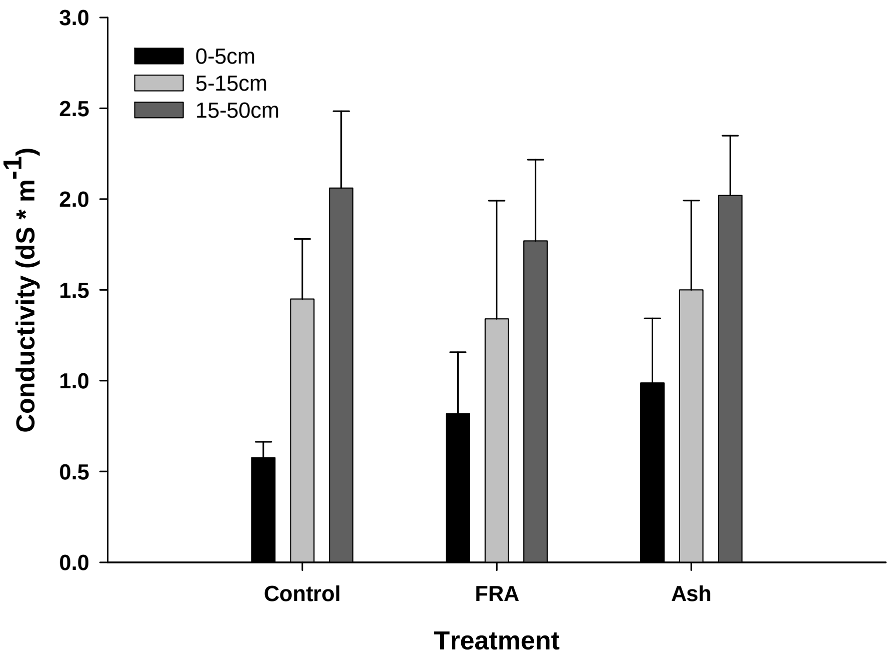

Figure 10. Electrical conductivity of soils by depth and treatment. Overall conductivity is with the range of non-salic forest soils, but is higher with depth.

Water competition from this vegetation is extremely likely and could be a contributing factor to poor seedling survival in the controls. The majority of the vegetation in the control plots is also not native.

As expected, water content at 50 cm is consistently higher than at 10 cm, although the upper soil profile does become quite wet at some times of the year (Figure 11). Also expected is the sharp drop in soil water during the summer and large increase in soil water with the onset of fall rains.

No one treatment always hadhigher or lower soil moisture, but FRA+Ash soil was often wetter than the other two treatments during the first year. In the winter this may be a problem for oxygen availability to roots. During the growing season, this may be an advantage. FRA soil was always driest in the upper 10 cm. This may be due to the fact that probes were placed in mounds and mounding was generally better in the FRA plots than in the FRA+Ash plots. This undoubtedly helped water move down from the upper mound areas to the lower soil profile. At depth, soil moisture was lowest in the control plots during the growing season, and again, this may be more of an issue for seedling survival than the presence of drier soil near the surface. Competition from extensive understory vegetation could also explain this difference as many of these species appear to root fairly deeply.Nevertheless, the control plot soil was often the wettest during the second year. Overall, no single treatment had a soil moisture or temperature that was consistently preferable for Douglas-fir seedlings.

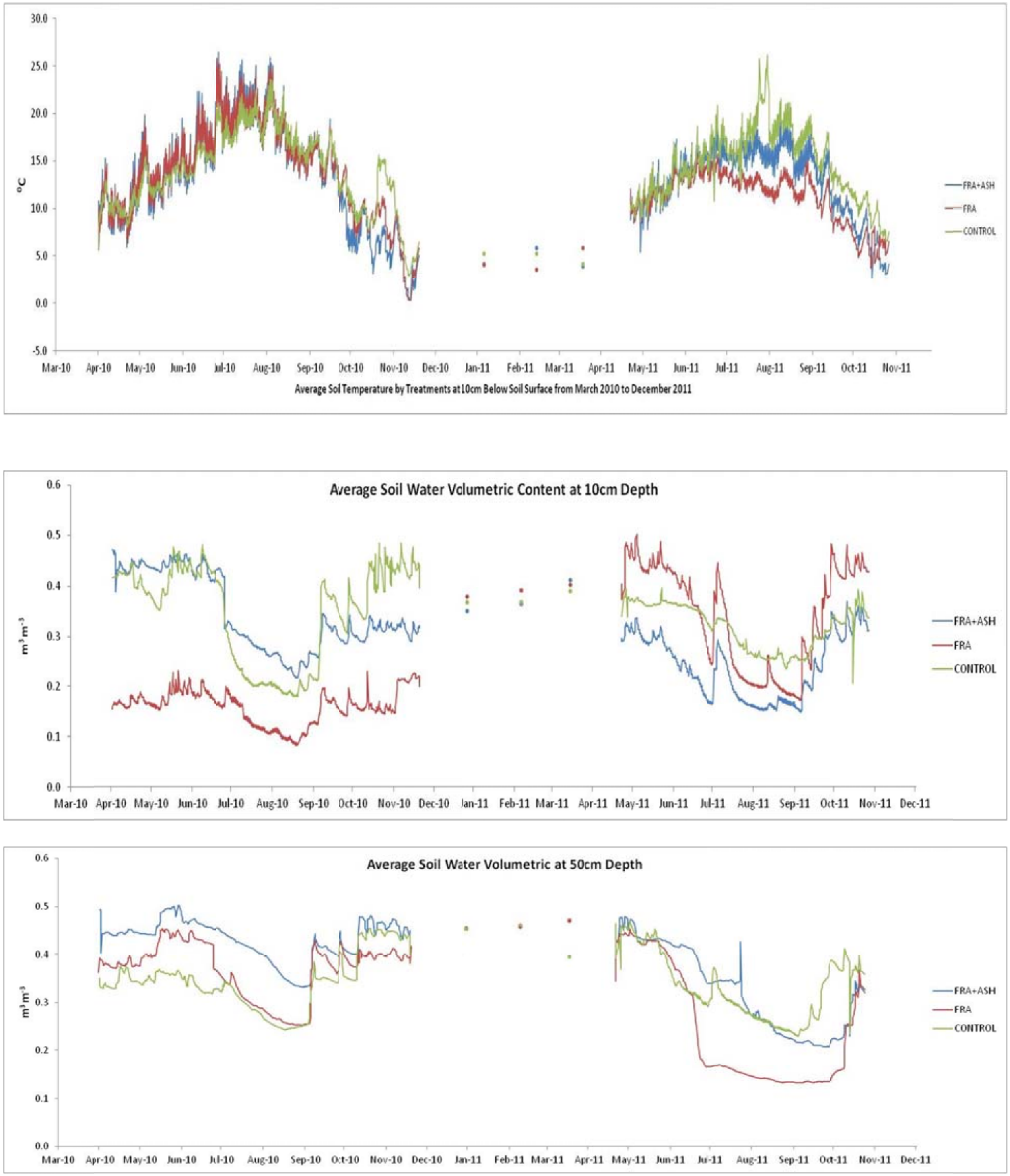

Figure 11. Average soil temperature at 10 cm depth and average volumetric soil water content at both 10 cm and 50cm depths for the 2010 and 2011 growing seasons.Dataloggers were not kept in the field over the winter but monthywinter soil moisture and temperature readings are shown.

Data from the soil water characteristic curves was used to set a water content at which the permanent wilting point would occur. Wilting point for the control and FRA plots were both 24% volumetric water content (VWC), and 21% for the FRA+ash plots as determined from the soil water characteristic curves (Figure 12). Interestingly, the FRA+Ash treatment which does contain some sand and gravel size particles has a slightly lower soil water content to soil tension relationship. In this heavy clay soil, this may be a benefit for drainage and aeration. Water saturation for the control plots soils was 37%, 36% for the FRA plots; and 32% for the FRA+ash plots. All treatment plots started to dip significantly in soil water concentration at 10cm depth from mid-June to mid-August to their lowest values of 18% for the control and FRA+ash plots, and 8% for FRA plots.

During summer, all soils at 10cm depth reached their wilting point and FRA plots were consistently lower in moisture throughout the growing season than FRA+ash and the control plots. Average soil surface moisture was replenished by several storm events on Sep.17th, and Oct. 10th and 24th 2010 and high precipitation continued through winter, with the control plots reaching its previous water storing capacity in spring at 48% in November. FRA and FRA+ash plots did not resume its previous high moisture content in spring, but stayed near 20% and 30%, respectively.

At 50cm below ground, average soil moisture for all three treatments dried down slower and did not hit the wilting point. FRA+ash plots showed greater water holding capacity than the other treatments throughout the summer with its lowest soil moisture at 33%, while the control and FRA plots reached 24% and 27%, respectively in the first year. All treatments regained moisture to above 42% at 50cm depth after September 2010.

Soil water-days (calculated from the number of days that soil moisture was above the wilting point) showed large differences across treatments at 10cm soil depth, with FRA+ash: 127 water-days, FRA: 0 and the control: 95 water-days (Table 3). For the 50cm depth however, the control plots (shutdown date: August 28th) had 136 water-days, but water availability did not become limiting (reached wilting point) for FRA and FRA+ash plots in summer (Table 3). The water-days results were consistent with the soil moisture pattern shown in Figure 11.The soil water-days method provides a base point for comparison of seedling survival in terms of water availability as a limiting factor. Overall it appears that FRA+Ash had better water availability during the growing season.

Table 3. Average Soil Water-Days at 10cm and 50cm below the soil surface by treatments. Soil-Water-Days were determined by counting the number of days from April 15th to when soil water was depleted to a tension of -1.5MPa (used as the permanent wilting point). FRA soils at 10cm never had volumetric water content high enough to indicate water availability throughout the growing season. FRA and FRA+ash soils at 50cm did not reach the wilting point for a consecutive of 10 days. (NL = Not Limiting)

Treatment	10cm Water-Days	50cm Water-Days
Control	95	136
FRA	0	NL
FRA+ASH	127	NL

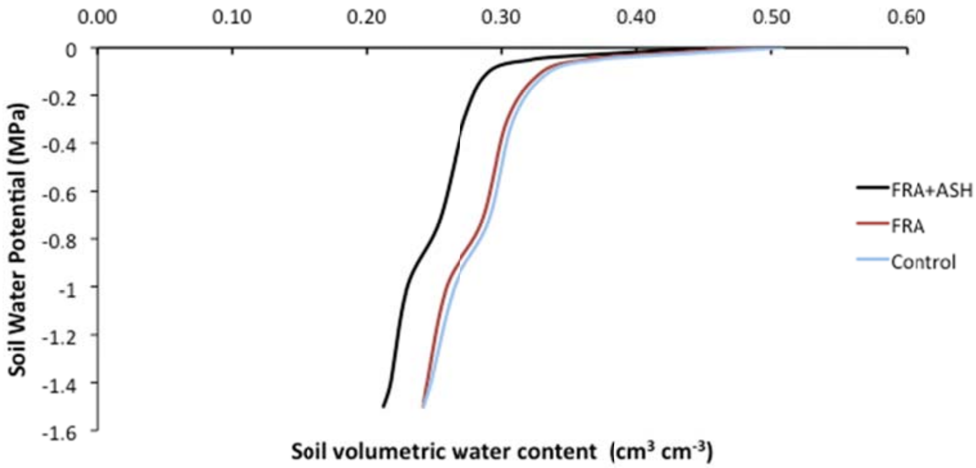

Figure 12. Soil water characteristic curves for each treatment.

Ground Cover, Erosion and Infiltration Rates

Table 4 shows the estimates of average soil erosion loss by treatment with average plot slope. Plot 4 is not included in the treatment averages as it was discovered that the planned location for Plot 4 had a gully going through it and that the plot would need to be turned 90 degrees. This was not completed until March during a rainy spring. This late disturbance probably led to the high erosion from this plot. Overall, erosion is not extremely high and average erosion rates did not differ significantly across treatments (F=1.95, p= 0.159) probably due to the high variability between and within treatment plots. The USDA tolerable agricultural erosion rate is 11 Mg ha^{-1} yr^{-1}. Only Plot 4 exceeded this level, which was undoubtedly due to the timing of the plot installation. Control was slightly lower than FRA but does not appear to be significantly different. The Ash plots did have the highest average erosion, but are still below 11 Mg ha^{-1} yr^{-1}, which is considered a tolerable soil loss. The addition of bottom ash to the mounded plots may have reduced aggregation by causing some dispersion due to salts. Figure 3 shows the electrical conductivity of the soils and the slightly elevated conductivity of the Ash treatment soils. The EC increases with depth in all treatments which may be the result of heavy Pacific Northwest precipitation leaching salts to lower in the soil profile, thus this salt effect of the ash may disappear with time.

The control plots were significantly different (F=13.02, p<0.0001) in ground cover percentage (94%) than FRA and FRA+ash plots (49.3% and 56%). All the control plots were consistently high in percent ground cover with the established grasses often growing taller than Douglas-fir seedlings. Percent ground cover ranged from 16 to 77% in FRA plots and from 24 to 91% in FRA+ash plots.

Table 4. Average and standard deviation (SD) of estimated erosion by area, percent vegetation ground cover, and infiltration rate, along with slope by treatments.

Treatment		Erosion mean + SD Mg ha^{-1}	Veg. Cover %	Bare Ground %	Infiltration cm min^{-1}	Slope
Control	Plot 1	2.3 ± 3.7	98	2	0.008	3
	Plot 2	2.3 ± 2.1	96	4	0.013	10
	Plot 6	0.5 ± 0.4	97	3	0.103	11
	Plot 10	0.5 ± 0.2	85	15	0.002	5
	Average	1.4 ± 1.0	94	6	0.032	7.3
FRA	Plot 3	2.8 ± 3.8	49	51	0.011	12
	Plot 5	3.1 ± 2.8	16	84	0.501	8
	Plot 11	0.2 ± 0.2	55	45	0.004	8
	Plot 12	0.5 ± 0.3	77	23	0.002	8
	Average	1.7 ± 1.5	49.3	50.8	0.130	9
FRA+ASH	Plot 4	(14.5 ± 10.1)	(63)	(37)	(0.061)	8
	Plot 7	6.1 ± 9.1	53	47	0.002	11
	Plot 8	2.2 ± 1.1	91	9	0.009	6
	Plot 9	4.1 ± 4.8	24	76	0.002	6
	Average	4.1 ± 2.0	56	44	0.004	7.8

*Plot 4 (with parenthesis) was excluded from calculation due to the delayed plot installation.

Mean infiltration rates of three treatments were considered low, with the highest rate 0.5 cm min^{-1} occurring at plot 5, where the soil surface was dry and cracked during data collection; followed by 0.1 cm min^{-1} at plot 6, where ground cover seemed to help water percolate downward. Infiltration values in FRA+ash plots appear lower than in both FRA and the control plots despite variations within treatments. Overall, infiltration rates were highly variable over all 12 plots ranging from 0.002-0.5 cm min^{-1} but low with all treatments undoubtedly due to the high clay content of the soil.

CONCLUSIONS

The primary goal of this project was to test different reclamation practices to see if survival of Douglas-fir seedlings could be improved by using the FRA or FRA+Ash methods adapted for Pacific Northwest forests plantations. Overall, survival after two years was best with the FRA+Ash treatment; both the FRA and FRA+Ash treatments had better survival than the control reclamation plots. Elk damage, water-logged soils, competition from understory vegetation and extremely dry soils late in the summer all appeared to reduce seedling survival. Containerized seedling did not have a higher survival than bare-root seedlings despite having a plug of fertile soil available for nutrient uptake, but survival was consistently better with the FRA+Ash treatment. Bare root seedlings did grow more than containerized seedlings in year two. Overall, all seedlings are nutrient deficient which may be due to poor nutrient availability or anaerobic soils. Soil properties did not vary consistently by treatment nor did they appear to have improved with any particular treatment, but there was high variability within treatments which may have prevented observing any statistical differences among treatments. We did not observed excessive erosion with any treatment but some erosion occurred with all treatments.

PRESENTATIONS AND PUBLICATIONS

Scientific and other presentations to date:

Arbor Day 2010 field trip at the TransAlta Centralia Mine with local schools.
Soil Science Society of America 2010:
Soil Science Society of America 2011:

MS Theses presentations to date:

Trevor King: Factors affecting the growth and survival of Douglas-fir on a reclaimed coal mine near Centralia, Washington

Grace King: Assessing a Modified Forestry Reclamation Approach for Douglas-fir in Southwestern Washington State.

Yu Rong Liu: Soil physical properties after application of a modified forest reclamation approach in Southwestern Washington State

Manuscripts in Progress:

Use of a modified Forest Reclamation Approach to establish Douglas-fir seedlings in Western Washington State

Soil physical properties after application of a modified Forest Reclamation Approach in Western Washington State

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