Long-Term Site Preparation Effects on Volcanic Ash Forest Soils and Douglas-Fir

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Abstract

Long-term site preparation effects on soil characteristics and Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) growth and foliar nutrition were measured over a 24-year period following a ground-based harvest in Northern Idaho, USA. Harvest unit soils were classified as Andisols overlaying metasedimentary parent material within a udic-frigid moisture and temperature regime. Douglas-fir site index at base age 50 was 29 m. Site preparation treatments included undisturbed control, broadcast burn, pile and burn, and mechanical scarification. Periodic soil-site measurements were collected on each treatment at regeneration stand ages 6, 14, and 24 years. Six- and 14-year soil bulk density on scarified treatments were significantly higher at 0-15 and 15-30 cm than all other treatments. At 24 years, scarified soil bulk density at 0-15 and 15-30 cm showed recovery to bulk densities observed in non-scarified soils. Scarified soil organic matter (SOM) and N were significantly reduced by 32% and 42% over control levels 6 years post-harvest. After 24 years, scarified SOM and N were significantly lower than that found in broadcast burn (44% and 54%) and pile and burn (33% and 49%). Douglas-fir needle mass and foliar N and P content on scarified soils were significantly lower than on broadcast burn or pile and burn treatments after 24 years ($p<0.1$). After 24 years, soil and foliar N content was significantly higher on microsites that received a burn treatment ($p<0.1$). Tree growth on either burn treatment showed significantly greater diameter (35%), height (14%), and volume (92%) when compared to trees growing on scarified soils after 24 years ($p<0.1$). These results indicate that tree growth on frigid, ash-mantled forest soils of Northern Idaho, USA, can be significantly reduced following soil compaction and displacement of organic matter and nutrient-rich topsoil. Where soil disturbance was minimized and organic matter retention was coupled with a burn treatment, soil and tree productivity was maintained or enhanced.

Keywords: Site preparation, soil disturbance, volcanic ash, Douglas-fir productivity, nutrition.
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Introduction

Maintenance or enhancement of soil-site productivity following silvicultural treatments is critical for meeting the future demands of traditional wood fiber markets and the emerging bioenergy sector (Mead and Pimentel 2006, Richardson 2006). Increasing wood fiber demand implies a greater utilization intensity of forest harvest residues, shorter stand rotations, or multiple thinning entries within a traditional stand rotation (Mead 2005a, Mead 2005b, O'Laughlin 2009, Janowiak and Webster 2010). In this context, it is paramount that the interactions between silvicultural treatments and soil-site conditions are understood in order to maintain long-term site quality and productivity.

Current knowledge of silvicultural impacts on site productivity indicates that site response to multiple thinning entries or to a final harvest entry is not uniform, but varies by soil and climatic conditions (Piatek et al. 2003, Powers et al. 2005, Ares et al. 2005, Geist et al. 2008, Tan et al. 2009). Ten-year data from the North American Long-Term Soil Productivity study (LTSP) suggest that biomass removal following clearfell silvicultural treatments did not affect long-term forest growth. However, mechanical soil-site disturbance during clearfelling or site preparation did affect long-term site productivity through soil compaction and/or removal of organic-rich surface horizons (Powers et al. 2005). However, these effects were not uniformly negative, but rather showed both neutral and positive growth response to soil disturbance.

Soil compaction has been found to benefit plantation establishment through reduction of macropore space in coarser-textured soils (Gomez et al. 2002, Ares et al. 2005, Tan et al. 2009), thereby increasing soil water holding capacity. Conversely, compaction-induced reduction of macropore space in finer-textured soils reduces plant-available water. Reduction in plant-available water and displacement of organic surface matter can induce plant drought stress earlier, thereby decreasing site productivity (Kimmins 1996). Soil bulk density increases of ≥18% on fine-textured soils have been reported to

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reduce tree height, shoot, and volume (Froehlich 1979, Froehlich and McNabb 1983, Froehlich et al. 1986, Gent and Morris 1986, Misra and Gibbons 1996). Long-term productivity decline on fine-textured soils following compaction may disappear as soil will naturally recover due to freeze/thaw cycles, soil faunal activity or root throw; however, natural recovery without mitigation in some soils may exceed 45 years (Froehlich and McNabb 1983, Reisinger et al. 1992).

Mechanical soil scarification or displacement effects on site productivity show similar dichotomous behavior to that of compaction. Clayton et al. (1987) found up to 50% volume reduction in a ponderosa pine plantation 25 years following lateral soil displacement on an ash-influenced forest soil in central Idaho, USA. While Clayton et al. (1987) did not speculate on the link between soil displacement and site productivity decline, other research has shown that displacement of surface organic matter leads to declines in soil carbon concentration and reduced nutrient availability (Powers et al. 2005). Similar productivity declines following soil disturbance have been found worldwide in radiata pine (*Pinus radiata* D. Don) plantations (Skinner et al. 1989, Murphy and Skinner 2004), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco.) plantations (Minore and Weatherly 1990, Page-Dumroese et al. 1997) and in South African forest plantations (Grey and Jacobs 1987). In contrast, Piatek et al. (2003) found scarification increased 20-year Douglas-fir volume over control volume by 80%, and 27% when compared to a broadcast burn or pile and burn site preparation treatment. Tan et al. (2009) found that after three growing seasons, there was no consistent effect of surface organic matter removal on Douglas-fir and lodgepole pine seedling growth; however, they speculated that three years was too soon to elucidate any shifts in long-term productivity. These authors suggest that a positive growth response following scarification is attributable to a reduction in understory vegetation competition for limited site resources and/or an increase in soil temperature following surface organic matter removal.

A near-universal constant across site disturbance/productivity studies with fine-textured soils, frigid soil moisture regimes, and soil organic matter <10% is an overall negative growth effect following both soil displacement and compaction (Clayton et al. 1987, Murphy and Skinner 2004, Ares et al. 2005, Geist et al. 2008, Tan et al. 2009). Notably, however, the majority of these long-term site productivity studies fall within 5-15 years, with only a few reaching two decades. Fifteen-year plantations may be adequate to assess growth effects following harvest and site preparation activities on short-rotation hardwoods or pine plantations in the southeast USA, but this timeframe may be too short for softwood plantations in Northern Idaho, USA. It is unknown whether these early growth declines are mitigated by site recovery within the third and fourth decades. Even with an increasing demand for forest resources in the bioenergy sector, stand rotations within Northern Idaho will necessarily extend to, at minimum, three decades following regeneration, driven primarily by the dry Mediterranean climate found within this region. Thus, many of these current studies will be unable to fully inform us of the long-term effects of site disturbance following silvicultural treatments on regional, fine-textured volcanic ash forest soils. Therefore, we wished to retrospectively examine how site preparation treatments affected long-term soil characteristics and Douglas-fir nutrition and growth over a three-decade period following a clearfell harvest in Northern Idaho, USA.

Materials and Methods

2.1 Study Site

The originating study was installed on Bertha Hill in the Clearwater range of Northern Idaho, USA. Site elevation is 1270 m. Mean annual air temperature (MAAT) is 5° C, and mean annual precipitation (MAP) is 127 cm. The frost-free season is typically 80 days. Slopes generally trend westerly and northwesterly, ranging from 10% to 40%. The vegetation community is classified as grand fir/queencup beadlily (*Abies grandis*/*Clintonia uniflora*) on the westerly, steeper slopes and western redcedar/queencup beadlily (*Thuja plicata*/*Clintonia uniflora*) on the gentler, northerly slopes (Cooper et al. 1991, Soil Survey Staff 2011). The 50-year site index for Douglas-fir is 29 m (Stoker 1990).

Three soil series classified by the USDA Soil Taxonomy system are found in the study area: Stepoff, Township, and Poorman. Stepoff soils are classified as ashy over loamy-skeletal, amorphic over isotic, frigid Ultic Udivitrands. Township soils are classified as ashy over loamy-skeletal, amorphic over paramicaceous, frigid Typic Udivitrands. Poorman soils are classified as coarse-loamy, paramicaceous, frigid Andic Hapludalfs (Soil Survey Staff 2011). These soils are all deep and well drained with an ash cap from 36 cm to 66 cm deep over mica schist and calc-silicate metasedimentary rocks. Available soil water holding capacity (AWC) in Stepoff and Poorman soils is 26.7 cm, whereas Township is 12.7 cm. The lower AWC on Township soils is due to steeper slopes and slope convexity (Soil Survey Staff 2011).

2.2 Harvest and Site Preparation

An 87-ha mixed-conifer stand was operationally clearfell harvested between 1979 and 1981. Harvest was accomplished using manual felling followed by ground skidding with crawler tractors. In the fall of 1981, the gentler slopes of the plantation were prepared for planting by piling slash with a straight blade-equipped crawler tractor. At the time of tractor piling, the operator was instructed to “root out” competing vegetation. Approximately 30% of the harvest unit was disturbed during mechanical site preparation (Stoker 1990). The slash piles were burned and the unpiled areas were broadcast burned in 1982 (Stoker 1990, Roché 1997). In the spring of 1983, a plantation was established by dibble-planting one-year old, 66 cm^3 container Douglas-fir seedlings on a 2.4 m X 2.4 m spacing to 1683 trees per ha. The seed source for the plantation was collected from local genetic stock (Roché 1997).

In 1988, nine points were randomly located across the harvest unit. At each point location, four site preparation treatments were identified in its vicinity: control (undisturbed);

broadcast burn (burned but otherwise undisturbed); pile and burn (tractor piles that were burned); and scarify (area from which coarse woody debris, organic matter, and surface top-soil was displaced during tractor piling). Individual study trees at each of the nine location points were selected by moving in a clockwise direction around a center stake. Each encountered tree was examined for evidence of any of the desired site preparation treatments. If the site preparation treatment for a tree could not be clearly determined within a radius of ca. 3 m, that tree was omitted and another tree was similarly selected and examined. Tree selection continued in concentric circles until five trees in each of the four treatments were located per point location (Figure 1). Each seedling then represented a replicate of a site preparation treatment with an area of 30 m^2. A total of 180 sample trees were selected within the harvest unit across the nine points and permanently marked for repeated measures.

Study points 1 through 5 and 7 through 9 are located on westerly-facing slopes, point 6 is on a northeast-facing slope. Points 1 through 4 and 7 through 8 are located on the Stepoff soil series. Points 5 and 6 are located on the Poorman soil series, and point 9 is located on the Township soil series.

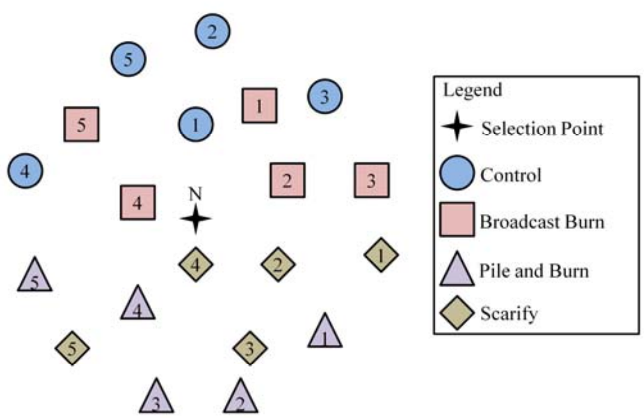

Figure 1. *A generalized example of individual tree selection for each site preparation treatment surrounding a randomly chosen location point within the Bertha Hill clearfell harvest unit in Northern Idaho, USA. Nine selection points were randomly placed across the harvest unit in 1988, replicating this design. Each colored site preparation treatment circle represents a 30 m^2 area, with the seedling in the center.*

2.3 Study Datasets

Three datasets were available for analysis. The originating dataset of 1988 measured soil chemistry and bulk density, and Douglas-fir height and foliar nutrition 6 years following stand regeneration (7 years following site preparation). This dataset did not include a tree diameter at breast height (DBH) measurement. A second set of data was collected 14 years post-regeneration, which included soil bulk density and the mensurational measurements of DBH and total height. This dataset did not include soil or foliar chemistry data. In 2006, 24-year post-regeneration measurements were collected on soil chemistry and bulk density, and Douglas-fir DBH, total height, periodic annual diameter increment and foliar nutrition. No baseline data were collected pre-harvest; consequently, all comparisons are between site preparation treatments post-harvest. We acknowledge that post-harvest control soil data may have differed from pre-harvest soil conditions; thus, we will limit our observations and analyses to post-harvest site preparation differences.

2.3.1 Soil Physical and Chemical Data: Soil bulk density was measured within the crown perimeter due north of the bole of up to two randomly selected trees in each site preparation treatment per selection point. Year 6 bulk density readings were collected via nuclear densitometer at a soil depth of 0-10, 10-20, and 20-30 cm. Multiple readings at each depth were averaged for a representative bulk density value. Years 14 and 24 bulk density data were collected using a 269 cm^3 slide hammer style, volumetric core sampler. Volumetric core samples were collected at 0-15 and 15-30 cm depths. Following core extraction, the samples were transferred into soil bags for transportation to the lab for analysis after oven-drying (Soil Survey Staff 2004).

To relate the two disparate bulk density measures, the 0-20 and 10-30 cm nuclear densitometer bulk density values were averaged to reflect similar sampling depths of the volumetric core sampler. Nuclear densitometer readings were assumed to return a dry bulk density value similar to that obtained by a processed bulk density core sample. This assumption is valid only if the densitometer was calibrated to soil moisture content (Jansson 1999). Documentation from the 1988 sampling state that the bulk densities were adjusted for soils with higher moisture content than the average soil moisture content across the research site (Stoker 1990). Densities are reported in grams per cubic centimeter.

Bulk soil samples were collected by a 1430-cm^3 bucket auger to a depth of 30 cm near the bulk density sampling location. Bulk soil samples were then combined by treatment to obtain one bulk soil sample per treatment per selection point. Due to budget constraints in Year 24, soil samples were further bulked by soil series, which resulted in three bulk soil samples per treatment per soil series. Air-dried soil samples were processed and chemically analyzed for soil organic matter (dichromate-H_2SO_4 extraction/colorimetric); mineralizable N (incubation extraction/colorimetric); available P (Na acetate extraction/colorimetric); and extractable cations K, Mg, and Ca (NH_4 acetate extraction/inductively coupled plasma). Soil organic matter is reported in grams per kilogram of soil and macronutrients in micrograms per gram of soil.

2.3.2 Tree Nutrition, Growth, and Mortality Data: In sampling Years 6 and 24, up to two trees in each site preparation treatment were randomly chosen per selection point for foliar nutrient analysis. It was assumed in Year 24 that the rooting area of each tree, and thus nutrient uptake, was predominately confined to the 30 m^2 microsite of each site preparation treatment. Douglas-fir foliage was collected on selected trees during the fall dormant season. Current-year lateral shoot growth was collected from the third whorl from the top of each selected tree by pruning pole. Foliage samples were processed for tissue chemical analysis of N, P, K, Ca, and Mg. Foliar N was determined using standard micro-Kjeldahl procedures, while all other nutrient determinations were by ICP emission. Dry needle weights and nutrient content are reported in grams per needle weight.

Diameter at breast height was collected in Years 14 and 24 using a standard diameter tape. Tree height in Year 6 was directly measured with a measuring stick. Tree heights in Years 14 and 24 were calculated from measurements obtained using a clinometer and measuring tape. Tree volume was calculated from height and diameter measurements using regional Douglas-fir taper equations (Wykoff et al. 1982). Periodic annual diameter growth was measured in Year 24 from increment bore samples on all plot trees. Increment cores were collected from the north side of the tree 0.5 m above the root collar to ensure against butt swell influence. This location was chosen to best represent diameter growth over the longest period of time relative to stand regeneration.

Of the original 180 sample trees at 24 years, eight trees were excluded from the sample due to mortality or physical deformity. Six trees were confirmed as *Armillaria ostoyae* mortality, with the remaining two showing extreme stem deformity from snow damage. No interaction between site preparation treatment and mortality was found. The confirmed mortality, combined with the stem-damaged trees, resulted in a 95.6% survival of the original sample.

2.4 Statistical Analysis

All soil and tree data were analyzed with PROC MIXED statements in SAS 9.2 using the restricted maximum likelihood estimation (REML) method (SAS 2008). Soil series was treated as a random (i.e., blocking) effect to account for variation in soil properties and physiographic processes. Fixed effects were monitoring year, site preparation treatment, and the interaction between monitoring year and site preparation treatment. Individual tree growth and foliar data were analyzed through repeated measures. The repeated measure was sampling year, and the individual tree was the subject. Covariance structure type was estimated through variance components, which yielded the lowest Akaike's Information Criterion (AIC) score. We were unable to utilize repeated measures for soil analyses due to bulking of individual samples by soil series during the 2006 measurement period. Post-hoc least-squares-means tests were conducted on each interaction term for soil and Douglas-fir growth and foliar nutrition measurements. Significant differences between interaction term means were noted at $p \leq 0.1$. Inherent variability in soil and tree growth factors motivated the use of a higher alpha value ($\alpha=0.1$), hence a higher p-value, in order to assess long-term treatment affects in this study.

Results

3.1 Soil Property Characterization

3.1.1 Soil Bulk Density: Soil bulk density at 0-15 cm soil depth did not show any significant differences between broadcast burning or pile and burn treatments, compared to the undisturbed control at Years 6 and 24 ($p>0.1$) (Figure 2). At Year 14, the pile and burn treatment showed a 19% increase over Year 6, which disappeared by Year 24. Soils that were mechanically scarified had 21% higher bulk densities at Year 6, 27% at Year 14, and 12% at Year 24 when compared to undisturbed control soils. By Year 24, soil density on scarified soils showed recovery to control treatments.

Soil bulk densities at 15-30 cm were not significantly different between the control and the two burn treatments at Year 6; however, the scarified treatment showed a 35% increase ($p<0.1$) over the other three site preparation treatments (Figure 2). A comparison of scarified soil bulk density means showed an 11%-16% increase in the 15-30 cm soil depths over the 0-15 cm soil depth across all sampling periods, although the differences were not significant by Year 24 ($p>0.1$). All treatments showed densification at Year 14, with no large compaction differences (<12%) observed between treatments. By Year 24, scarified soils showed recovery to control bulk density levels as observed in Year 6; however, scarified soils continued to show significantly higher bulk densities at Year 24 over control and broadcast burn soils ($p<0.1$, 21%).

3.1.2 Soil Organic Matter and Macronutrients: Soil organic matter concentration in the upper 30 cm was not significantly different between the undisturbed control and either burn treatments 6 years after harvest (Table 1). Similar results were

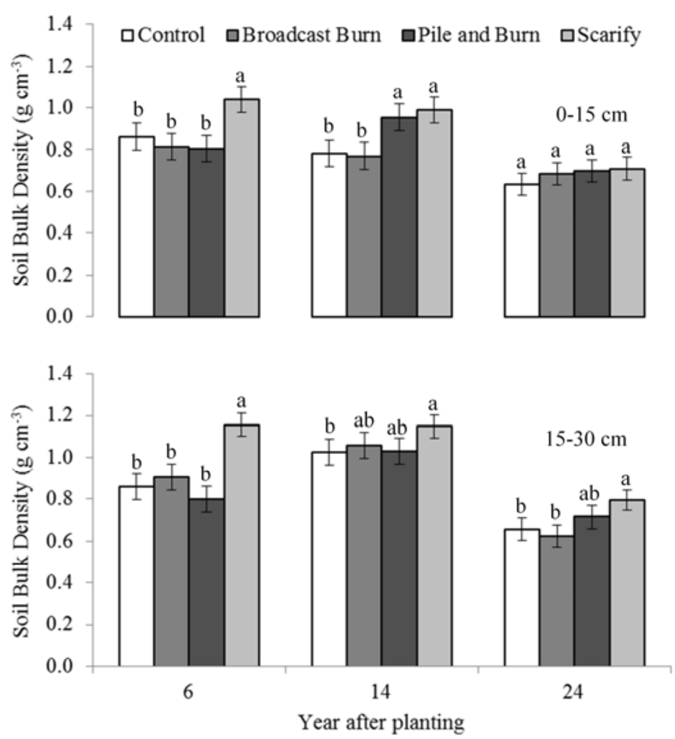

Figure 2. *Soil bulk density across an array of site preparation treatments at 0-15 and 15-30 cm—6, 14, and 24 years after stand establishment. Different letters represent a significant treatment effect at p≤0.1. Letters for treatment comparisons are only by sampling year and soil depth.*

Table 1. *Site preparation effects on soil properties 6 and 24 years following stand establishment.*

Year After Planting	Site Prep Treatment	Organic Matter	Mineralizable N	Available P	Exchangeable Cations K	Ca	Mg
		g kg^{-1} soil	-------------------------	µg g^{-1} soil	-------------------------		
6	Control	62[a]	52[a]	3.5[b]	369[a]	2500[a]	152[a]
	Broadcast Burn	59[a]	46[a]	5.7[a]	362[a]	2561[a]	136[a]
	Pile and Burn	63[a]	47[a]	7.0[a]	334[ab]	2882[a]	152[a]
	Scarify	42[b]	31[b]	3.4[b]	260[b]	1369[b]	121[a]
24	Control	58[ab]	31[bc]	3.7[a]	430[b]	1573[ab]	106[ab]
	Broadcast Burn	72[a]	63[a]	4.9[a]	743[a]	2720[a]	138[a]
	Pile and Burn	60[a]	57[ab]	4.2[a]	365[b]	1867[ab]	126[ab]
	Scarify	40[b]	29[c]	2.5[a]	300[b]	1213[b]	69[b]

Within columns and year after planting, different superscript letters indicate significant differences (p<0.1).

found in Year 24; however, soil organic matter concentration was significantly higher in the burn treatments (60-72 g kg^{-1}) than the scarified treatment (40 g kg^{-1}). The scarified soil organic matter mean at 24 years was 31% lower than the undisturbed control mean; however, the variation within control soil organic matter prevented these values from being significantly different (p>0.1). Overall, scarification significantly reduced soil organic matter over non-scarified treatments by 32% in Year 6 and 37% in Year 24 (p<0.1).

All soil macronutrients, except Mg, were significantly lower in scarified soils than either burn treatment at 6 years (p<0.1) (Table 1). The undisturbed control soil macronutrient concentrations at 6 years showed similar levels as those in burn treatments; however, P was 65%-100% lower, showing greater similarity to levels seen in scarified soils. After 24 years, considerable variation was seen in soil macronutrients regardless of site preparation treatment; however, burn treatments consistently showed higher mean levels of all macronutrients, although not all means were significantly different than control or scarify treatments (p>0.1). Overall, there was a strong correlation in Year 24 between soil organic matter concentration and the exchangeable cations K, Ca, and Mg as influenced by site preparation treatment (Table 1, Figure 3).

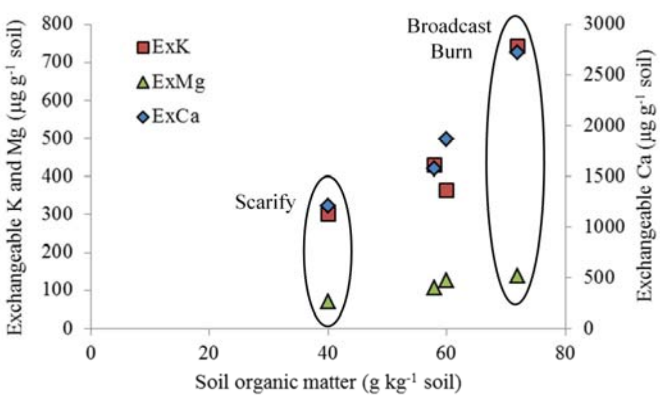

Figure 3. *Exchangeable soil cation concentrations as a function of soil organic matter and site preparation treatments to a depth of 30 cm 24 years post-regeneration on a volcanic ash soil.*

3.2 Douglas-fir Growth and Nutrition

3.2.1 Douglas-fir Growth: Year 6 growth data, while limited to height only, showed a 56% decrease in height on scarified soils relative to all other site preparation treatments (Table 2). There was no significant difference in height across non-scarified treatments. Similar growth differences between scarified and non-scarified treatments were shown for DBH and height in Year 14. A stem volume mean comparison in Year 14 showed a 62% reduction on scarified versus non-scarified soils; however, the variation in stem diameters and height within this age class was large enough to mask any statistically significant volume differences (p>0.1). By Year 24, both burn treatments showed approximately 12% greater volume over the undisturbed control and 92% greater volume than the scarified treatment. Despite the significant growth differences between the control and both burn treatments, control growth had significantly more individual tree volume (72%) than trees growing on scarified soils after 24 years.

For simplicity of comparison, incremental diameter stem growth was grouped by undisturbed control, burn, and scarify treatments. Broadcast burn and pile and burn showed no significant DBH, height or volume differences across all sampling years (p>0.1); therefore, these treatments were combined into a single burn treatment (Figure 4). Overall, all treatments showed increasing diameter growth during the first decade but began to decline during the second decade. Within 10 years of peak annual diameter growth at Year 14, diameter growth had declined by 35, 32, and 30 percent within the undisturbed control, burn, and scarify treatments.

As seen with sampling year DBH measurements in Table 2, annualized diameter growth on control and burn treatments significantly outperformed scarified treatments (p<0.1) (Figure 4). By Year 10, burn diameter growth began to differentiate from control growth and became significantly greater by Year 15, remaining significant up to the last measurement cycle. Comparison between control and burn diameter means after the first sampling period (5-9 years) show burn growth outperforming control growth by 8%, 12%, and 13%. Annu-

Table 2. *Site preparation effects on individual tree diameter at breast height (DBH), total height, and volume 6, 14, and 24 years following stand establishment.*

Year After Planting	Site Prep Treatment	DBH (cm)	Height (m)	Volume (m^3)
6	Control	-	3.1^a	-
	Broadcast Burn	-	3.3^a	-
	Pile and Burn	-	3.2^a	-
	Scarify	-	1.8^b	-
14	Control	9.6^a	6.3^a	0.024^a
	Broadcast Burn	10.4^a	6.4^a	0.028^a
	Pile and Burn	10.1^a	6.5^a	0.027^a
	Scarify	6.5^b	4.9^b	0.010^a
24	Control	20.2^b	13.5^a	0.187^b
	Broadcast Burn	22.2^a	13.4^a	0.213^a
	Pile and Burn	21.9^a	13.5^a	0.206^a
	Scarify	16.3^c	11.8^b	0.109^c

Within columns and year after planting, different superscript letters indicate significant differences (p<0.1). Note: DBH was not measured in Year 6.

alized diameter growth over the entire 24-year period showed a 17% and 26% diameter increase on control and burn treatments over scarification. Means comparisons across the four periodic intervals indicated that annual control diameter growth outperformed scarification by 17%, 22%, 15%, and 14%; whereas annualized diameter growth on burn treatments increased by 14%, 32%, 29%, and 29% over scarified treatments.

3.2.2 Douglas-fir Needle Mass and Nutrition: Similar to Year 6 non-scarified soil chemistry, there were no significant differences in needle mass and nutrient content across non-scarified site preparation treatments (p>0.1) (Table 3). However, the 6-year needle mass on the scarified site preparation treatment showed a significant 29% reduction in needle mass and a 25%-42% reduction in the nutrients N, P, K, Ca, and Mg over non-scarified site preparation treatments. After 24 years, needle mass and nutrient content (except for Mg) were no longer significantly different between undisturbed control and scarify (p>0.1). Interestingly, both burn site preparation treatments showed 20% higher needle mass (p<0.1) and thus a higher content of N (32%), P (20%), K (24%), and Mg (19%) over the control. Except for Ca and Mg, needle mass and nutrient content on burn site preparation treatments continue to be significantly greater than the scarified treatment after 24 years (p<0.1). Additionally, needle N and P content after 24 years followed closely the higher soil N and P concentrations seen in Year 24 (Tables 1 and 3), with foliar and soil N highly correlated (r = 0.97,

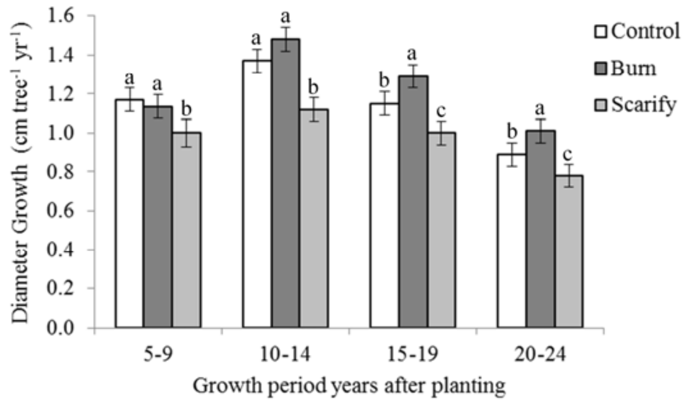

Figure 4. *Individual tree, periodic annual diameter increment (taken 0.5 m above root collar) after stand establishment. Burn treatment reflects the average periodic diameter increment mean of the broadcast burn and pile and burn site preparation treatments. Within growth periods, different superscript letters indicate significant differences (p<0.1).*

p<0.01). Needle nutrient concentrations did not follow needle mass or nutrient content patterns, showing no significant or consistent differences between site preparation treatments in Years 6 and 24 (p>0.1, data not shown).

Discussion

4.1 Soil Bulk Density

Compaction of volcanic ash following scarification was not surprising based on similar studies of silvicultural impacts on regional volcanic ash soils (Clayton et al. 1987, Powers et al. 2005, Geist et al. 2008) (Figure 2). In these studies, compaction from either harvest or site preparation activities increased volcanic ash bulk density in the upper 30 cm by 14%-50%, depending on ash mantle purity (i.e., degree of coarse fragment mixing, soil aggregation), which is within the maximum compaction we observed of 35% at the 15-30 cm soil depth. Little recovery of scarified soil bulk density 14 years post-compaction in our study supports other research that shows minimal bulk density recovery in fine-textured soils 5-10 years following severe soil compaction (Powers et al. 2005, Page-Dumroese et al. 2006). Our data suggest that frigid, ash-mantled soils will require at least two decades to recover from compaction, which may indicate that freeze-thaw cycles alone may not be very effective in overcoming soil compaction in these fine-textured soils (Powers et al. 2005).

The apparent densification of 0-15 cm pile and burn soils and the 15-30 cm control and burn site soils at Year 14 (Figure 1) suggest either a sampling method artifact or an actual increase in soil bulk density. We cannot ignore the fact that two differing methods were used to collect soil bulk density measurements in Years 6 and 14. There is potential for variation within the two methods to account for these differences. This is often a problem with long-term studies, which often suffer from changes in technology usage and personnel, thus contributing to variation and sampling error.

Table 3. *Site preparation effects on needle mass and nutrient content (mg needle^{-1}) 6 and 24 years following stand establishment.*

Year After Planting	Site Prep Treatment	Needle Mass	N	P	K	Ca	Mg
6	Control	4.1^{a}	0.062^{a}	0.009^{a}	0.037^{a}	0.020^{a}	0.005^{a}
	Broadcast Burn	3.9^{a}	0.060^{a}	0.008^{a}	0.037^{a}	0.020^{a}	0.005^{a}
	Pile and Burn	4.0^{a}	0.061^{a}	0.009^{a}	0.037^{a}	0.020^{a}	0.005^{a}
	Scarify	3.1^{b}	0.044^{b}	0.006^{b}	0.027^{b}	0.016^{b}	0.004^{b}
24	Control	6.0^{b}	0.071^{b}	0.010^{bc}	0.052^{b}	0.029^{a}	0.008^{b}
	Broadcast Burn	7.5^{a}	0.095^{a}	0.011^{ab}	0.061^{a}	0.033^{a}	0.009^{a}
	Pile and Burn	7.2^{a}	0.094^{a}	0.013^{a}	0.068^{a}	0.033^{a}	0.010^{a}
	Scarify	6.2^{b}	0.076^{b}	0.009^{c}	0.051^{b}	0.033^{a}	0.009^{a}

Within columns and year after planting, different superscript letters indicate significant differences ($p<0.1$).

4.2 Soil Organic Matter and Macronutrients

Outside the LTSP study, very few studies exist that document long-term effects (>10 years) on volcanic ash soil nutrient pools following disturbance, with most focusing on soil compaction (Clayton et al. 1987, Geist et al. 2008). One three-year study on ash-mantled soil in Northern Idaho showed a reduction in total soil N, organic matter, exchangeable cations (K, Ca, Mg) and cation exchange capacity (CEC) following the loss of forest floor and mineral topsoil to a depth of 10 cm (Page-Dumroese et al. 1997). Soil organic matter, not only a long-term source for plant essential nutrients, is also an important regulator of CEC (Fisher and Binkley 2000). Thus, any removal will degrade soil nutrient content and retention (Page-Dumroese et al. 2000). This may account for the often significantly lower exchangeable cations we observed 24 years after regeneration on scarified soils (Table 1, Figure 3).

Depending on burn severity, fire can have either a beneficial or degrading influence on site quality and productivity (Kimmins 1996). In our study, the influence of fire on long-term soil nutrient status shows that a broadcast burn or a pile and burn site preparation treatment can often significantly enhance soil N, P and exchangeable cation content up to 24 years post-regeneration (Table 1). While nutrient pulses into soil are often found in the short-term following either harvest or fire activity (Lamontagne et al. 2000, Simard et al. 2001, Kimmins 2004, Thiffault et al. 2007), long-term effects have been attributed to the translocation of hydrophobic organic matter from the surface into mineral soil (Johnson and Curtis 2001). This may explain why at Year 6, the undisturbed control soil nutrient status is not significantly different from either of the burn treatment soils, as the assart effect from harvesting is contributing similar pulses of nutrients. However, after 24 years, the pulse of nutrients from the harvest effect is waning (now no longer significantly different from scarified treatments), but burn areas continue to show near-harvest levels of soil nutrients.

We had expected the soil nutrient concentrations in the pile and burn treatment to exceed those observed in the broadcast burn treatment, due to the heavier concentration of organic materials. While Year 6 soil nutrient concentration means were overall higher in the pile and burn, they were not significantly different from broadcast burn means, nor at 24 years (Table 1). We attribute this lack of separation to burn severity. Despite higher concentrations of organic matter at pile and burn locations, the quantity of combustible materials resulted in a higher heat intensity than broadcast burning, thereby volatilizing nutrients and potentially mitigating any advantage of pile and burn nutrient pulses in the long-term.

4.3 Douglas-fir Growth

The site preparation treatments analyzed in this dataset both stimulated and reduced tree growth. Trees in the control and either burn treatment outgrew those in scarified treatments, while trees within a burn treatment had greater overall growth than all other treatments after 24 years (Table 3, Figure 3). Height growth was not positively or negatively affected by either burn site preparation treatment (compared to the control); however, diameter growth following a burn application showed significant separation from control diameter growth beginning in the latter half of the second decade, which resulted in greater volume additions. Scarification overall had lower diameter and height growth across all monitoring periods, resulting in significant declines in tree volume. The mechanisms behind this separation within the site preparation treatments can probably be attributed to relative changes in native soil bulk density and soil nutrient supply during crown closure and subsequent tree competition for site resources. Each of these factors is discussed below.

Zabowski et al. (2000) found that Douglas-fir growth in the eastern Cascade Mountain region of Washington State was not negatively affected by bulk densities up to 1.15 g cm^{-3}. Other studies have shown Douglas-fir root growth limitations occurring at 0.9 g cm^{-3} for fine-textured soils and 1.8 g cm^{-3} for coarse-textured soils; however, in these studies, shoot growth was not generally limited in either field trials or pot studies (Forristall and Gessel 1955, Minore et al. 1969, Heilman 1981, Singer 1981). Based on these observations, our volcanic ash bulk density data would suggest that during the seedling to sapling stage, scarified soils were consistently at or near both root and shoot growth limiting densities, particularly at the 15-30 cm soil depth (Figure 2). The relative increase of 21%-35% in scarified soil bulk density across both sampling horizons is well over the 18% level reported to reduce tree height, shoot and volume growth (Froehlich 1979, Froehlich and McNabb 1983, Froehlich et al. 1986, Gent and Morris 1986, Misra and Gibbons 1996), and at or above the 20% threshold used by the United States Forest Service (USFS) to indicate detrimental soil disturbance in volcanic ash soils (Craigg and Howes 2007). Thus, the observed increase in scarified soil bulk density within our datasets can be correlated with either reduced water-holding capacity and soil aeration, increased root penetration resistance, or a combination of both, any of which is contributing to reduced Douglas-fir growth relative to the control.

The perturbation of surficial organic matter has differing long-term consequences for tree growth on ash-mantled soils, depending on whether a scarification or burn treatment is applied. Our data suggests that as Douglas-fir transitions from the sapling to pole stage and competition for site nutrient resources intensifies, a post-harvest burn treatment can mitigate competition-induced growth reduction (Figure 4). Plantation spacing of 2.4 m at this research site ensured that crown closure would occur between 15 and 20 years of age. At this stage of stand development, underground competition for resources increases dramatically, while the assart period is ending (Kimmins 2004). A burn site preparation treatment significantly increased soil nutrient status relative to the control, thus providing additional plant essential nutrients during a critical stage of later stand development. Conversely, scarification significantly reduced plant essential nutrients, which—in combination with soil densification—has retarded Douglas-fir growth. Similar results were reported by Clayton et al. (1987) and Geist et al. (2008) on volcanic ash soils, showing significant reductions in tree growth following soil displacement and compaction.

Additionally, visual classification of Douglas-fir growing on scarified treatments showed that the majority of these trees are rapidly moving into intermediate tree form and within the fourth decade may either be suppressed or dead. We qualitatively observed that the surrounding height growth of more robust trees on either control or burn treatments are reducing light interception for the trees on scarified soils, potentially further acerbating growth loss from soil nutrient depletion and compaction.

4.4 Douglas-fir Needle Mass and Nutrient Content

Six-year Douglas-fir foliar nutrition reflects observations made earlier that nutrient pulses into soil from harvesting and the application of fire are similar in the short-term, as we found no significant differences between the control and burn site treatment foliar nutrition levels (Tables 1 and 3). However, similar to findings by Thiffault et al. (2007), we found that long-term foliar nutrition benefits from fire treatments. Thus, the observed long-term nutritional benefit to needle mass development and overall volume growth following a burn site preparation treatment is a direct response to fire-induced incorporation of organic matter into the soils and a corresponding increase in soil nutrient content (particularly for K).

The pulse of nutrients attributed to harvest only (control—no site preparation) is evident in the control foliage at 6 years when compared to the scarify foliage; however, this difference disappears after 24 years. Because we have no baseline data (pre-harvest) against which to compare foliar nutrient levels, we must conclude that the control soils (and hence foliar nutrition) are returning to a pre-harvest state following the assart effect (Kimmins 1996). This further suggests that the scarified soil nutrients, and thus foliar nutrition, are beginning to recover to pre-harvest conditions following the re-establishment of a forest floor and subsequent organic matter mineralization. The lack of separation in needle nutrient concentration between the various site preparation treatments at either sampling year can be attributed to foliar nutrient regulation for maintenance of optimum nutrient balances.

Conclusions

Harvest and site preparation activities must account for the site and soil conditions contributing to forest growth. Awareness of site properties that can be negatively impacted through the implementation of silvicultural prescriptions is crucial to maintaining long-term site productivity. Specifically, our data supports findings from the North American Long-Term Soil Productivity study that fine-textured volcanic ash soils of Northern Idaho, USA, are sensitive to long-term compaction. Furthermore, displacement of organic matter and nutrient-rich surface soil, in conjunction with soil compaction, can significantly reduce Douglas-fir growth into the third decade after regeneration. While scarification as a site preparation treatment is not commonly applied as a regeneration tool within this region today, it should be acknowledged that machine scarification (i.e., organic matter and surface soil displacement) and soil compaction can occur during harvest activities or during pile and burn site prep treatments. Therefore, mitigation of ground-based site disturbance is best achieved through operator education of local site limitations and active oversight by supervisors. These actions coupled with an appropriate site preparation treatment can mitigate future site productivity loss on fine-textured volcanic ash soils within Northern Idaho, USA.

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