Site Preparation Effects on Volcanic Ash Forest Soils and Douglas-fir Regeneration

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ABSTRACT

Physical and chemical soil characteristics along with Douglas-fir (*Psuedotsuga menziesii* var. *glauca*) growth and foliar nutrition were tracked over a 24 yr period following a ground based regeneration harvest and site preparation in northern Idaho, USA. Harvest unit soils were classified as Andisols overlaying metasedimentary parent material within an udic-frigid moisture and temperature regime. Douglas-fir site index at base age 50 was 29 m. Four site preparation conditions were monitored: undisturbed control, broadcast burn, pile and burn, and mechanical scarification. Periodic soil-site measurements were collected on each condition at regeneration stand ages 6, 14 and 24 yrs. Six and 14-yr soil bulk density on scarified conditions were significantly higher at 0-15 and 15-30 cm than all other conditions. Scarified soil bulk density showed recovery to non-scarify condition levels at 0-15 cm and 15-30 cm after 24 yrs. Scarified soil organic matter (SOM) and N were significantly reduced by 32 and 42% over control levels 6 yrs post-harvest. After 24 yrs, 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 conditions were significantly lower than broadcast burn or pile and burn conditions after 24 yrs ($p<0.1$). Soil and foliar N content was significantly higher in those conditions receiving a burn application after 24 yrs ($p<0.1$). Tree growth on either burn condition showed significantly greater diameter (35%), height (14%) and volume (92%) when compared to trees growing on scarified conditions after 24 yrs ($p<0.1$). These results indicate that tree growth on frigid, ash-mantled forest soils of the Inland Northwest can be significantly reduced following soil compaction and displacement of organic-rich topsoil. Where soil disturbance is minimized and organic matter retention is coupled with a burn treatment, soil and tree productivity will be maintained or enhanced.

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

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INTRODUCTION

The maintenance or enhancement of 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). Forest biofuels research has shown that the net energy production from converted woody residues is equal to or higher than energy derived from agricultural byproducts such as corn stover, wheat straw and switchgrass (Malmsheimer et al., 2008). Recent projections estimate that global consumption of these alternative biofuels will increase significantly over the next several decades (IEA, 2008). Within the US, the Renewable Fuels Standard of the Energy Independence and Security Act of 2007 stipulates that by 2022 cellulosic ethanol must account for over 40 percent of targeted annual ethanol usage or 16 billion gallons (White, 2009). The implication of these requirements is 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 does not affect forest growth; however, site disturbance through soil compaction and/or removal of organic rich surface horizons does affect productivity (Powers et al., 2005). 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 drought stress earlier, thereby decreasing site productivity (Kimmins, 1996). In addition, this shift from macropores to micropores in fine textured soils will decrease the saturated hydraulic conductivity of the soil, increase the non-saturated hydraulic conductivity, and decrease aeration (Cullen et al., 1991; Gent et al., 1983; Hillel, 1982; Huang et al., 1995; Miyazaki, 1996). Inhibited root growth has been attributed to the reduced aeration and increased penetration resistance associated with compaction (Pritchett and Fisher, 1987; Misra and Gibbons, 1996; Atwell, 1993). Soil bulk density increases of as little as 18% on fine (or coarse) textured soils have been reported to 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 effects on fine-textured soils may disappear as soil will naturally recover from compaction 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).

Soil scarification or displacement affects on vegetation productivity shows 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*) plantations (Skinner et al., 1989; Murphy et al., 2004), Douglas-fir (*Psuedotsuga menziesii*) 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 yr 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 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.

The near constant across 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 soil compaction (Clayton et al., 1987; Murphy et al., 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 yrs, 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 time frame may be too short for softwood plantations in the Inland Northwest, USA. It is unknown whether these early growth declines are mitigated by site recovery within the third and fourth decade. Even with an increasing demand for forest resources in the bioenergy sector, stand rotations within the Inland Northwest 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 multiple thinning entries or final regeneration harvests and site preparation treatments on forest soils of the Inland Northwest, USA. Therefore, our objective was to augment the existing body of data with findings midway through the third decade of growth following harvest and site preparation activities on a frigid, fine textured, ash mantled forest soil in north Idaho, USA. To achieve this objective, we collated and analyzed a series of datasets collected over a 24 yr interval to assess site preparation effects on selected soil properties and Douglas-fir growth and nutrition following a regeneration harvest.

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 1,270 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 – 40%. The vegetation community is classified as *Abies grandis*/*Clintonia uniflora* on the westerly, steeper slopes and *Thuja plicata*/*Clintonia uniflora* on the gentler, northerly slopes (Cooper et al., 1991; Soil Survey Staff, 2010). The 50-yr site index for Douglas-fir is 29 m (Stoker, 1990).

Three soil series 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, 2010). These soils are all deep and well drained with an ash cap from 36 – 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, 2010).

2.2 Harvest and Site Preparation

An 87-ha mixed-conifer stand was clear-cut 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 mechanically 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 percent 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, 4 in^3 container Douglas-fir seedlings on a 2.4 m X 2.4 m spacing to 1,683 trees per ha. The seed source for the plantation was collected from local genetic stock. At the time of planting poor root system development was observed and noted on much of the planting stock (Roché, 1997).

In 1988 nine plots were randomly located across the harvest unit. At each plot location four site preparation conditions were identified: control (undisturbed); broadcast burn (burned but otherwise undisturbed); pile and burn (tractor piles that were burned); and scarify (area from which organic matter, coarse woody debris, and topsoil was displaced during tractor piling). Individual study trees were selected by starting from the plot center stake in a northerly direction and working clockwise in concentric circles. The microsite around each tree (radius equal to approximately one tree height) was examined for evidence of any of the desired site preparation conditions. If the site preparation condition for a tree could not be clearly determined, 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 conditions were located per plot center location. A total of 180 sample trees were selected and classified into one of four site preparation conditions within the harvest unit across the nine plots.

Plots one through five and seven through nine are located on westerly facing slopes, plot six is on a northeast facing slope. Plots one through four and seven through eight are located on the Stepoff soil series. Plots five and six are located on the Poorman soil series and plot number nine is located on the Township soil series.

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 yrs following stand regeneration (7 yrs following site preparation). This dataset did not include a tree diameter at breast height (DBH) measurement. A second set of data was collected 14 yrs 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 yr 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 was collected pre-harvest, consequently, all comparisons are between site preparation conditions 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 condition per plot. 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).

In order to relate the two disparate bulk density measures, the upper and lower two 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 only valid 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 condition to obtain one bulk soil sample per condition per plot. Due to budget constraints in year 24, plot-treatment 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 by standard American Society of Agronomy (ASA) soil procedures for soil organic matter and the macronutrients N, P, K, Mg and Ca (Page et al., 1982). Macronutrients are reported as mineralizable N, available P and extractable K, Mg and Ca. 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 were randomly selected within each plot by treatment class for foliar nutrient analysis. Douglas-fir foliage was collected on selected plot trees by treatment after dormant season in the fall. 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, 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 one hundred needles.

Diameter at breast height was collected in yrs 14 and 24 using a standard diameter tape. Tree height in yr 6 was directly measured with a measuring stick. Tree heights in yrs 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 yr 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 yrs, 8 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 method and mortality was found. The confirmed mortality, combined with the stem damaged trees, resulted in a 95.6% survival of the original sample.

2.5 Statistical Analyses

All soil and tree data were analyzed with PROC MIXED statements in SAS 9.2 (SAS, 2008). Plot 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 condition, and the interaction between monitoring year and site condition. 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 plot 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 $p \leq 0.1$.

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 conditions compared to the undisturbed control at years 6 and 24 (p>0.1) (Fig. 1). At year 14, the pile and burn condition 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 conditions.

Ash mantle bulk densities at 15-30 cm were not significantly different between the control and the two burn conditions at year 6; however, the scarified condition showed a 35% increase (p<0.1) over the other three site conditions (Fig. 1). 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 conditions 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; although, scarified soils continues to show significantly higher bulk densities at year 24 over control and broadcast burn soils (p<0.1, 21%).

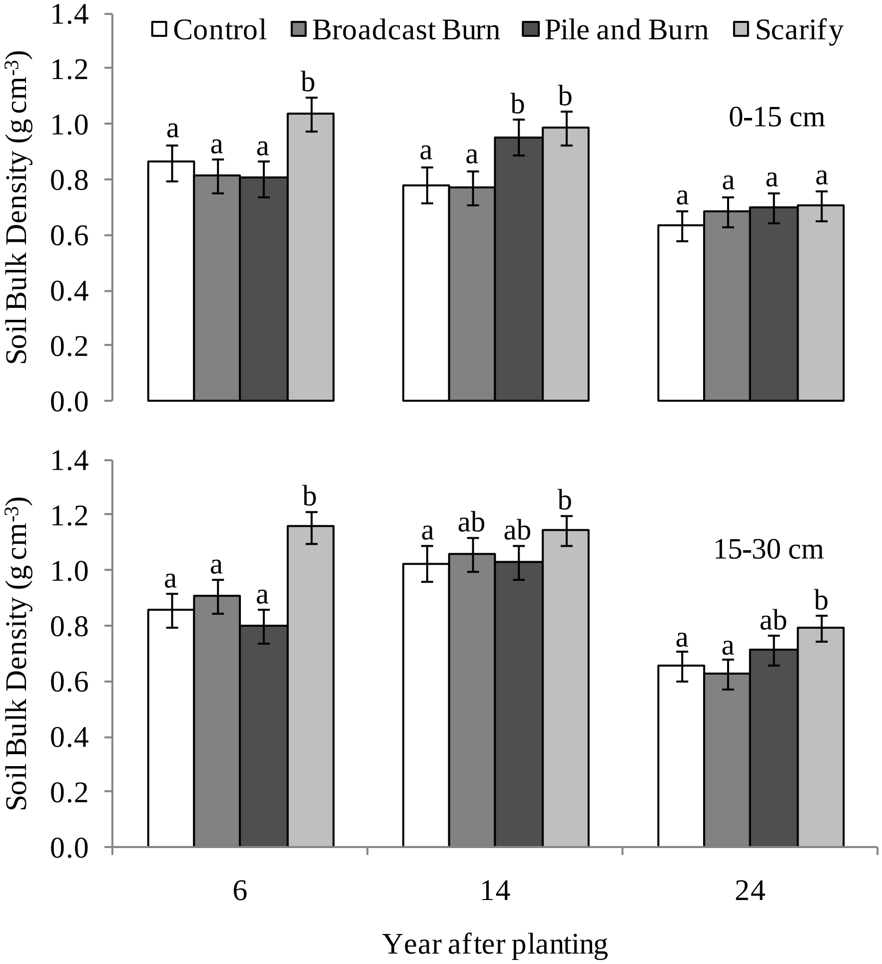

Figure 1. Volcanic ash soil bulk density across an array of site preparation conditions at 0-15 and 15-30 cm 6, 14 and 24 years after stand establishment. Different letters represent a significant treatment effect at $p \leq 0.1$. Letters for treatment comparisons are only by sampling year and soil depth.

3.1.2 Soil Organic Matter and Macronutrients

Soil organic matter content in the upper 30 cm was not significantly different between the undisturbed control and either burn conditions six years after harvest (Table 1). Similar results were found in year 24; however, soil organic matter accumulation was significantly higher in the burn conditions (60-72 g kg^{-1}) than the scarified condition (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 conditions by 32% in year 6 and 37% in year 24 ($p < 0.1$).

Table 1. Site preparation effects on volcanic ash soil properties 6 and 24 years following stand establishment. Means followed by the same letter are not significantly different at p≤0.1. Letters for treatment comparisons are only within sampling year.

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

All soil macronutrients, except Mg, were significantly lower in scarified soils than either burn condition at six years ($p < 0.1$) (Table 1). The undisturbed control soil macronutrient concentrations at six years showed similar levels as those in burn conditions; 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 condition; however, burn conditions consistently showed higher mean levels of all macronutrients, although not all means were significantly different than control or scarify conditions ($p > 0.1$). 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 condition (Table 1, Fig. 2).

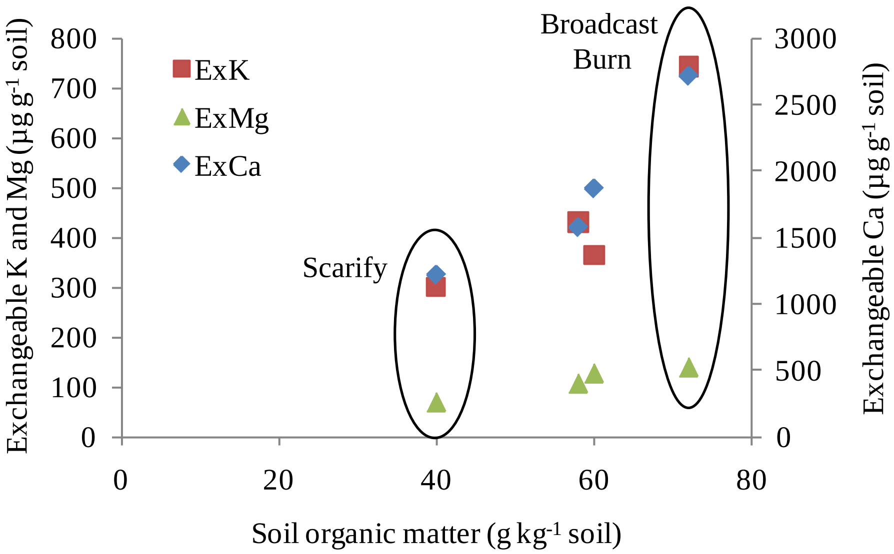

Figure 2. Exchangeable soil cation concentrations as a function of soil organic matter and site preparation conditions to a depth of 30 cm 24 yrs post-regeneration on a volcanic ash soil.

3.2 Douglas-fir growth and nutrition

3.2.1 Douglas-fir growth

Year 6 growth data, while limited to height only, shows a 56% decrease in height on scarified soils relative to all other site conditions (Table 3). There is no significant difference in height across non-scarified conditions. Similar growth differences between scarified and non-scarified conditions 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 conditions showed approximately 12% greater volume over the undisturbed control and 92% greater volume than the scarified condition. Despite the significant growth differences between the control and both burn conditions, control growth had significantly more individual tree volume (72%) than trees growing on scarified soils after 24 yrs.

Table 3. Site preparation effects on individual tree diameter at breast height (dbh), total height, and volume 6, 14 and 24 years following stand establishment. Means followed by the same letter are not significantly different at p≤0.1. DBH was not measured in year 6. Letters for treatment comparisons are only within sampling year.

Year after planting	Site Preparation	Dbh	Height	Volume
		cm	m	m^3
6	Control	-	3.1a	-
	Broadcast Burn	-	3.3a	-
	Pile and Burn	-	3.2a	-
	Scarify	-	1.8b	-
14	Control	9.6a	6.3a	0.024a

	Broadcast Burn	10.4a	6.4a	0.028a
	Pile and Burn	10.1a	6.5a	0.027a
	Scarify	6.5b	4.9b	0.010a
24	Control	20.2a	13.5a	0.187a
	Broadcast Burn	22.2b	13.4a	0.213b
	Pile and Burn	21.9b	13.5a	0.206b
	Scarify	16.3c	11.8b	0.109c

For simplicity of comparison, incremental diameter stem growth was grouped by undisturbed control, burn and scarify conditions. 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 condition (Fig. 3). Overall, all conditions 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 conditions.

As seen with sampling year DBH measurements in Table 3, annualized diameter growth on control and burn conditions significantly outperformed scarified conditions ($p<0.1$) (Fig. 3). 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 yrs) show burn growth outperforming control growth by 8%, 12% and 13%. Annualized diameter growth over the entire 24 yr period shows a 17% and 26% diameter increase on control and burn conditions over scarification. Means comparisons across the four periodic intervals indicate that annual control diameter growth outperformed scarification by 17%, 22%, 15% and 14%; whereas, annualized diameter growth on burn conditions increased by 14%, 32%, 29% and 29% over scarified conditions.

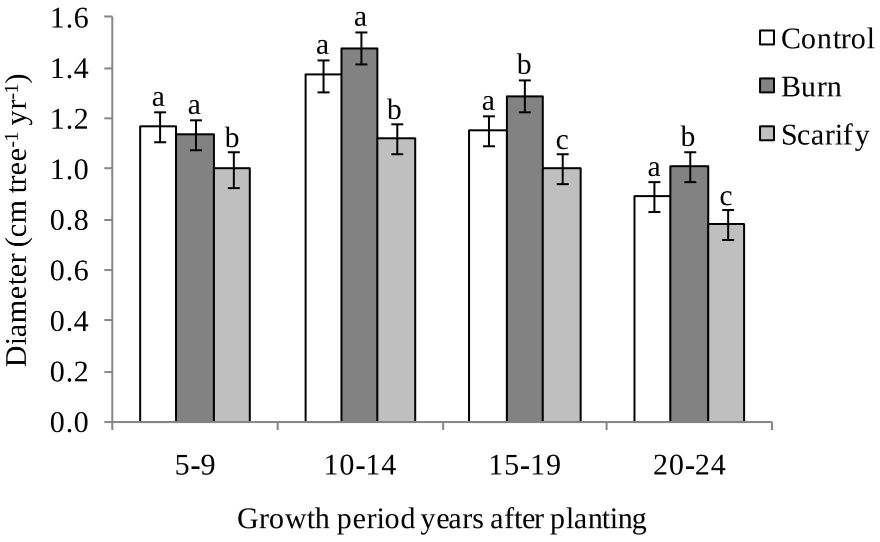

Figure 3. Individual tree, periodic annual diameter increment (taken 0.5 m above root collar) after stand establishment. Burn condition reflects the average periodic diameter increment mean of the broadcast burn and pile and burn site conditions. Different letters represent a significant condition effect at $p \leq 0.1$. Letters for condition comparisons are only within sampling year.

3.2.2 Douglas-fir needle mass and nutrition

Similar to year 6 soil chemistry in non-scarified condition soils, there were no significant differences in needle mass and nutrient content across non-scarified conditions (p>0.1) (Table 2). However, the six year needle mass on scarified condition 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 conditions. After 24 years, needle mass and nutrient content (except for Mg) are no longer significantly different between the undisturbed control and scarified conditions (p>0.1). Interestingly, both burn conditions now show 20% higher needle mass (p<0.1) and thus a higher content of N (32%), P (20%), K (24%) and Mg (19%) over control conditions. Except for Ca and Mg, burn condition needle mass and nutrient content continue to be significantly greater than the scarified condition after 24 years (p<0.1). Additionally, needle N and P content after 24 yrs follow closely the higher soil N and P concentrations seen in yr 24 (Tables 1 and 2), with foliar and soil N highly correlated (r = 0.97, p<0.01). Needle nutrient concentrations did not follow needle mass or nutrient content patterns, showing no significant or consistent differences between conditions in years 6 and 24 (p>0.1, data not shown).

Table 2. Site preparation effects on needle mass and nutrient content 6 and 24 years following stand establishment. Means followed by the same letter are not significantly different at p≤0.1. Letters for treatment comparisons are only within sampling year.

Year after planting	Site Preparation	Needle Mass	N	P	K	Ca	Mg
		---------------------------- g/100 needles -----------------------------					
6	Control	0.41a	0.62a	0.09a	0.37a	0.20a	0.05a
	Broadcast Burn	0.39a	0.60a	0.08a	0.37a	0.20a	0.05a
	Pile and Burn	0.40a	0.61a	0.09a	0.37a	0.20a	0.05a
	Scarify	0.31b	0.44b	0.06b	0.27b	0.16b	0.04b
24	Control	0.60a	0.71a	0.10ab	0.52a	0.29a	0.08a
	Broadcast Burn	0.75b	0.95b	0.11bc	0.61b	0.33a	0.09b
	Pile and Burn	0.72b	0.94b	0.13c	0.68b	0.33a	0.10b
	Scarify	0.62a	0.76a	0.09a	0.51a	0.33a	0.09b

Discussion

4.1 Soil bulk density

Compaction of volcanic ash within scarified soil conditions 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) (Fig. 1). In these studies, compaction from either harvest or site preparation activities increased volcanic ash bulk density in the upper 30 cm by 14-50 percent depending on ash mantle purity (i.e., degree of coarse fragment mixing, soil aggregation), which is within the maximum compaction we observed of 35 percent at the 15-30 cm soil depth. Little recovery of scarified soil bulk density 14 yrs post-compaction in our study supports other research that shows minimal bulk density recovery in fine-textured soils 5-10 yrs following severe soil compaction (Powers et al., 2005; Page-Dumroese et al., 2006). Our data suggests 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 (Fig. 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. However, our findings are not alone in reporting soil densification following harvest activities. Several studies have shown that following harvest, heterotrophic respiration increases with an associated increase in soil CO_2 efflux, allowing soil particles to settle, resulting in a natural densification (Gordon et al., 1987; Chen at al., 2000; Powers et al., 2005). Whether this may play a role in the patterns observed is indiscernible from the data available; however, we can hypothesize that it may be a factor in the patterns observed. By year 24, stand establishment and canopy closure would have reduced soil temperature and moisture, thereby decreasing soil heterotrophic respiration, which, coupled with several decades of freeze/thaw cycles, soil fauna and root re-establishment, have led to the disaggregation of the densified soils.

4.2 Soil organic matter and macronutrients

Outside the LTSP study, very few studies exist that document long-term effects (>10 yrs) on volcanic ash soil nutrient pools following disturbance, with most focusing on soil compaction (Clayton et al., 1987; Geist et al., 2008). One 3 yr study on an ash mantled soil in northern Idaho showed a significant reduction in total soil N, organic matter and CEC following the loss of forest floor and mineral topsoil to a depth of 3 cm (Page-Dumroese et al., 1997). Soil organic matter, which is not only a long-term source for plant essential nutrients, is also an important regulator of soil cation exchange capacity (CEC) (Fisher and Binkley, 2000). Thus, any removal will degrade soil nutrient retention and increase nutrient leaching (Page-Dumroese et al., 2000). This may account for the often significantly lower exchangeable cations we observed 24 yrs after regeneration on scarified soils (Table 1, Fig. 2). The removal of organic-rich topsoil during scarification has contributed to a reduction of CEC in these soils. Thus, we can conclude from our data and other supporting research that the removal of surface organic litter and the displacement of organic-rich topsoil from a frigid, volcanic ash mantle will have a significant, long-term impact on soil cation retention.

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 pile and burn conditions can often significantly enhance soil N, P and exchangeable cation content up to 24 yrs post-regeneration (Table 1). While nutrient pulses into soil are often found in the short-term following either harvest or fire activity (Kimmins, 2004, Lamontagne et al., 2000; Simard et al., 2001; 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 condition soils, as the assart effect from harvesting is contributing similar pulses of nutrients. However, after 24 yrs, the pulse of nutrients from the harvest effect is waning (now no longer significantly different from scarified conditions), but burn areas continue to show near-harvest levels of soil nutrients.

We had expected the soil nutrient concentrations in the pile and burn condition to exceed those observed in the broadcast burn treatment due to the heavier concentration of organic materials. While year 6 soil nutrient content means were overall higher in the pile and burn, they were not significantly different than broadcast burn means, nor at 24 yrs (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 conditions analyzed in this dataset both stimulated and reduced tree growth. Trees in the control and either burn condition outgrew those in scarified conditions, while trees within a burn condition had greater overall growth than all other conditions after 24 yrs (Table 3, Fig. 3). Height growth was not positively or negatively affected by non-scarification, 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 conditions 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 (Fig. 1). 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 (Fig. 3). Plantation spacing of 2.4 m at this research site ensured that crown closure would occur between 15 and 20 yrs 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.

The overall decline in radial growth across all site conditions in the last decade illustrates the effect of stand crown closure and a subsequent increase in site resource competition (Fig. 3). The effect of site resource competition on radial growth was mitigated by a burn application when compared to either the control or scarify conditions. The higher fertility of soils in a burn treatment provided additional resources unavailable to the control soils, which no longer benefit from the assart period; or to scarified soils, which did not benefit from either the assart period or site nutrient retention. Additionally, visual classification of Douglas-fir growing on scarified conditions 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 conditions are reducing light interception for the trees on scarified soils; potentially further acerbating growth loss from soil nutrient depletion and compaction. Thus, our data suggests that to maintain the early stand growth trajectory for similar forest stand types within the Inland Northwest, USA, it would be recommended to thin densely stocked stands by age 15. Depending on technology development and demand, this thinning regime may shift from a pre-commercial thin to a biofuel extraction.

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 condition foliar nutrition levels (Tables 1 and 2). 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 and CEC (particularly for K).

The pulse of nutrients attributed to harvest only (control – no site preparation) is evident in the control foliage at 6 yrs when compared to the scarify foliage; however, this difference disappears after 24 yrs. Since we have no baseline data (pre-harvest) to compare foliar nutrient levels against, 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 conditions 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. This is crucial if forests of the drier interior Northwest, USA are intensively utilized as a source for bioenergy. Specifically, our data suggests that volcanic ash mantles of the forested Inland Northwest, USA are sensitive to long-term compaction and displacement of organic-rich topsoil organic matter, which in turn will significantly reduce long-term Douglas-fir growth. While scarification as a site preparation treatment is not commonly applied as a regeneration tool within Inland Northwest forests today, it should be acknowledged that scarification (i.e., topsoil displacement) and compaction can occur during harvest activities or during pile and burn site prep treatments. The movement of heavy track and wheeled equipment during harvest and post-harvest activities can create the same disturbance observed with an intentional scarification treatment. Although, these effects may impact less areal percentage of a harvest area when compared to a silvicultural scarification prescription, multiple entries or shorter rotations from bioenergy removals could have similar results in the long-term. Therefore, mitigation of ground-based site disturbance is best achieved through operator education of local site limitations and active oversight by contract compliance supervisors. These actions coupled with a burn site preparation treatment of residual slash, will maintain or significantly enhance future forest productivity of volcanic ash soils within this region.

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Sources Cited

Ares, A., Terry, T.A., Miller, R.E., Anderson, H.W., and Flaming, B.L. 2005. Ground-based forest harvesting effects on soil physical properties and Douglas-fir growth. Soil Sci. Soc. Am. J. 69: 1822-1832.

Atwell, B.J. 1993. Response of roots to mechanical impedance. Environ and Exper. Botany 33: 27-40.

Chen, H., Harmon, M.E., Griffits, R.P., and Hicks, W. 2000. Effects of temperature and moisture on carbon respired from decomposing woody roots. For. Ecol. Manage. 138: 51-64.

Clayton, J.L., Kellogg, G., and Forrester, N. 1987. Soil disturbance-tree growth relations in central Idaho clearcuts. USDA For. Serv. Res. Note INT-372. 6 p.

Cooper, S.V., Neiman, K.E., and Roberts, D.W. 1991. Forest habitat types of northern Idaho: A second approximation. USDA For. Serv. Gen. Tech. Rep. INT-236. 143 p.

Craigg, T.L., and Howes, S.W. 2007. Assessing quality in volcanic ash soils. In: Page-Dumroese, D.; Miller, R.; Mital, J.; McDaniel, P.; and Miller, D. (ed.). Volcanic-ash-derived forest soils of the Inland Northwest: Properties and implications for management and restoration. USDA For. Serv. Proc. RMRS-P-44. p. 47-66.

Cullen, S.J., Montagne C., and Ferguson H. 1991. Timber harvest trafficking and soil compaction in western Montana. Soil Sci. Soc. Am. J. 55: 1416-1421.

Fisher, R.F., and Binkley, D. 2000. Ecology and management of forest soils. John Wiley and Sons, Inc. New York. 489 p.

Forristall, F.F., and Gessel, S.P. 1955. Soil properties related to forest cover-type and productivity in the Lee Forest, Snohomish County, Washington. Soil. Sci. Soc. Am. Proc. 19: 384-389.

Froehlich, H.A. 1979. Soil compaction from logging equipment: Effects on growth of young ponderosa pine. J. Soil Water Conser. 34: 276-278.

Froehlich, H.A., and McNabb, D.H. 1983. Minimizing soil compaction in Pacific Northwest forests. In: Stone, E.L. (ed.). Forest soils and treatment impacts: Proc. of Sixth N. Am. For. Soils Confer. Univ. of Tenn. Conferences. Knoxville, Tenn. p. 159-192.

Froehlich, H.A., Miles, D.W.R. and Robbins, R.W. 1986. Growth of young Pinus ponderosa and Pinus contorta on compacted soil in Central Washington. For. Ecol. and Manage. 15: 285-294.

Geist, J.M., Hazard, J.W., and Seidel, K.W. 2008. Juvenile tree growth on some volcanic ash soils disturbed by prior forest harvest. USDA For. Serv. Res. Paper PNW-RP-573. 22 p.

Gent, J.A., Ballard, R., and Hassan, A.E. 1983. The impact of harvesting and site preparation on the physical properties of Lower Coastal Plain forest soils. Soil Sci. Soc. Am. J. 47: 595 - 598.

Gent, J.A., and Morris, L.A. 1986. Soil compaction form harvesting and site preparation in the Upper Gulf Coastal Plain. Soil Sci. Soc. Am. J. 50: 443 - 446.

Gomez, A., Powers, R.F., Singer, M.J., and Horwath, W.R. 2002. N uptake and N status in ponderosa pine as affected by soil compaction and forest floor removal. Plant and Soil. 242: 263-275.

Gordon, A.M., Schlentner, R.E., and Van Cleve, K. 1987. Seasonal patterns of soil respiration and CO^2 evolution following harvesting in the white spruce forests of interior Alaska. Can. J. For. Res. 17: 304-310.

Grey, D.C., and Jacobs, E.O. 1987. The impacts of harvesting on forest site quality. South Afr. For. J. 140: 60-66.

Heilman, P. 1981. Root penetration of Douglas-fir seedlings into compacted soils. For. Sci. 27: 660-666.

Hillel, D. 1982. Introduction to Soil Physics. Academic Press Limited. 364 p.

Huang, J., Lacey, S.T., and Ryan, P.J. 1995. Impact of forest harvesting on the hydraulic properties of surface soil. Soil Sci. 161(2): 79-86.

IEA. 2008. Energy Technology Perspectives 2008. International Energy Administration, Paris, France. 500 p.

Janowiak, M.K., and Webster, C.R. 2010. Promoting ecological sustainability in woody biomass harvesting. J. For. 108(1): 16-23.

Jansson, K.J. 1999. Comparison of density and water content determinations using soil cores and a dual probe density gauge. Int. J. For. Eng. 10(2): 83-90.

Johnson, D.W., and Curtis, P.S. 2001. Effects of forest management on soil C and N storage: meta analysis. For. Ecol. Manage. 140: 227-238.

Kimmins, J.P. 1996. Importance of soil and role of ecosystem disturbance for sustained productivity of cool temperate and boreal forests. Soil Sci. Soc. Am. J. 60: 1643-1654.

Kimmins, J.P. 2004. Forest ecology. Prentice Hall. Upper Saddle River, New Jersey.

Lamontagne, S., Carignan, R., D'Arcy, P., Prairie, Y.T., and Paré, D. 2000. Element export in runoff from eastern Canadian Boreal Shield drainage basins following forest harvesting and wildfires. Can. J. Fish. Aquat. Sci. 57(2): 118-128.

Malmsheimer, R.W., Heffernan, P., Brink, S., Crandall, D., Deneke, F., Galik, C., Gee, E., Helms, J.A., McClure, N., Mortimer, M., Ruddell, S., Smith, M., and Stewart, J. 2008. Forest management solutions for mitigating climate change in the United States. J. For. 106(3): 136-140.

Mead, D.J. 2005a. Opportunities for improving plantation productivity. How much? How quickly? How realistic? Biomass and Bioenergy. 28: 249-266.

Mead, D.J. 2005b. Forests for energy and the role of planted trees. Critical reviews in plant sciences. 24: 407-421.

Mead, D.J., and Pimentel, D. 2006. Use of energy analysis in silvicultural decision making. Biomass and Bioenergy. 30: 357-362.

Minore, D., Smith, C.E., and Woollard, R.F. 1969. Effects of high soil density on seedling root growth of seven northwester tree species. USDA For. Serv. Res. Note. PNW-112.

Minore, D., and Weatherly, H.G. 1990. Effects of site preparation on Douglas-Fir seedling growth and survival. West. J. Appl. Forestry 5(2): 49-51.

Misra, R.K., and Gibbons, A.K. 1996. Growth and morphology of eucalypt seedling-roots in relation to soil strength arising from compaction. Plant and Soil 182: 1-11.

Miyazaki, T. 1996. Bulk density dependence of air entry suctions and saturated hydraulic conductivities of soils. Soil Sci. 161(8): 484-490.

Murphy, G., and Skinner, J.G. 2004. Long term impacts of forest harvesting related soil disturbance on log product yiels and economic potential in a New Zealand forest. Silva Fennica. 38: 279-289.

O'Laughlin, J. 2009. Wood Bioenergy: Homegrown baseload energy for Idaho. Forestry Task Force Report prepared for the Idaho Strategic Energy Alliance, Boise, Idaho. 95 p.

Page, A.L., Miller, R.H., and Kenney, D.R. (ed.). 1982. Methods of Soil Analysis. Part 2. Chemical and Microbial Properties. 2nd Ed. Edited by ASA SSSA Publication. Madison, WI. #9 in monograph Series.

Page-Dumroese, D., Jurgensen, M. Harvey, A.E., Graham, R.T., and Tonn, J.R. 1997. Soil changes and tree seedling response associated with site preparation in northern Idaho. West. J. Appl. For. 12: 81-88.

Page-Dumroese, D., Jurgensen, M., Elliot, E., Rice, T., Nesser, J., Collins, T., and Meurisse, M. 2000. Soil quality standards and guidelines for forest sustainability in northwestern North America. For. Ecol. Manage. 138: 445-462.

Page-Dumroese, D., Jurgenson, M.F., Tiarks, A.E., Ponder, F., Sanchez, F.G., Fleming, R.L., Kranabetter, J.M., Powers, R.F., Stone, D.M., Elioff, J.D., and Scott, D.A. 2006. Soil physical property changes at the North American Long-Term Soil Productivity study sites: 1 and 5 years after compaction. Can. J. For. Res. 36(3): 551-564.

Piatek, K.B., Harrington, C.A., and DeBell, D.S. 2003. Site preparation effects on 20 year survival and growth of Douglas-fir (*Pseudotsuga menziesii*) and on selected soil properties. West. J. Appl. For. 18(1): 44-51.

Powers, R.F., Scott, D.A., Sanchez, F.G., Voldseth, R.A., Page-Dumroese, D., Elioff, J.D., Stone, D.M. 2005. The North American long-term soil productivity experiment: Findings from the first decade of research. For. Ecol. Manage. 220: 31-50.

Pritchett, W.L., and Fisher, R.F. 1987. Properties and management of forest soils. 2nd Ed. John Wiley & Sons. 494 p.

Richardson, J. 2006. Sustainable production systems for bioenergy: Impacts on forest resources and utilization of wood for energy. Biomass and Bioenergy. 30: 279–280.

Reisinger, T.W., Pope, P.E. and Hammond, S.C. 1992. Natural recovery of compacted soils in an upland hardwood forest in Indiana. North. J. Appl. Forestry 9: 138-141.

Roché, D.M. 1997. Effects of ground based harvesting and site preparation on the height growth of Douglas-fir: A second look. MS Thesis. University of Idaho, Moscow. 74 p.

SAS Institute Inc. 2008. SAS/STAT® 9.2 User's Guide. Cary, NC: SAS Institute Inc.

Simard, D.G., Fyles, J.W., Paré, D. and Nguyen, T. 2001. Impacts of clearcut harvesting and wildfire on soil nutrient status in the Quebec boreal forest. Can. J. Soil Sci. 81: 229-237.

Singer, M.J. 1981. Soil compaction-seedling growth study. Tech. Rep. Cooperative Agreement USDA-7USC-2202. Suppl. 43. USDA Forest Service. Pacific Southwest Region. San Francisco, CA.

Skinner, M.F., Murphy, G., Robertson, E.D., and Firth, J.D. 1989. Deleterious effects of soil disturbance on soil properties and subsequent early growth of second-rotation radiata pine. In: Dyck, W.J. and Mees, C.A. (Eds.). Research Stragetgies for Long-term Site Productivity. IEA/BE A3 Report NO. 8 FRI Bulletin No. 152. New Zealand Forest Research Institute. Rotorua. p. 201-211.

Soil Survey Staff. 2004. Soil survey laboratory methods manual. USDA-NRCS Soil Surv. Invest. Rep. No. 42. Version 4.0. US Gov. Print. Office, Washington, DC.

Soil Survey Staff. 2010. Keys to Soil Taxonomy, 11th ed. USDA-Natural Resources Conservation Service, Washington, DC.

Stoker, R. 1990. The relationship of harvesting and site preparation activities to site productivity: Effects on height growth, foliage nutrient levels, and soil properties in three north-central Idaho Douglas-fir plantations. MS Thesis. University of Idaho, Moscow. 58 p.

Tan, X., Curran, M., Chang, S., and Maynard, G. 2009. Early growth responses of lodgepole pine and Douglas-fir to soil compaction, organic matter removal, and rehabilitation treatments in southeastern British Columbia. For. Sci. 55(3): 210-220.

Thiffault, E., Bélanger, N., Paré, D., and Munson, A.D. 2007. How do forest harvesting methods compare with wildfire? A case study of soil chemistry and tree nutrition in the boreal forest. Can. J. For. Res. 37: 1658-1668.

White, E.M. 2009. Woody biomass for bioenergy and biofuels in the United States – A briefing paper. College of Forestry. Oregon State University, Corvallis. 72 p.

Wykoff, W.R., Crookston, N.L., and Stage, A.R. 1982. Users guide to the stand prognosis model. USDA For. Serv. Gen. Tech. Rep. INT-133. 112 p.

Zabowski, D., Java, B., Scherer, G., Everett, R.L., and Ottmar, R. 2000. Timber harvesting residue treatment: Part 1. Response of conifer seedlings, soils and microclimate. For. Ecol. Manage. 126: 25-34.