United States
Department of
Agriculture

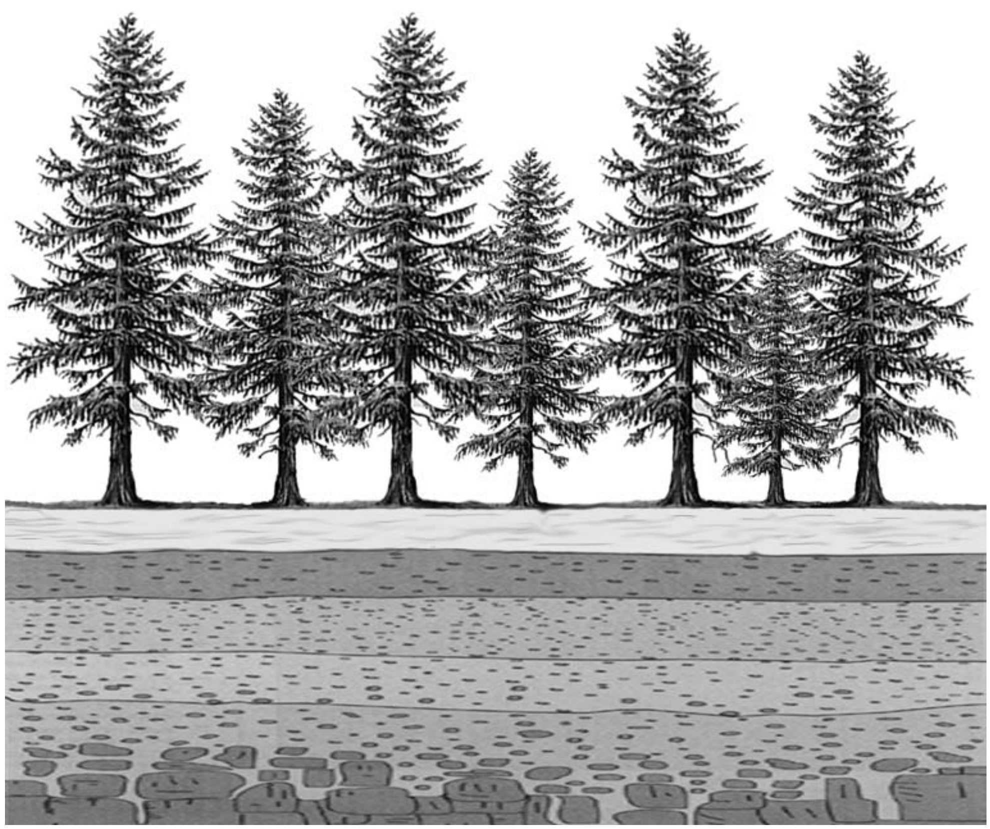
Forest Service

Pacific Northwest
Research Station

Research Paper
PNW-RP-573
February 2008

Juvenile Tree Growth on Some Volcanic Ash Soils Disturbed by Prior Forest Harvest

J. Michael Geist, John W. Hazard, and Kenneth W. Seidel



Authors

J. Michael Geist was supervisory research soil scientist (retired), Forestry and Range Sciences Laboratory, 1401 Gekeler Lane, now 701 Sunset Drive, La Grande, OR 97850; **John W. Hazard** (deceased) was Station statistician, Pacific Northwest Research Station, Portland, OR; **Kenneth W. Seidel** was principal research silviculturist (retired), Silviculture Laboratory (closed), now 2955 NE Alpen Glow Place, Bend, OR 97701.

Abstract

Geist, J. Michael; Hazard, John W.; Seidel, Kenneth W. 2008. Juvenile tree growth on some volcanic ash soils disturbed by prior forest harvest. Res. Pap. PNW-RP-573. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 22 p.

The effects of mechanical disturbance from traditional ground-based logging and site preparation on volcanic ash soil and associated tree growth were investigated by using two study approaches in a retrospective study. This research was conducted on volcanic ash soils within previously harvested units in the Blue Mountains of northeast Oregon and southwest Washington. We assessed soil and tree attributes and their association with higher and lower levels of soil disturbance. The two approaches were independent efforts that yielded very different results.

In the first study approach, we used larger measurement plots linked to a portion of some randomly established monitoring transects in 10 harvest units. Sets of higher and lower disturbance plots were chosen and positioned in each unit based on predetermined soil bulk densities along the midlines of the plots. Crop trees in the plots were then measured. Although our two sets had significantly different bulk densities, we found no associated differences between sets of tree attributes.

The second approach involved soil disturbance in five harvest units. Therein we mainly used visual cues to identify portions having higher and lower levels of soil disturbance. Smaller plots were purposely assigned and positioned within some of those conditions. Plot sampling of soils and trees followed, and the results reflected significant differences in soil disturbance, i.e., 24 percent greater bulk density (from compaction) and 38 percent less ash thickness (from displacement and compaction) between disturbance levels. Soil disturbance differences were associated with 17 to 29 percent less juvenile tree size and growth. Longer term effects are unknown.

Keywords: Volcanic ash soils, soil disturbance, soil displacement, soil compaction, soil productivity, logging, harvest impacts, site preparation, juvenile forest growth, forest regeneration.

Summary

Volcanic ash soils occur extensively in the Blue Mountains of northeast Oregon and southeast Washington and they support productive conifer forests. The ash layer originated from Mount Mazama in south-central Oregon, and it is readily displaced and compacted by mechanized equipment traditionally used in ground-based logging and site preparation. Whether these soils might be altered enough to reduce subsequent tree growth has been a common and sometimes controversial question among forest managers and the public. We sought to answer this question in a retrospective study of some harvested areas showing mechanical soil disturbance imposed by logging and site preparation. Attributes of the subsequent crop of juvenile trees and associated volcanic ash soils were compared between lower and higher levels of soil disturbance.

Two study approaches were used. One approach used larger measurement plots (about 7 by 16 m) where soil disturbance level was assigned based on the bulk density of soil samples taken at about 3-m intervals along the midline of the plot. The plots were centered on a portion of several randomly oriented transects previously used in standardized soil monitoring of 10 forest harvest units.

A subsequent independent approach involved a more restricted population of soil disturbance, smaller plots (about 5 by 8 m), more intensive soil assessments, and five harvest units. We used mainly visual characteristics of the soil surface and groundcover vegetation, plus occasional shovel probing, to find areas of higher and lower mechanical disturbance within each harvest unit. Measurement plots were then purposely located and positioned within a portion of those disturbance conditions. Assessments of tree and soil attributes followed and were more intensive for soils, as compared to larger plots. Measured soil attributes included a grid sampling of bulk density, ash thickness, and some chemical properties.

The larger plots mostly involved harvest units that contained a varied mix of tree species, whereas smaller plots involved units that were essentially monocultures of either lodgepole (*Pinus contorta* Dougl. var. *latifolia* Engelm.) or ponderosa (*Pinus ponderosa* Dougl. ex Laws.) pines. In both study approaches, measurement of all plot trees, 1.2 m or taller, followed after soil measurements.

The results we obtained differed according to study approach. Our methods of choosing plots for their contrasting soil disturbance and using larger plots produced significantly different sets of bulk density between the disturbance classes, but there were no associated differences in tree attributes. The methods used with a more restricted population of soil disturbance and smaller plots revealed some differing sets of soil properties that did have associated differences in tree size and growth.

Our field observations with larger plots revealed a varied and complex array of machine-caused soil disturbance. That perspective was consistent with the variable nature of bulk densities along transects. We found this variation prevented us from constructing a higher average bulk density for higher disturbance plots to potentially contrast more with lower disturbance plots. We interpreted this as an indication that using only the midline bulk density may be problematic as a way to characterize soil disturbance conditions of whole plots. Unfortunately, we have no scientific means to test whether this speculation is correct.

We found the scale of smaller plots fit well within the field conditions selected as higher and lower soil disturbances. Smaller plots appeared more homogeneous, and both soil bulk density and ash thickness results appeared to support the visual designations of higher and lower disturbance. Height, height growth, and radial growth ranged from 17 to 29 percent less at higher disturbance. Associated differences in soil properties included 38 percent less thickness of volcanic ash and 24 percent greater bulk density at higher disturbance. We inferred that both soil displacement and compaction had occurred with mechanical disturbance. Because they occurred together and our study is retrospective, we could not separate and assess their individual effects. We do not know the larger scale or longer term effects of higher disturbance. We would, however, expect them to vary in relation to the specific conditions within a harvest unit. We cannot extend our results to stand levels on a per-acre basis, because our sampling focused on mechanical impacts within tree-producing areas and intentionally excluded intermediate disturbance conditions, burned slash piles, and haul roads. Further, we did not measure proportions or areas of lower or higher disturbance.

The mixed findings in our research and among findings of research elsewhere indicate broad generalizations and extrapolations of findings are inappropriate. Differences among studies include the kind and degree of disturbance impacts, harvesting equipment used, tree species and other vegetation present, climate, geology, soils, measuring tools, and experimental methodology.

Only our smaller plot approach produced results that offer some credence to concerns about early tree growth loss with higher levels of mechanical disturbance of volcanic ash soils from logging and site preparation in the Blue Mountains. Long-term effects are unknown, but we believe it would be prudent for managers to apply strategies and practices that avoid or minimize higher levels of mechanical disturbance of volcanic ash soils.

Introduction

The disturbance effects of forest harvest practices on subsequent tree growth and long-term productivity of the soil have attracted considerable attention from land managers and private citizens. An expanding body of research indicates forest logging and site preparation can affect subsequent tree survival and growth. Rennie (1955) reported doubts about the sustainability of continuous forest growth in relation to harvest removal of nutrient reserves from the relatively infertile soils of Yorkshire, England. In his early concerns about nutrients, he has since been joined by other researchers who now share a broad array of concerns that constitute a worldwide focus on forest soil productivity and forest sustainability. Several symposia have addressed logging and site preparation effects on physical and chemical soil properties, soil biology, nutrient cycling, soil erosion, and their relations to productivity (Ballard and Gessel 1983, Harvey and Neuenschwander 1991, Perry et al. 1989, Slaughter and Gasbarrow 1988).

In the Northwestern United States, conventional logging with ground-based machines has adversely impacted forest soils (Dyrness 1965, Geist et al. 1989, Lull 1959, Sullivan 1988, Wert and Thomas 1981). Impacts differ both in kind and severity, but soil compaction has commonly been identified. In some cases, compaction was associated with reduced tree reproduction or growth (Cochran and Brock 1985, Froehlich 1979, Helms and Hipkin 1986, Lull 1959, Wert and Thomas 1981), but this is not always the case (Miller et al. 1996). The broad view of the literature shows mixed results, but the majority of studies indicate growth losses with compaction. In a review of 142 studies from 1970 to 1977, Greacen and Sands (1980) reported 82 percent found yield reduced, 8 percent found yield increased, 6 percent found yield both increased and decreased, and 4 percent showed no effects related to compaction.

The possibility of reduced productivity from harvest impacts, often narrowly focused on compaction, has been a special concern with volcanic ash soils that occur east of the Cascade Mountains in the Pacific Northwest. Origin of the ash is dominantly Mount Mazama in the Cascade Range. These soils support the more productive forests of the Blue Mountains in eastern Oregon and southeastern Washington. Our field and research experience indicates volcanic ash is easily compacted and displaced by mechanized equipment (Geist and Strickler 1978, Geist et al. 1989). Snider and Miller (1985) found no significant change in bulk density from tractor logging in eastern Oregon. In central Oregon, Cochran and Brock (1985) found compaction of volcanic ash originating from Mount Jefferson was associated with reduced tree growth, but they stated other unidentified factors were also involved. Page-Dumroese (1993) found Mazama ash in northern Idaho was easily compacted by machine activity, and the compaction was greater with increased intensity of site preparation. In the Blue Mountains, volcanic ash soils can locally represent 50 percent or more of the commercial forest area, and much of that has already been influenced by one or more logging entries with ground-based equipment. Bulk densities of compacted volcanic ash after logging do not seem particularly high when compared to many other soils of different origins and textures. Compacted values of ash are usually less than 1.0 Mg m^{-3}, which to some observers does not appear problematic. Yet, these elevated levels commonly represent bulk density increases of 15 to 50 percent above those of adjacent unlogged areas. Calculated in accordance with regional standards, the amount of area with detrimental soil conditions, reported dominantly as soil compaction, in logging areas ranges from 10 to 70 percent of the harvested unit, excluding the main haul roads (Geist et al. 1989, Sullivan 1988). There are potentially long-term considerations about production losses from compaction, because research indicates compaction below the surface few centimeters may require decades to recover naturally (Froehlich et al. 1985, Geist et al. 1989, Greacen and Sands 1980, Perry 1964, Wert and Thomas 1981).

Soil displacement during logging and site preparation affects surface organic layers and mineral soil. Displacement creates localized reductions in nutrient capital and water storage capacity, and subsequent growth reductions in nearby trees (Ballard 1978, Clayton et al. 1987, Nielson-Gerhardt 1986, Swindell et al. 1986, Tew et al. 1986). Displacement may also have long-term effects on growth. Because compaction, displacement, and other impacts often occur together or in proximity, their effects on production are often inseparable, thus experimentally confounded. In such situations, we must refer to tree growth reductions as associated with the aggregate of those disturbance impacts.

Earlier research of volcanic ash soils in the Blue Mountains has not included growth relations of regenerated trees to soil conditions imposed by prior timber harvest. To begin addressing this deficiency, we initiated two retrospective studies that involved different approaches. Both approaches sought to answer the same question: are soil compaction and other machine impacts, i.e., mechanical soil disturbance, from ground-based logging and site preparation on volcanic ash soils great enough to cause growth differences in the subsequent tree crop?

In this report, the terminology "harvest impacts" includes both logging and site preparation, i.e., skidding logs, loading logs, piling slash, and other incidental movement of mechanized equipment. Soil areas impacted by fire in slash reduction and areas devoted to the transportation system within harvest units were excluded from both study approaches.

Materials and Methods

We sampled a total of 12 timber harvest units in our two approaches. Eleven were clearcut units and one was a seed-tree unit. The units were on the Wallowa-Whitman, Umatilla, and Malheur National Forests in the Blue Mountains of northeast Oregon and southeast Washington. The periods since harvest of the units ranged from 14 to 23 years. Units of these ages were chosen to provide a growth history of regeneration beyond the first few postharvest years. Skidding and slash piling were done with crawler tractors on 11 hand-felled units; 1 was whole-tree logged by feller-buncher in conjunction with rubber-tired skidders. Machine travel was unrestricted. These units provided a broad representation of ash soils and the effects of harvest practices typically used on extensive portions of the Blue Mountains.

Plant communities associated with the harvest units are lodgepole pine/pinegrass/grouse huckleberry (*Pinus contorta* Dougl./*Calamagrostis* Adans./*Vaccininum scoparium* Leiberg); lodgepole/grouse huckleberry; grand fir/twin-flower/forb (*Abies grandis* Dougl./Linnaea L.); and grand fir/grouse huckleberry (Hall 1973). Elevations range from 1460 to 1800 m; precipitation ranges from 600 to 1500 mm, coming mostly in winter as snow; July and August are dry; slopes range from 3 to 35 percent.

The undisturbed soils associated with these plant communities typically have 35 to 70 cm of silt loam or very fine sandy loam volcanic ash that commonly overlies a buried soil of loam to clay loam texture. The volcanic ash originated from the eruption of Mount Mazama about 6,600 years ago (Harward and Youngberg 1969). These soils include members of the Tolo series (medial over loamy, mixed, frigid Typic Vitrandepts), Helter series (medial over loamy, mixed Entic Cryandepts), Olot series (loamy skeletal, mixed Mollic Eutroboralfs) and closely-related Andic intergrades with shallower depths. We sought a broad array of ash soils, so no attempt was made to correlate specific series or taxonomic entities with the harvested study units. The volcanic ash surface layer has a naturally weak platy structure. Throughout the ash overburden there is little cohesiveness, few coarse fragments, and a high water-holding capacity. Natural bulk densities of the ash average 0.67 Mg m^{-3} and are comparatively uniform. Organic matter content is comparatively high in the surface and declines rapidly down the soil profile. The buried soils were residuum and colluvium, dominantly from basalts, andesites, and sedimentary rocks. At the buried soil boundary, the bulk density increases abruptly, as does clay content and coarse fragment content, but water-holding capacity is less (Geist and Strickler 1978).

We measured soil and tree-growth attributes to assess whether differences existed between higher and lower degrees of soil disturbance found within the harvest units. We hypothesized that if no growth reductions were detected at the higher disturbance conditions, then none should occur with intermediate conditions.

It is noteworthy that the retrospective nature of our study precluded our ability to control the kind or degree of disturbance assessed. We used what was available to us. This also precluded any possibility of separating compaction from displacement or other impacts. Thus, the context of our study paralleled that of land managers who must prescribe practices in light of existing resource conditions. We believed this strengthened the practical relevance of study findings.

We used two, very different sampling approaches to make our assessments. Because the first approach was completed before the second began, our efforts could be viewed as two separate studies. Owing to their commonality of objective, we chose to report this work as one study with two parts. Size of measurement plot (larger and smaller) was one of the approach differences and became a simple way to label discussion of the two approaches. The two study efforts were independent except for commonality of geographic area and some commonality in harvest units sampled. We designated at least three measurement plots in each of the two disturbance conditions (higher and lower) within harvest units studied by each approach. The procedures used to locate measurement plots and assign the two levels/conditions of soil disturbance were markedly different between the two approaches, and they are described below. No buffer strip was specified around either larger or smaller measurement plots.

Larger Measurement Plots

We took advantage of soil monitoring transects established earlier by cooperating national forests in joint (research-management) efforts to assess soil impacts of logging (Geist et al. 1989). Larger measurement plots were linked to some of the transects in the 10 harvest units monitored. A randomly positioned grid of starting points had been established in each harvest unit for 15 randomly oriented transects, each about 30 m (100 ft) long. The larger plots were 7 by 16 m (20 by 50 ft) and straddled a portion of a monitoring transect. We used soil bulk density assessments obtained by core sampling at intervals along the whole length of all line transects of a unit to determine the location of potential plots and to assign each plot a disturbance condition. Ten soil core samples (each about 25 mm long and 50 mm in diameter) spaced about 3 m (10 ft) apart were extracted from the 10- to 15-cm (4- to 6-in) soil depth to measure bulk density. Sufficient thickness of volcanic ash was required, so only volcanic ash was included in the cores. The higher and lower disturbance conditions and plot locations were determined by using sets of five consecutive core samples that provided the highest or lowest sets of bulk density values among the transects of each unit. Thus, we sought to achieve as much contrast in disturbance between plot conditions as possible, as accorded by the sets of bulk densities. The five consecutive core samples defined the midline of the long dimension of each large plot. At least three of the set of five bulk densities of a higher disturbance plot had to exceed the reference level of bulk density for the unit by 15 percent. The reference level was the average bulk density of core samples from three other transects (30 core samples total) that were randomly situated on unharvested area bordering the unit. All the bulk densities of lower disturbance plots had to be less than 15 percent above the reference level. Slash piles, fire-discolored soil areas, and the road system were excluded from soil sampling.

Soil cores were oven dried and and sieved to <2 mm, and both fractions were weighed. Bulk density was determined for the soil fraction by adjusting for the weight and volume of coarse fragments (mineral matter >2 mm) by using a particle density of 2.65 Mg m^{-3} (Geist and Strickler 1978).

After designation of plots and disturbance conditions, all species of trees that were at least 1.2 m (4 ft) in height were hand felled and measured. Tree measurements included total height, prior-3-years height and growth, and diameter outside bark at breast height (d.b.h.). Measurements at 30 cm height included age, diameter outside bark, radial growth for the most recent 5 years (RG 1–5) and for the next prior 5 years (RG 6–10). Where tree stems were not round, the recorded values for diameter and radial growth were the average of two measurements, one taken along the long axis and the second at right angles thereto. A mixture of tree species usually occurred within the larger measurement plots and included grand fir, Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco), lodgepole pine, and ponderosa pine. Data were not separated by species because we sought overall growth comparisons. Further, separation would presume an unlikely similar exposure to within-plot soil disturbances by similar numbers and positioning of each species. One of the units had been precommercially thinned the year prior to our sampling.

Smaller Measurement Plots

We drew from our larger plot experiences in follow-on efforts to investigate the study question. Size of plot and numerous other study elements were revised. Less time and fewer resources resulted in only five harvest units sampled with the smaller plots. The geographic area involved was very similar, in fact, three of the five units were previously sampled with the larger plot approach, but the smaller plot approach was completely independent of larger plots and monitoring transects.

A more restricted population of ash soil disturbance was investigated with smaller plots. Harvest units were reconnaissance surveyed for visual evidence of soil disturbance, while tree and stand characteristics were ignored. The visual cues related to soil disturbance were surface organic layer displacement and exposure of mineral soil, mineral soil discolored by slash burning, uneven soil surface that could indicate soil displacement or traffic depressions, and ground cover vegetation that indicated disturbance. The surface soil was occasionally probed with a shovel for evidence of increased firmness. As in all larger plot units, operational conventions at the time of harvest resulted in considerable machine movement within and around the units. Skid trails were not designated, and burned slash piles made with heavy equipment were common over the units and by landings. Soil disturbance was generally higher near slash piles, in and around landings, and in other places where more machine influence occurred. It was in the more machine-influenced areas that measurement plots for higher disturbance were situated. In each of the five harvest units, we purposely established three small measurement plots in both lower and higher conditions of soil disturbance (i.e., six plots per unit) discovered during reconnaissance. Prior observations of units helped define the smaller plot dimensions we thought would usually fit within the various disturbance situations. Measurement plots were about 5 by 8 m (15 by 25 ft), and were oriented as much within the respective disturbance conditions as possible. Plots were also scattered as much as conditions in each unit permitted. Although the specific nature, extent, and juxtaposition of disturbance varied within and among harvest units, our disturbance criteria for assignment of plots were consistent throughout. No change in plot assignments to disturbance conditions occurred after their original field designations. Our goal in locating plots was objective consistency within and among units. Lower disturbance conditions were indicated by the following: a soil surface with most of the preharvest organic layers and groundcover vegetation intact, comparatively little exposed mineral soil, little or no uneven soil surface indicative of vehicle mechanical influences, little or no increased firmness in the surface soil compared to unharvested area adjacent to each unit. Higher disturbance conditions were indicated by the following: a soil surface with disturbed or removed preharvest organic layers so exposed mineral soil was relatively common, prior groundcover vegetation commonly disturbed, presence of disturbance-related species (native or invader) or introduced erosion control species, commonly tracked and uneven soil surface, commonly increased firmness in the surface soil.

We did not attempt to locate, map, or measure all the areas of lower and higher disturbance conditions that could have potentially been sampled within each of the five harvest units. As with larger plots, slash piles, fire-discolored soil areas, and the road system were excluded from sampling, because our study question related to mechanical soil disturbance within tree production areas.

Our soil sampling was more intensive within this approach. Both tree and soil attributes were sampled only after establishing the measurement plots within their respective disturbance conditions. We hand-felled all trees within the plots that met the same size criteria and performed measurements as on the larger plots, except age and radial growth were taken at ground level. The trees in two of the five harvest units were planted ponderosa pine, and in the other three units, the trees were naturally seeded lodgepole pine. We again sought an overall growth response of trees, so we made no attempt to separate species for reasons similar to those noted above for larger plot sampling. Precommercial thinning by hand felling had occurred a year before we measured one of the lodgepole pine units and 4 years before in the two units supporting planted ponderosa pine. Two units were unthinned. Other vegetation was not measured.

Soil bulk density was sampled at nine points of a systematic grid within each small plot. Core samples were rejected and replaced where inadequate ash thickness remained to obtain ash-only cores at the 10- to 15-cm depth. This avoided misinterpretation of differing bulk densities related to parent material and textural differences. At the four corners of each small plot, a bucket auger was used to sample the 0- to 15-cm soil depth and measure the thickness of the volcanic ash layer. The four auger samples were aggregated into a single sample per small plot, air dried, mixed, and sieved to <2 mm diameter for subsequent chemical analysis. The same soil coring equipment and core processing was employed as in large-plot sampling. Soil chemical analyses included total nitrogen (N) by Kjeldahl method, organic matter by the modified Walkley-Black method (Jackson 1958), and net mineralizable N. The latter was the difference between the gross amount of ammonium-N mineralized during anaerobic soil incubation for 7 days at 40 °C and the initial ammonium-N extracted by 2M potassium chloride (KCl) (Keeney and Bremner 1966).

It was not experimentally possible to restrict stocking among the units to some predetermined range, and we did not conduct overall stocking assessments on the units. Stocking variation was obvious among units, but we avoided potential confounding effects of stocking on growth parameters, because field observations indicated stocking to be similar for higher and lower disturbance plots within a given harvest unit. We relied upon local silviculturists to make tree measurements on larger plots. They did not find, and no concern was raised about, within-unit stocking disparities among or between higher and lower soil disturbance conditions. After establishment of smaller plots, tree counts were made on the plots, and those counts offered no evidence that tree numbers would have an influence on tree growth comparisons between levels of soil disturbance.

Statistical Analysis of the Attributes Measured

Data from the two study approaches were analyzed separately by applying a randomized block design and using standard ANOVA methods. We tested for differences between two "treatments," represented by lower and higher levels of soil disturbance, and blocks represented by harvest units. Thus, with larger measurement plots, the statistical analysis we applied for each variable (soil or tree attribute) was a 2 (treatments) by 10 (harvest units/blocks) randomized block design (n = 10). In smaller plot sampling we applied a 2 (treatments) by 5 (harvest units/blocks) randomized block design (n = 5). The larger and smaller measurement plots were treated experimentally as subplots in the statistical analyses. The alpha level we chose to assign statistically significant differences in attributes between lower and higher disturbance conditions was 0.05. However, we have reported the observed P-values of attribute tests.

Results

The marked differences in sampling approaches were accompanied by marked differences in the results obtained. Tables 1 and 2 show the overall means for, and the standard deviations of, attributes among the harvest units within lower and higher levels of soil disturbance as designated within each sampling approach. We could not test attribute differences between approaches, because of methodology differences, and we did not design our sampling with that intent.

Larger Measurement Plots

The results show that with this process we were able to construct two data sets for bulk density that were significantly different. But, all other attributes sampled within larger plots were not significantly different between our disturbance conditions, constructed in this way, at or near our chosen 0.05 level of significance (table 1). The lower disturbance mean of bulk density, 0.64 Mg m^{-3}, was very close to the 0.67 Mg m^{-3} mean of relatively undisturbed ash soils in the Blue Mountains reported by Geist and Strickler (1978). The mean bulk density for higher disturbance, 0.83 Mg m^{-3}, was about midrange for harvest-affected ash soils reported by Geist et al. (1989) and was 0.19 Mg m^{-3} or 29 percent greater than the lower disturbance mean. At both levels of disturbance, the standard deviations of bulk density among units were low. We viewed these low variability values as some assurance of consistency in our methodology.

Table 1—Volcanic ash soil and tree attributes sampled in 10 cutting units with larger plots to assess differences between lower and higher levels of mechanical soil disturbance from prior logging and site preparation

Attribute	Units	Lower disturbance Mean	Lower disturbance Standard deviation	Higher disturbance Mean	Higher disturbance Standard deviation	Mean difference	Observed P-value
						Percent	
Bulk density	Mg/m^3	0.64	0.05	0.83	0.07	+29*	<0.001
Tree height	cm	333	142	312	124	-6	.622
3-year height growth	cm	97	30	99	30	+2	.697
D.b.h.	cm	6	4	6	4	-5	.816
Diameter at 30 cm	cm	7	4	7	4	-7	.638
Radial growth 1–5	mm	12	5	12	5	0	.314
Radial growth 6–10	mm	13	5	14	6	+8	.468
Age at 30 cm	years	12	4	11	3	-8	.208

Mean difference (percent) for a given attribute is calculated as the higher disturbance mean minus the lower disturbance mean, divided by the lower disturbance mean, times 100. D.b.h. = diameter at breast height.
* indicates a statistically significant difference at alpha = 0.05.
P-value is the statistical probability of observing a test statistic as extreme or more extreme than that observed assuming the null hypothesis is true.

Table 2—Volcanic ash soil and tree attributes sampled in five cutting units with smaller plots to assess differences between lower and higher levels of mechanical soil disturbance from prior logging and site preparation

Attribute	Units	Lower disturbance Mean	Lower disturbance Standard deviation	Higher disturbance Mean	Higher disturbance Standard deviation	Mean difference	Observed P-value
						Percent	
pH	—	5.1	0.4	5.0	0.3	-2	0.267
Total soil N	g/kg	1.2	0.4	1.0	0.2	-17	.364
Organic matter	g/kg	48	19	35	11	-26	.057
Net mineralizable N	mg/kg	25	7	19	6	-24	.143
Extractable NH_4-N	mg/kg	8	2	6	1	-25	.089
Bulk density	Mg/m^3	0.74	0.06	0.92	0.07	+24*	<.001
Ask thickness	cm	48	13	30	8	-38*	.042
Tree height	cm	399	150	284	157	-29*	<.001
3-yr height growth	cm	142	30	107	41	-25*	.005
Diameter at 30 cm	cm	11	6	8	6	-24*	<.001
Radial growth 1–5	mm	23	10	18	11	-22*	.004
Radial growth 6–10	mm	18	11	15	11	-17*	<.001
Age at ground	years	12	2	11	2	-8*	.014

Mean difference (percent) for a given attribute is calculated as the higher disturbance mean minus the lower disturbance mean, divided by the lower disturbance mean, times 100.
* indicates a statistically significant difference at alpha = 0.05.
P-value is the statistical probability of observing a test statistic as extreme or more extreme than that observed assuming the null hypothesis is true.

In the array of large-plot averages, some tree growth or size attributes were slightly less at higher disturbance, whereas others were slightly more or were the same. Standard deviations for tree growth and size attributes were all much higher than for bulk density, especially in relation to their respective means.

We experienced sampling design concerns with the larger plot approach soon after going to the field and then again when we began to designate measurement plots. In the former instance, marked variability in soil disturbance was visually observed within potential measurement plots along transects. In the latter instance, our beginning criteria for designating higher disturbance plots required immediate modification so we could consistently designate three higher disturbance plots somewhere in every unit. Lower disturbance criteria did not require modification. We had initially planned for higher disturbance plots to have five consecutive bulk densities that exceeded a 20-percent increase above the reference value for each unit. That proved impossible with the variability in bulk density encountered. Instead, we had to settle on at least three of five consecutive bulk densities exceeding 15 percent of the reference value, as we reported above in "Materials and Methods."

Smaller Measurement Plots

As with the larger plots, there were sampling design challenges with the smaller plot approach. In some units it was more difficult to identify potential plot locations with contrasting disturbance conditions than others, thus greater time was required for reconnaissance surveys than first anticipated. Disturbance variability among units and among timber sales was very evident when using this or the larger plot approach.

Test results from sampling with smaller measurement plots showed the means of 8 of the 13 attributes were significantly different (alpha equal to 0.05) between higher and lower disturbance conditions (table 2). The eight attributes included soil bulk density, ash thickness, and all tree growth and size parameters. Soil chemical attributes appeared to reflect less favorable conditions for plant growth at higher disturbance, but none tested significantly different at the 0.05 level of significance. Observed P-values associated with differences between higher and lower disturbance conditions for organic matter and extractable ammonium were fairly close to our chosen significance level.

The difference between bulk density means of disturbance levels was 0.18 Mg m^{-3}, virtually the same as in the larger plot sampling. In contrast, the means themselves, 0.74 Mg m^{-3} and 0.92 Mg m^{-3}, were notably higher in smaller plots, apparently indicating a different range covered. Standard deviations of bulk density among units were relatively low at both disturbance levels. As with larger plots, these low variability values offered some assurance of consistency in our methodology. The mean bulk density for the lower disturbance condition may reflect some machine activity, because it was 10 percent higher than the mean of 0.67 Mg m^{-3}

reported by Geist and Strickler (1978) for relatively undisturbed ash soils. The coefficients of variation (CV) of their means for undisturbed ash in similar Blue Mountain localities were comparatively low and ranged from 9 to 11 percent. So the 10-percent difference provided some confirmation of our lower disturbance designations. The mean bulk density for higher disturbance was 0.27 Mg m^{-3} or 37 percent above the undisturbed mean of Geist and Strickler (1978). The higher disturbance mean was, as with larger plots, well above the 15- and 20-percent increases in bulk density commonly used in the Pacific Northwest to define detrimentally compacted soil conditions (Meurisse 1988; Sullivan 1988; Geist et al. 1989, 1991). The higher disturbance mean was not unusually high but did fall within the upper ranges of ash bulk densities reported in harvested areas by Geist et al. (1989). All bulk densities in the aforementioned references were corrected for coarse fragment content.

The overall mean of ash thickness for higher disturbance was 18 cm or 38 percent less than the corresponding mean for lower disturbance. Ours is a retrospective study, so we cannot guarantee that lower and higher disturbance plots within a given unit had the same ash thickness before harvest occurred. The variability of ash thickness (CV = 22 percent) found by Geist and Strickler (1978) was about twice that for bulk density on relatively undisturbed areas, so thickness data offer a much less consistent benchmark for change. Therefore, our study design with multiple measurement plots per unit and unit replication was important to the strength of statistical testing and interpretation of the difference in ash thickness.

At higher soil disturbance, tree size and growth attributes averaged 17 to 29 percent less than corresponding attributes at lower disturbance. Consistently more variability among units, particularly in relation to their respective means, was noted for all tree attributes at higher disturbance compared to lower disturbance. The statistically significant (alpha equal to 0.05) 1-year difference in average tree age may indicate higher disturbance caused a delay in the natural establishment of lodgepole pine (ponderosa pine was all planted the same year). A season less growing time may account for part of the smaller growth with higher disturbance. Whether thinning in three of the units affected the data is speculative. Thinning at this age typically has minor influences on height growth, but radial growth is more sensitive and commonly increases. Thinning operations typically favor retention of the better performing trees and eliminate part of the poorer performers. If this were consistently the case in our units, we might expect a narrowing of growth differences between the two disturbance categories. However, a thinning effect on radial growth, if present, appears to be just the opposite. Radial growth was less in the earlier (RG 6–10) than the later (RG 1–5) growth period, and the radial growth differences between disturbance categories were less in the earlier than the later period. We observed no reason to speculate further about thinning influences, and we are confident thinning had little or no bearing on our results and conclusions.

Discussion

We believe both outcomes from our two study approaches provide valid information within the context of disturbance conditions in the field and the methodologies we used. Both approaches sought to determine if there was credible evidence of tree growth differences between higher and lower levels of mechanical disturbance of volcanic ash soil. Disturbance contrasts with one categorization approach yielded no difference in tree growth, whereas followup contrasts with a different disturbance categorization were associated with significant differences in growth. Given the many differences involved, we feel both challenged and obliged to provide our interpretation of the two findings, based on our observations, tested measurements, and our related experience. Our interpretations include speculation about the outcomes, but there is no way to scientifically assess their relative merit. We cannot quantitatively compare our two sampling approaches. There is no basis to statistically test the different outcomes, and we did not design our study with that objective.

Our two outcomes and the mixed results obtained from related research elsewhere indicates broad generalizations of findings from one study are inappropriate. Many variables exist among studies including the kind and degree of disturbance impacts, types of mechanized equipment used in harvesting operations, tree species and other vegetation, topography, geology, climate, soils, measuring tools, and experimental methodology. Given such an array of variables, a mixture of results could be expected. The 1980 review by Greacen and Sands reflects this, although the great majority of 142 studies found reduced tree growth associated with forest soil compaction.

We could speculate at great length about why our two sampling approaches yielded such different results. With the many differences in our methodologies, the fact that we had differences in outcomes might not be surprising. Smaller plots being about one-third the size of larger plots often allowed them to be positioned wholly within a given disturbance situation. The processes for disturbance categorization with smaller plots resulted in a more restricted population of higher and lower soil disturbance than in larger plots where only midline bulk densities were used. Variation in bulk densities along transects in larger plots negated our ability to construct a greater average bulk density for higher disturbance plots that might contrast more with lower disturbance plots. Although the average differences in bulk density with both approaches were similar, being in a higher part of the range with smaller plots may have been an advantage to detecting tree growth differences. Whether there were similar associated differences in ash thickness is unknown, because ash thickness was not measured on larger plots. The near monocultures in smaller plots may have been an advantage over larger plots containing a varied mix of tree species that together may respond differently to soil disturbance. Fewer samples of bulk density in relation to plot size and fewer soil attributes were sampled in larger measurement plots compared to the smaller plots. Instead of simply using a midline sampling of bulk density, a grid of samples was used to improve characterization of compaction in smaller plots, and ash thickness was measured as an indication of soil displacement. Visual cues and probing coupled with more measures of soil condition provided a potentially stronger characterization of disturbance conditions associated with smaller plots. Taken in total, the potential to detect tree-growth differences between properly characterized disturbance conditions appears more favorable and consistent with our research objective when using the smaller plot approach. However, given our limited efforts, we do not know how applicable and usable elsewhere the smaller plot approach might be.

The midline bulk densities used to position larger plots on the transects initially seemed to hold promise as a rational method of identifying and sampling any effects of higher and lower soil disturbance on associated tree growth. In retrospect, disturbance appeared to be so patchily distributed, that larger plots located on randomly oriented transects incorporated considerable heterogeneity that lessened the potential to detect associated differences in tree attributes where they may exist, especially if the differences are small. Field observations and measurements in both sampling efforts led us to infer that harvest activities imposed a complex and variable kind, degree, and pattern of soil and vegetation conditions. Much of the soil disturbance was neither uniform nor simply straight-line in nature. Given enough complexity, the use of only midline bulk density may be insufficient to detect and assign a disturbance level that truly reflects the overall character of a sample plot this large. Regardless of the difficulties, questions, and findings that arose in the larger plot study, they have no bearing on the original utility or validity of monitoring general soil conditions with the random transect method developed by Hazard and Geist (1984) and further elaborated by Geist et al. (1991).

We believe the second study's results provide some credible evidence that higher degrees of ash soil disturbance from traditional ground-based harvest can be detrimental to the early growth of associated trees. In this case, the trees were ponderosa and lodgepole pines. Sampling refinements and population restriction in conjunction with smaller plots showed higher soil bulk density (interpreted as soil compaction) and lesser ash thickness (interpreted as soil displacement and compaction) at higher disturbance were associated with significantly less tree growth and size. Association is not necessarily evidence of direct cause and effect.

We saw no necessity to construct, and we doubt we achieved, worst-case comparisons of soil disturbances in our methods, yet we offer some comments in that regard. The lower and higher disturbance means for bulk density in both larger or smaller plot approaches were indicative that neither approach achieved worst-case comparisons of soil compaction. In both approaches, our ranges were notably less than the ranges of bulk densities for mechanically disturbed volcanic ash soils reported by Geist et al. (1989). With larger plots, the lower disturbance value was near the low end and the higher disturbance value was about midrange for bulk densities of mechanically disturbed volcanic ash soils reported by Geist et. al. (1989). With smaller plots, the lower disturbance value was above the low end but less than midrange, and the higher disturbance mean was in the upper range of mechanically disturbed volcanic ash soils. Our results indicate disturbance effects on ash thickness should also be considered in constructing or assessing a worst-case comparison, but reference data comparable to that of bulk density are lacking. Further, more knowledge would be needed about what combinations of bulk density, ash thickness, and perhaps other attributes exist to help characterize a worst-case comparison of disturbance.

We are unable to use data from smaller plots to estimate what the overall effect of growth reductions from higher disturbance areas might be, or from either sampling, what an overall average growth would be for a stand, a harvest unit, or all units combined. Estimation of those values was beyond the scope of our study objective, and we did not sample with that intent. Overall effects require assessments spanning the range of soil disturbance, associated tree growth, and proportions of harvest units represented by each. In neither approach did we determine the amounts of higher and lower disturbance present in harvest units sampled. We purposely excluded assessment of intermediate mechanical disturbance and some other disturbances, as described earlier.

Our visual surveys indicated higher mechanical disturbance represented less area than the combination of moderate and lower disturbance, but we made no area measurements to confirm that perspective. Our experience further indicates the kinds and relative proportions of various disturbances can vary greatly among harvest units. There would likely be little effect on overall growth from higher disturbance areas where they are proportionately small. But, we do not know what growth effects might exist within intermediate mechanical disturbances and other disturbances we excluded. We also do not know longer term effects. Regardless of these unknowns, we expect that standard inventory processes conducted in the usual course of forest management will account for whatever soil disturbance effects may exist within the overall growth and yield of forest stands. Therefore, no special monitoring should be needed in this regard.

The overall percentage differences for most soil and tree parameters associated with our smaller plots showed considerable similarity in their magnitudes, although they varied among units. Our overall differences with smaller plots agreed well with a relationship constructed by Froehlich and McNabb (1984) who suggested that percentage difference in bulk density might relate better to the percentage growth loss associated with compaction than would absolute values of bulk density. Of course, the results from our larger plots showed no such agreement. Our overall percentage differences with smaller plots were also similar to those of Cochran and Brock (1985) who studied compaction relations to tree growth in central Oregon on deep soils with 50 to 60 cm of surface volcanic ash from Mount Jefferson (coarser textured than our Mazama ash). They used plots similar in size to our larger plots that were also linked to randomly oriented transects. Plot averages of total height or periodic height increment for 5-year-old seedlings of ponderosa pine were regressed against plot averages of soil bulk densities associated with the measured trees. They found both growth measures declined significantly with increased bulk density. Clayton et al. (1987) studied soil disturbances and young tree growth within three clearcuts in the northern Rocky Mountains of central Idaho; soils contained significant ash content in the upper 30 cm (generally much thinner ash than our study locations). The specifics of which soil assessments related to which tree growth assessments differed among locations and sampling tools. They did, however, find some instances where soil compaction and/or displacement were associated with less growth of trees aged 15 to 25 years. Bosworth and Studer (1991) studied early tree growth following clearcutting on volcanic ash soils of northern Idaho. They assessed juvenile tree performance in relation to three site preparation methods: broadcast burn, bulldozer pile, or no site preparation. Among the methods studied, they found greater height growth in 8 of 9 years with broadcast burning. Lower tree growth in bulldozer-piled areas was attributed to both soil compaction and the excessive displacement of surface litter and humus layers into slash piles. They speculated the removal of litter and humus resulted in decreased nutrient supply compared to broadcast burning.

Tree growth effects detected with smaller plot sampling appear large enough to warrant some management consideration. Our results coupled with findings by others lend support for harvesting methods that prevent and minimize excessive machine disturbance of volcanic ash soils in the Blue Mountains (Clayton et al.

1987, Dyrness 1965, Froehlich et al. 1981, Geist et al. 1989, Greacen and Sands 1980, Sullivan 1988, Wert and Thomas 1981). Management concerns about adverse soil conditions from past timber harvests in the Blue Mountains were bolstered when 68 percent of the harvest units monitored on the Malheur National Forest by Sullivan (1988) averaged between 28 and 70 percent detrimental soil conditions. Detrimental compaction (defined in the Northwest Region as at least a 15 or 20 percent increase in soil bulk density) dominated his findings in volcanic ash and other soils following ground-based logging and site preparation. Our findings cannot validate definitions of detrimental soil compaction or displacement for ash soils as applied in the Pacific Northwest Region by the U.S. Forest Service. Validation would have required a different study that involved the whole range of soil disturbances.

Our results arise from traditional ground-based harvest operations, but they potentially apply to newer ground-based mechanical harvest systems. The latter are gaining popularity in cultural operations such as thinning of overstocked timber stands to address concerns about forest health, growth, and catastrophic wildfire. We would encourage operational guidelines that minimize skid trails, landings, and other high-disturbance areas and reuse of such areas when possible and appropriate. Consideration of soil disturbance is important with every management entry because of the potential for cumulative negative effects on tree growth and possibly other ecosystem attributes. Mechanical treatment to reduce soil compaction remains problematic, and treating compaction does not resolve soil displacement and other disturbance concerns.

If values are corrected for coarse fragments (>2 mm), then the bulk density of Mount Mazama ash provides a comparatively sensitive attribute to use for detecting change from compacting influences. Natural bulk densities are reported to be quite uniform both spatially and throughout the deposited thickness, so the local variability is relatively low (Geist and Strickler 1978, Geist et al. 1989). Yet, cores must be extracted in the field with considerable care, and this is time-consuming, tedious work. Diligence and consistency in both field and laboratory processes is crucial to the integrity and validity of soil disturbance studies that use core sampling to measure bulk density for assessment of compaction. Unfortunately, the higher natural variability of ash thickness makes averages more problematic for assessments of displacement in disturbed areas.

Managers would benefit from less time- and labor-demanding assessments of soil disturbance that have reasonably wide quantitative ranges reflective of tree growth. Clayton et al. (1987) found that higher classes of soil penetration resistance (higher soil strength) were associated with less growth in young trees.

They used shovel probing to assign trees to classes after they checked their ability to distinguish those classes with penetrometer measurements. Penetrometer readings between classes differed in the range of two- and threefold. Lull (1959) stated infiltration was commonly the soil characteristic most sensitive to compaction. Perry (1964) applied this concept and used a simple infiltration measurement to link compaction to reduced growth of juvenile southern pines.

Conclusions

Our study approaches yielded valuable insights to the complexity of soil disturbance associated with traditional ground-based harvest. We concluded that natural and harvest-imposed variability in ash soil conditions make possible tree growth-differences associated with mechanical disturbance difficult to detect, especially if the differences are small. Simply stated, the results we obtained differed between the two study approaches. In our first study approach, we found no differences in tree attributes between lower and higher soil disturbance. In our second approach, with a more restricted population of disturbances and modified sampling, we did find some credible evidence of tree size and growth differences between soil disturbance levels. Because our sampling efforts with both approaches were limited in number, we cannot say how representative our findings may be overall in the Blue Mountains.

With our second approach, it appeared we were able to discriminate between higher and lower levels of soil disturbance mainly by visual means supplemented by occasional shovel probing. We do not know how well our procedures would work elsewhere, but the significant differences between disturbance levels for soil bulk density and ash thickness offered a measured confirmation of visual assignments. We would hope visual indicators can be useful to forest managers in identifying problem soil conditions on the landscape.

Findings from our second approach offer some credence to concerns raised by the general public and land managers about potential tree-growth reduction from ash soil disturbance. Those concerns about soil disturbance have commonly focused only on compaction. We believe concern is also needed about the frequent and confounded association of soil displacement with compaction. It appears displacement is not only a valid concern, it might affect juvenile tree growth as much as or perhaps more than compaction. But there is no simple remedy for either impact. We do not know the long-term effects on growth of trees and tree stands, but we expect they will differ among units according to the amount and specific nature of the disturbances therein. Regardless, we believe it would be prudent for managers to use strategies and practices that prevent and minimize higher levels of mechanical disturbance of volcanic ash soils like those of the Blue Mountains. This strategy is relevant to current and future management entries of any kind.

We addressed a relatively small number of soil and tree attributes in our study of harvest-associated impacts within forest ecosystems. From our smaller plot approach we concluded some of these attributes were relevant to the question investigated. Yet, there remains an immense ecological complexity that extends beyond our narrow investigation. That complexity includes a host of other attributes we did not measure, such as other vegetation associated with the tree crop. Those attributes could be working in concert with or in opposition to the ones we found relevant to tree growth. So, the knowledge we gain in a narrowly focused study is just one of many steps toward a fuller understanding of the natural and human-caused complexity of forest ecosystems. Mindful of that complexity, we are less likely to oversimplify the issues and questions we address and the answers we find.

Acknowledgments

The authors gratefully acknowledge the assistance and cooperation of the following: U.S. Forest Service, Pacific Northwest Region soil scientists Dr. Bob Meurisse (retired) and Steve Howes; regional silviculturist Walt Knapp (retired); forest soil scientists Dan Harkenrider, Tom High, Earle Rother, and Tim Sullivan; district silviculturists Lyle Kuchenbecker (retired), Gary Rollins, and Kenneth Rockwell; and Pacific Northwest Research Station research technician Michael Snider. We also gratefully acknowledge the valuable contributions of reviewer comments from Dr. Pat Cochran, retired research soil scientist; Dr. Bob Meurisse, retired regional soil scientist; Dr. Hersch McNeil, soil scientist Malheur National Forest; Dr. Richard Miller, emeritus research soil scientist, and Dr. Tim Max, Station Biometrician, Pacific Northwest Research Station.

English Equivalents

When you know:	Multiply by:	To find:
Millimeters (mm)	0.0394	Inches (in)
Centimeters (cm)	0.394	Inches (in)
Meters (m)	3.28	Feet (ft)
Milligrams (mg)	3.5×10^{-5}	Ounces (oz)
Grams (g)	0.035	Ounces (oz)
Kilograms (kg)	2.21	Pounds (lb)
Megagrams per cubic meter (Mg/m^3)	62.4	Pounds per cubic foot (lb/ft^3)
Degrees Celsius (C)	1.8 °C + 32	Degrees Fahrenheit

Literature Cited

Ballard, R. 1978. Effect of slash and soil removal on the productivity of second rotation radiata pine on a pumice soil. New Zealand Journal of Forest Science. 8: 248–258.

Ballard, R.; Gessel, S.P., eds. 1983. I.U.F.R.O. Symposium on forest site and continuous productivity. Gen. Tech. Rep. PNW-GTR-163. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 406 p.

Bosworth, B.; Studer, D. 1991. Comparisons of tree height growth on broadcast-burned, bulldozer-piled, and non-prepared sites 15 to 25 years after clearcut logging. In: Harvey, A.E.; Neuenschwander, L.F., comps. Proceedings, management and productivity of western montane forest soils. Gen. Tech. Rep. INT-GTR-280. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 197–200.

Clayton, J.L.; Kellogg, G.; Forrester, N. 1987. Soil disturbance tree growth relations in central Idaho clearcuts. Res. Note INT 372. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 6 p.

Cochran, P.H.; Brock, T. 1985. Soil compaction and initial height growth of planted ponderosa pine. Res. Note PNW-434. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 4 p.

Dyrness, C.T. 1965. Soil surface condition following tractor and high lead logging in the Oregon Cascades. Journal of Forestry. 63(4): 272–275.

Froehlich, H.A. 1979. Soil compaction from logging equipment: effects on growth of young ponderosa pine. Journal of Soil and Water Conservation. 34: 276–278.

Froehlich, H.A.; Aulerich, D.E.; Curtis, R. 1981. Designing skid trail systems to reduce soil impacts from tractive logging machines. Res. Pap. PNW-44. Corvallis, OR: Oregon State University, Forest Research Laboratory, School of Forestry. 13 p.

Froehlich, H.A.; McNabb, D.H. 1984. Minimizing soil compaction in Pacific Northwest forests. In: Stone, E.L., ed. Forest soils and treatment impacts: proceedings, 6th North American forest soils conference, Knoxville, TN: University of Tennessee, Department of Forestry, Wildlife and Fisheries: 159–192.

Froehlich, H.A.; Miles, D.W.R.; Robbins, R.W. 1985. Soil bulk density recovery on compacted skid trails in central Idaho. Soil Science Society of America Journal. 49: 1015–1017.

Geist, J.M.; Hazard, J.W.; Seidel, K.W. 1989. Assessing physical conditions of some Pacific Northwest volcanic ash soils after forest harvest. Soil Science Society of America Journal. 53: 946–950.

Geist, J.M.; Meurisse, R.T.; Max, T.A. 1991. Monitoring forest soil properties to maintain productivity. In: Harvey, A.E.; Neuenschwander, L.F., comps. 1991. Proceedings, management and productivity of western montane forest soils. Gen. Tech. Rep. INT-GTR-280. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 90–94.

Geist, J.M.; Strickler, G.S. 1978. Physical and chemical properties of some Blue Mountain soils in northeast Oregon. Res. Pap. PNW-236. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 19 p.

Greacen, E.L.; Sands, R. 1980. Compaction of forest soils. [Article review]. Australian Journal of Soil Research. 18: 163–189.

Hall, F.C. 1973. Plant communities of the Blue Mountains in eastern Oregon and southeastern Washington. Region 6, Area Guide 3-1. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 62 p.

Harvey, A.E.; Neuenschwander, L.F., comps. 1991. Proceedings, management and productivity of western montane forest soils. Gen. Tech. Rep. INT-GTR-280. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 254 p.

Harward, M.E.; Youngberg, C.T. 1969. Soils from Mazama ash in Oregon: identification, distribution and properties. In: Pedology and Quaternary Research Symposium. Edmonton, Canada: University of Alberta: 163–178.

Hazard, J.; Geist, J.M. 1984. Sampling forest soil conditions to assess impacts of management activities. In: Stone, E., ed. Forest soils and treatment impacts. Proceedings of the 6th North American forest soils conference. Knoxville, TN: University of Tennessee: 421–430.

Helms, J.A.; Hipkin, C. 1986. Effects of soil compaction on tree volume in a California ponderosa pine plantation. Western Journal of Applied Forestry. 1(4): 121–124.

Jackson, M.L. 1958. Soil chemical analysis. Englewood Cliffs, NJ: Prentice Hall, Inc. 498 p.

Keeney, D.R.; Bremner, J.M. 1966. Comparison and evaluation of laboratory methods of obtaining an index of soil nitrogen availability. Agronomy Journal. 58: 498–503.

Lull, H.W. 1959. Soil compaction on forest and range lands. Misc. Publ. 768. Washington, DC: U.S. Department of Agriculture. 33 p.

Meurisse, R.T. 1988. Soil productivity protection and improvement: objectives, policy, and standards in the Pacific Northwest Region of the Forest Service. In: Slaughter, C.W.; Gasbarro, T., eds. Proceedings of the Alaska forest soil productivity workshop. Gen. Tech. Rep. PNW-GTR-219. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 63–68.

Miller, R.E.; Scott, W.; Hazard, J.W. 1996. Soil compaction and conifer growth after tractor yarding at three coastal Washington locations. Canadian Journal of Forest Research. 26: 225–236.

Nielson Gerhardt, M. 1986. Effects of logging and mechanical site preparation on levels of ammonium nitrogen and organic matter in forest soils. Moscow, ID: University of Idaho. 74 p. M.S. thesis.

Page-Dumroese, D.S. 1993. Susceptability of volcanic ash-influenced soil in Northern Idaho to compaction. Res. Note INT-409. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 5 p.

Perry, D.A.; Meurisse, R.; Thomas, B. [et al.], eds. 1989. Maintaining the long-term productivity of Pacific Northwest forest ecosystems. Portland, OR: Timber Press. 256 p.

Perry, T.O. 1964. Soil compaction and loblolly pine growth. Tree Planters Notes. 67: 9.

Rennie, P.J. 1955. The uptake of nutrients by mature forest growth. Plant and Soil. 7: 49–95.

Slaughter, C.W.; Gasbarro, T., eds. 1988. Proceedings of the Alaska forest soil productivity workshop. Gen. Tech. Rep. PNW-GTR-219. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 120 p.

Snider, M.D.; Miller, R.F. 1985. Effects of tractor logging on soils and vegetation in eastern Oregon. Soil Science Society of America Journal. 49: 1280–1282.

Sullivan, T.E. 1988. Monitoring soil physical conditions on a national forest in eastern Oregon: a case study. In: Slaughter, C.W.; Gasbarro, T., eds. Proceedings of the Alaska forest soil productivity workshop. Gen. Tech. Rep. PNW-GTR-219. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 69–76.

Swindell, B.F.; Conde, L.F.; Smith, J.E. 1986. Windrowing affects early growth of slash pine. Southern Journal of Applied Forestry. 10: 81–84.

Tew, D.T.; Morris, L.A.; Allen, H.A.; Wells, C.G. 1986. Estimates of nutrient removal, displacement and loss resulting from harvest and site preparation of a *Pinus taeda* plantation in the piedmont of North Carolina. Forest Ecology and Management. 15: 257–267.

Wert, S.; Thomas, B.R. 1981. Effects of skid roads on diameter, height and volume growth in Douglas fir. Soil Science Society of America Journal. 45: 629–632.

Pacific Northwest Research Station

Web site	http://www.fs.fed.us/pnw/
Telephone	(503) 808-2592
Publication requests	(503) 808-2138
FAX	(503) 808-2130
E-mail	pnw_pnwpubs@fs.fed.us
Mailing address	Publications Distribution Pacific Northwest Research Station P.O. Box 3890 Portland, OR 97208-3890

U.S. Department of Agriculture
Pacific Northwest Research Station
333 SW First Avenue
P.O. Box 3890
Portland, OR 97208-3890