Ponderosa Pine Growth Response to Soil Strength in the Volcanic Ash Soils of Central Oregon

Robert T. Parker, Douglas A. Maguire, David D. Marshall, and Pat Cochran

ABSTRACT

Mechanical harvesting and associated logging activities have the capacity to compact soil across large portions of harvest units, but the influences of compaction on long-term site productivity are not well understood. Previous research in central Oregon has shown that volcanic ash soils compact readily under both compression and vibration loads, resulting in long-term alteration in soil density and a decline in tree growth. In this study, soil strength (SS) and tree growth were assessed in areas subject to repeated timber harvesting with the objective of quantifying the relationship between ponderosa pine (*Pinus ponderosa Laws.*) growth and SS. Two thinning treatments (felled only versus felled and skidded) in 70- to 80-year-old ponderosa pine stands were replicated at three sites in 1991. Subsequent 5-year growth in diameter, height, and volume of residual trees were assessed with respect to SS measured by a recording penetrometer. Felled and skidded plots had 44% higher SS values than felled-only plots ($P = 0.05$). Although no treatment effect on growth was detected at the plot level, diameter, height, and volume growth of individual trees within plots declined significantly as average SS within a 30-ft zone of influence increased from approximately 800 to 2,500 kPa. Results show the potential use of SS measurements for monitoring impacts of harvesting operations on tree growth.

Keywords: site productivity, tree growth, ponderosa pine, compaction, volcanic ash, bulk density

The potential loss of site productivity caused by the compaction of forest soils during timber harvesting is a concern often expressed by forest managers and various publics. Soil compaction is a general term that can be regarded as an overall description of the condition of the soil after various machine operations (Froehlich and McNabb 1984). Compaction alters many forest soil physical properties such as bulk density, soil strength (SS), infiltration, aeration, macroporosity, hydraulic conductivity, and cation exchange capacity. Because the term soil compaction implies a concurrent change in numerous soil parameters, compaction may be quantified in many ways. SS, defined as the ability to support an externally imposed load or resist penetration, can be readily quantified in the field with a recording penetrometer. SS also integrates or indicates a number of soil attributes that may influence tree growth, such as the ability of roots to penetrate soil and the amount of available pore space (Allbrook 1986).

Establishing a functional link between soil compaction and changes in long-term site productivity faces some challenges. Until recently, sampling was done in only a few locations and the duration of studies on a given site have been relatively short (Froehlich 1979, Clayton et al. 1987). The USDA Forest Service and affiliated partners have established more than 100 long-term soil productivity (LTSP) studies in the United States and Canada to provide a better understanding of soil compaction and its biological effects (Powers et al. 1989). The LTSP studies focus on two principle soil parameters governing site productivity, which are most likely to be affected by harvesting, soil organic matter, and soil porosity (or soil compaction; Cline et al. 2006). In the first 10 years of study, no evidence was found that soil productivity was seriously impaired (Powers et al. 2004). A possible explanation for these results may be the relatively short time frame or the moderate degree of compaction achieved by treatments. Other research indicates that compaction effects range from an increase in productivity to a decrease or neutral effect, depending on local site conditions and biological differences among tree species (Miller et al. 1996, Gomez et al. 2002, Heninger et al. 2002). In coarse-textured soils, compaction has been shown to improve ponderosa pine and Douglas-fir growth compared with undisturbed areas (Powers and Fiddler 1997, Heninger et al. 2002). Conversely, ponderosa pine growing in compacted soil of a different texture grew at rates equivalent to one full site class less than trees growing in uncompacted soil, a reduction of approximately 10–12% (Helms and Hipkin 1986). Ponderosa pines in southwestern Oregon growing in heavily used skid trails likewise grew only about one-third of the volume that grew on undisturbed soil (Froehlich 1979). Lodgepole pine (*Pinus contorta* Laws.) seems to penetrate compacted soils better than many other Northwest conifer species and seems less influenced by compaction (Minore et al. 1969, Froehlich et al. 1985). With such widely varying results on the relationship between soil compaction and tree growth, continuing efforts to establish new studies and maintain both new and old ones will be essential for valid inferences (Miller and Hazard 1987).

Compaction of Volcanic Ash Soils

The volcanic ash-derived soils of central Oregon are comparatively young and unweathered, a product of Mount Mazama (Crater Lake) eruptions approximately 7,000 years ago. Soils of the region generally are poorly developed Andisols with loamy sand and sandy loam textures. They typically have a poorly represented A horizon

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Robert T. Parker (Bob.Parker@oregonstate.edu), Baker City, OR 97814. Douglas A. Maguire (Doug.Maguire@oregonstate.edu), Oregon State University, Corvallis, OR 97331. David D. Marshall (dmarshall@fs.fed.us) Olympia Forestry Sciences Laboratory, Pacific Northwest Research Station, Olympia, WA 98512. Pat Cochran (retired), Bend, OR 97702.
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containing little organic matter and are markedly deficient in nutrients (Youngberg and Dyrness 1965, Cochran 1978, Busse and Riegel 2005). The young parent material and semiarid conditions of the region are principally responsible for the poor fertility that limits plant growth and soil organic matter input. These ash soils are noted for their unique physical properties, such as very low bulk density, unusually high porosity, low organic matter content, low shear strength, nonplasticity, rough surface texture, and well-graded surface horizons. These properties make the soils highly susceptible to compaction, from compression as well as vibration (Geist et al. 1989, Cullen et al. 1991, Page-Dumroese 1993).

With increasing soil compaction, essential porosity declines as macropore space is lost, leading to increased bulk density, reduced water infiltration, and restricted gas exchange (Greacen and Sands 1980, Froehlich and McNabb 1984, Amaranthus and Steinfeld 1997). In highly graded ash soils with particle size ranging from extremely fine powder to grape-sized nuggets, compaction leads to filling of the macropores by fine particles, increasing soil density and SS, and impeding the ability of tree roots to penetrate the soil and acquire water and nutrients (Allen et al. 1997, Hillel 1998, Gomez et al. 2002). In New Zealand, rough surface-textured pumice soil particles were shown to have the unique feature of "bridging," or interlocking together when compacted, forming a nonyielding structure that severely limited root growth (Will and Stone 1967). Central Oregon volcanic soils experience similar particle bridging and, consequently, resistance to penetration by tree roots can be extremely high even though the bulk density of compacted soil remains relatively low (Cochran 1972). As SS in sandy soil increased, radiata pine (*Pinus radiata* D. Don) tree root elongation decreased at a geometric rate and essentially ceased at SS levels exceeding 3,000 kPa, a level easily exceeded in well-compacted skid trails and landings (Sands et al. 1979).

Ground-based equipment can impact a high percentage of a harvest unit in a single entry and the majority of all the compaction that ultimately occurs in a skid trail is created from the first few machine passes (Sidle and Drilca 1981, Adams 1991). Among the variables that can influence compaction, the number of passes is the most important variable (Weaver and Jamison 1951, Sidle and Drilca 1981). However, logging slash left on a skid trail provides a cushioning effect, reducing the intensity and depth of compaction (Zaborski 1989).

In some soils, freezing and thawing action tends to loosen the soils and ameliorate the effects of compaction. However, ash soils, in general, often contain less than 20% clay. The central Oregon ash soils are particularly low at approximately 8% clay content by weight; therefore, very little shrink-swell action takes place (Page-Dumroese 1993, Busse and Reigel 2005). Thus, once compacted, ash soils stay compacted for decades, and with repeated harvest cycles adding successive layers of compaction, the potential for cumulative effects increases (Froehlich et al. 1981, Vora 1988, Geist et al. 1989).

In areas where compaction is considered undesirable, compacted soils in skid trails and logging units can be returned to predisturbance conditions by ripping the soil, particularly with winged subsoilers. This practice is common in California and Oregon and has been used in the volcanic ash soils of central Oregon by the Forest Service and private industry (Miles et al. 1976, Heninger et al. 2002).

Quantifying Compaction

Visual evaluation of the degree of site disturbance has compared well with known levels of soil disturbance after timber harvesting (Tepp 2002). Although visual estimates of soil disturbance greatly simplify fieldwork, precise quantification of growth losses from soil compaction is not possible, because of, in large part, the loose relationship between surface disturbance and compaction. Likewise, subjective evaluation of compaction by rating degree of resistance to devices such as a t-handled probe or shovel is crude at best; so the efficacy of this technique for assessing compaction and quantifying growth loss is also questionable. Bulk density provides a more precise alternative to subjective estimates of compaction, but the process of obtaining accurate estimates of bulk density tends to be very time-consuming and expensive (Miller et al. 2004). It also has been established that soils can show significantly increased resistance to penetration with a relatively small increase in bulk density (Sands et al. 1979, Allbrook 1986, Clayton 1990). For these reasons, as well as convenience of data collection, recording penetrometers provide a distinct advantage for scientific investigation and it is not surprising that they have been recommended as a national standard for indicating compaction (Powers et al. 1999).

Increased resistance to penetration has clear implications for tree roots. However, there are considerable sources of natural variation that must be accounted for to isolate changes caused by solely treatment effects (Landsberg et al. 2003). Even in undisturbed soil, resistance to penetration tends to increase with increasing depth because of the weight of the soil above the point of measurement. This weight applies lateral forces on the penetrometer cone, requiring additional force to penetrate (Sands et al. 1979). Likewise, changes in soil texture, soil structure, and level of biological activity with depth also can influence resistance to penetration. Accurate assessment of the same microsites before and after treatment is one means of controlling for local variation, but this option is not available in retrospective studies, necessitating larger sample sizes and limiting cause-effect inferences.

History of Central Oregon Forests

In the early years of the 20th century, large areas of the gentle terrain in central Oregon were dominated by old-growth ponderosa pine stands. Many of these stands were clearcut, leading to the development of thousands of acres of densely stocked second-growth stands. By the early 1990s, increasing fiber values, an emphasis on stand density control, and improving harvesting technology made it economically feasible to enter stands at relatively young ages and at increasing frequencies.

Despite recent research in central Oregon that suggested declines in ponderosa pine productivity on compacted soils, ash soils often were considered by forest managers and loggers to be resistant to compaction, or if compaction did occur, this condition was thought to rapidly reverse with repeated frost heaving. The net effect of these perceptions can lead to poor control of mechanical harvesting in young ponderosa pine stands, resulting in substantially elevated SS conditions over 40–70% of harvest areas after only a single entry (Parker 2000).

Tree Growth Impacts

Although research around the world has found an inconsistent relationship between tree growth and compaction, the evidence indicates soil compaction may reduce ponderosa pine site productivity in the volcanic ash soils of central Oregon. In one study, seedling growth on moderate to heavily compacted soils tended to lag progressively behind seedlings growing on less compacted soil (Froehlich 1979). Well-established trees also exhibit growth reductions after compaction. In one case, basal area (BAL) growth was reduced by 12% over a 16-year period after harvest (Froehlich 1979). In regard to this particular combination of tree species and soil type, the evidence suggests that soil compaction may reduce site productivity of ponderosa pine in volcanic ash soils and that intelligent harvest planning is essential for limiting or ameliorating adverse impacts.

Ponderosa Pine Rooting Characteristics in Central Oregon Ash Soils

The rooting patterns of ponderosa pine in central Oregon ash soils may provide insight into observed losses of productivity associated with compaction. Ponderosa pine in central Oregon has been found to have long lateral roots close to the soil surface extending 20–30 ft from the trunk (see Figure 8 in Hermann and Petersen [1969]). Height growth also can increase sharply when a deep taproot penetrates into buried subsoil. The buried soils provided far more moisture and nutrients than were available in the 34- to 56-in. pumice cap. Two soil-associated mechanisms could account for reductions in tree growth after harvesting. First, lateral development of shallow roots could be inhibited by compaction or by direct mechanical damage from harvesting equipment. This mechanism is supported by the progressive decline in tree growth as the percentage of soil compacted around the tree increases (Moehring and Rawls 1970). The second mechanism involves compaction in the C horizon, possibly impeding development of the deep taproot and increasing the length of time required for trees to reach the buried subsoil (Hermann and Petersen 1969).

Study Goals

The objective of this study was to determine if the growth of ponderosa pine trees growing in volcanic ash soils is impacted by differences in SS. SS is a potential indicator of compaction in a harvested area. SS is used in this study because of its relative ease of measurement, but it is only one of the many physical properties that are potentially impacted because of harvesting (e.g., bulk density, soil moisture content, porosity, and hydraulic conductivity; Carter et al. [2000]).

Methods and Materials

Study Sites

In the late 1980s, the Deschutes National Forest and the Pacific Northwest Research Station in Bend, Oregon established the Black Bark or Bend Long-Term Site Productivity study (LTSP) to improve understanding of the ecology of ponderosa pine forests in the region (Cochran et al. 1988). Mountain pine beetle (*Dendroctonus ponderosae*) outbreaks were causing extensive lodgepole pine mortality in the area and the risk of damage to ponderosa pine stands was a significant concern to the Deschutes National Forest. Because research had shown stand density reduction through thinning was an effective tool for reducing beetle mortality risks (Waring and Pitman 1985), the Forest Service targeted 247,000 ac of second-growth ponderosa pine stands for stocking reduction. Pat Cochran (PNW Soil Scientist), Bill Hopkins (Area Ecologist), and Don Peterson (Timber Staff Officer), conceived the Bend LTSP study as an opportunity to capitalize on ponderosa pine management efforts and evaluate soil and plant responses to manipulation of site organic matter (Busse and Riegel 2005).

The study comprised three separate sites within 16 mi of Bend, Oregon, including Swede Ridge (SR) to the southwest, Sugarcast (SC) to the South, and East Fort Rock (FR) to the southeast (Table 1). The three study areas followed a west-to-east declining moisture gradient corresponding to distance east of the Cascade crest. Average annual precipitation ranged from 26 to 15 in., most of which fell as snow between the months of September and May. SR was closest to the Cascade crest and receives approximately 26 in. of precipitation; SC was located further east and receives around 20 in. of precipitation. East FR was at the eastern limits of ponderosa pine and receives only 15 in. of precipitation (Table 1). Generally, summers are hot and dry, with temperatures ranging from 21 to 30° C. Nights are predominantly cool with the chance of frost occurring any time during the year.

Each of the three sites contains 19 individual plots. For this study, two plots from each site were selected for their relative similarity in dbh, height, age (47–63 years breast height), development history, soil type, site potential, and stocking levels (Table 1). The pair of plots from each study site was thinned but received no other treatment. In 1992, 1994, and 1996, the Pandora moth (*Coloradia pandora* Blake) defoliated ponderosa pine at the LTSP study sites during severe outbreaks. Percentage of crown loss from defoliation (DEF) was estimated to account for the effect of DEF on growth. The mean, minimum, and maximum values for diameter, height, and volume periodic annual increment (PAI), average SS, initial tree size parameters, and percent DEF by plot are shown in Table 2.

Between June and November of 1991, all six plots were thinned from below to create even-aged paired plots with similar stocking. Prethinning stocking data are not available but a comparison between thinned and unthinned plots within the three study areas suggests stocking was reduced on average by approximately 44%. Trees on one plot from each pair of thinned plots were felled and delimbed with chainsaws and left on site (No Removal treatment). Trees on the other plot were felled with mechanical harvesters, delimbed by chainsaw, and the boles removed by rubber-tired grapple skidders (Removal treatment). The exact size and type of equipment used is unknown but the mechanical harvesters were thought to have front-mounted shears. Therefore, only the Removal plots were potentially compacted by mechanical harvesting and skidding activity (Bill Hopkins, Area Ecologist, personal communication, 2006).

Field Measurements

Study plots were approximately 0.40 ac in size. SS in the rooting zone was estimated by establishing a square grid across each plot and measuring SS at 1-in. increments to a depth of 24 in. with a Rimiks CP-20 recording penetrometer (Agridry Rimick PTY LT, Queensland, Australia). Although other studies have indicated that maximum compaction occurs at depths much shallower than 24 in., one goal of this study was to characterize soil conditions throughout the majority of the rooting zone and 24 in. represents approximately 80% of the rooting zone for ponderosa pine (Froehlich 1979). The cone diameter, angle, and surface area of the penetrometer were 1.27 cm, 30°, and 1.27 cm^2, respectively. Soil measurements were made between the months of May and October. Although there was some variation in soil moisture through those months, variation in SS due to moisture was not apparent. Sands et al. (1979) noted that in sandy soils, resistance to penetration was largely independent of water content but was directly related to the bulk density of the soil. A 5 × 5 ft grid was used on the Removal plots, and a 10 × 10 ft grid was used on the No Removal plots because the variation in soil conditions was predicted to be much lower. SS was measured also within a 15-ft buffer around the plots to characterize soil conditions outside of the plots and adjacent to edge trees. The sampling grid

Table 1. Stand and site attributes for SR, SC, and East FR research plots on long-term site productivity in ponderosa pine.

	SR		SC		East FR	
Stand and site stributes postthinning	Plot 4 No removal	Plot 2 Removal	Plot 3 No removal	Plot 18 Removal	Plot 15 No removal	Plot 4 Removal
Avgerage dbh (in.)	11.6	12.1	12	12.5	12.6	11.3
Avgerage height (ft)	61	57.9	64.5	58.7	50.6	46.6
Trees/ac	150	155	73	88	95	98
Avgerage BAL/:Tree (ft^2)	0.71	0.78	0.88	0.81	0.87	0.68
BAL/ac ($ft^2\ ac^{-1}$)	104	116	62	70	81	65
Avgerage SDI	122	117	49	64	66	82
Elevation (ft)	4,500–5,000		4,500–4,700		4800–5100	
Latitude	43°50′56″		43°50′08″		43°50′16″	
Longitude	121°20′43″		121°20′07″		121°19′06″	
Site index (Meyers[a])	65–85		70–90		50–70	
Precipitation (in.)	26		20		15	
Soil type	Cryand andisol		Cryand andisol		Cryand andisol	
Surface soil depth (in.)	24–60		24–50		20–40	
Buried soil type	Cobbly sandy loam		Sandy loam		Sandy loam	

[a] Dominant height at 100 yr.

insured that the locations of all SS readings were known and facilitated mapping of all trees within each plot. Each tree was measured for total height, length of crown, crown width, and dbh in the spring of 1992 and again in the fall of 1996 (Matt Busse, USDA Forest Service, Redding, CA, personal communication, 2006). To characterize the local SS experienced by individual trees, weighted average SS was computed from all readings within a 30-ft radius around each subject tree, with weights equal to the proportion of the sample area associated with each penetrometer reading that fell within the 30-ft zone of influence.

Because different grid sizes were used on the Removal and No Removal plots, the local SS estimates for individual trees were based on a varying number of sample points; therefore, each observation (tree) was weighted by the number of sample points within its 30-ft zone of influence for the purpose of statistical analysis.

Data Analysis

Plot-level treatment effects were first tested by randomized block analysis of variance (ANOVA) with both SS and stem volume growth as plot-level response variables (SAS Institute, Inc. 1982). All growth was expressed as PAI for the 5-year growth period. To account for possible differences in initial stocking among the plots, an ANOVA also was run on the ratio of volume PAI to initial volume. Average SS values at depths of 6, 12, 18, or 24 in. were available in the database. However, rocks, tree roots, and other obstacles occasionally prevented the soil probe from penetrating to 24 in., resulting in some missing data. Because nearly 100% of the samples penetrated to a depth of 12 in. and because soil at this depth should be more heavily impacted than deeper layers, SS in this upper soil layer was selected as the measure of soil condition. No initial measurements of SS were taken before harvest treatments. Consequently, no estimates of compaction (i.e., increase in SS) were possible. Tests of treatment effects assume the random assignment of treatments to plots minimized the probability that initial conditions differed among plots receiving the same treatments.

The effect of SS on diameter, height, and volume growth of individual trees was evaluated also because individual trees were expected to respond to a finer and more local scale of soil conditions. In particular, if plot-level treatment effects were masked by high within-plot variability in soil condition, then the growth responses of individual trees to local SS would help assess the effect of spatial scale on this relationship.

Individual tree growth was evaluated with a mixed-effects model containing a random block effect and a fixed treatment and SS effect. Other covariates were considered also in an effort to isolate the effects of SS (Table 3). Because tree locations were mapped, several distance-dependent competition indices were added to the list of potential predictor variables (Biging and Dobbertin 1992, 1995).

An all-subsets approach was taken to identify variables and models with the greatest descriptive potential, initially leaving out the random block effect (see Table 3 for list of candidate predictor variables). SS was transformed to ensure a threshold below which declining SS has little or no additional effect on tree growth. Because tree growth also should become asymptotic to zero at high SSs, the net effect is a reverse sigmoid shape over SS. Alternative SS variables were created by raising SS to successively increasing powers in increments of 0.5, starting with 0.5 and ending with 3.5. A set of candidate models was selected on the basis of statistical performance and expected behavior of tree growth over SS and other covariates. The final candidates were then fitted in the following form as a mixed-effects model (Schabenberger and Pierce 2002):

$$\ln(\Delta Y) = \beta_1 + \beta_2 X_1 + \beta_3 X_2 + \dots + \beta_k X_k + \gamma + \varepsilon \quad (1)$$

where ΔY is 5-year tree diameter, height, or volume growth; β_i are parameters fitted to the data; X_i are covariates for tree size, competition, SS, and DEF; γ is a random block effect with $\gamma \sim N(0, \sigma^2_\gamma)$; and ε is a random disturbance term on individual tree observations with $\varepsilon \sim N(0, \sigma^2_\varepsilon)$.

Results

The ANOVA of the Removal versus No Removal treatments showed that units receiving mechanical thinning treatments had significantly greater SS ($P < 0.001$). SS on the Removal plots averaged 1,757 kPa of resistance compared with 1,222 kPa for the No Removal plots, a 44% difference. However, plot-level volume growth was not significantly different between the two treatments ($P = 0.554$), and correcting for initial volume of each plot did not change the outcome ($P = 0.405$).

The final mixed-effects models describing individual tree diameter, height, and volume growth, respectively, were

$$\ln(\Delta Y) = \beta_1 + \beta_2\mathrm{TRT} + \beta_3\mathrm{DEF} + \beta_4\mathrm{dbh} + \beta_5\mathrm{BAL} + \beta_6(\mathrm{SS}/1{,}000)^{2.5} + \gamma + \varepsilon \quad (2)$$

Table 2. Means, minima, maxima, and SDs for tree-level variables by block and treatment.

		Minimum	Mean	Maximum	SD
			Diameter (in./yr)		
SR	No removal	0.02	0.07	0.12	0.03
	Removal	0.02	0.08	0.16	0.04
SC	No removal	0.02	0.09	0.12	0.03
	Removal	0.08	0.16	0.28	0.06
FR	No removal	0.02	0.05	0.10	0.02
	Removal	0.04	0.08	0.16	0.03
			Height (ft/yr)		
SR	No removal	0.48	0.85	1.24	0.19
	Removal	0.18	0.57	1.08	0.20
SC	No removal	0.06	0.37	1.38	0.44
	Removal	0.06	0.44	1.20	0.30
FR	No removal	0.06	0.34	0.94	0.20
	Removal	0.04	0.24	0.76	0.18
			Volume (ft^3/tree per yr)		
SR	No removal	0.14	0.46	0.86	0.18
	Removal	0.06	0.38	1.26	0.26
SC	No removal	0.14	0.39	1.00	0.26
	Removal	0.10	0.62	1.18	0.32
FR	No removal	0.08	0.24	0.70	0.16
	Removal	0.06	0.20	0.70	0.12
			SS (kPa)		
SR	No removal	830.15	1116.97	1430.16	205.62
	Removal	1309.77	1933.86	2531.87	319.50
SC	No removal	972.09	1023.78	1091.61	39.29
	Removal	1108.95	1349.31	1647.18	163.30
FR	No removal	788.31	891.68	1035.18	79.68
	Removal	1402.47	1659.04	1848.36	114.43
			dbh 1991 (in.)		
SR	No removal	7.40	11.34	14.50	1.67
	Removal	8.00	11.52	16.30	1.79
SC	No removal	8.70	12.45	14.30	1.94
	Removal	6.10	12.41	17.70	2.89
FR	No removal	7.40	12.32	21.00	3.33
	Removal	7.60	10.54	14.00	1.72
			Height 1991 (ft)		
SR	No removal	41.40	57.59	68.00	6.68
	Removal	41.70	55.42	72.50	7.31
SC	No removal	55.40	64.03	77.00	7.57
	Removal	41.80	59.17	75.70	7.90
FR	No removal	34.00	50.00	68.70	9.23
	Removal	34.10	44.05	52.10	5.40
			Percent DEF		
SR	No removal	1.83	12.36	29.00	7.21
	Removal	1.33	16.95	55.80	12.94
SC	No removal	51.70	58.57	63.30	3.81
	Removal	46.67	55.35	63.67	6.03
FR	No removal	20.00	45.83	61.70	12.08
	Removal	23.33	51.17	75.17	12.77

$$\ln(\Delta Y) = \beta_1 + \beta_2\text{DEF} + \beta_3(\text{SS}/1{,}000)^{2.5} + \gamma + \varepsilon \quad (3)$$

$$\ln(\Delta Y) = \beta_1 + \beta_2\text{TRT} + \beta_3\text{DEF} + \beta_4\text{dbh} + \beta_5\text{BAL} + \beta_6(\text{SS}/1{,}000)^{2.5} + \gamma + \varepsilon \quad (4)$$

where ΔY is 5-year diameter, height, or volume growth of the subject tree; TRT is an indicator variable for the tree removal treatment; DEF is % DEF by Pandora moth; dbh is initial (1991) dbh; BAL is the BAL in trees with dbh larger than subject dbh (ft^2/ac); SS is soil strength; β_i's are fixed-effect parameters estimated from the data; γ is a random block effect with $\gamma \sim N(0, \sigma^2_\gamma)$; and ε is a random disturbance term on individual tree observations with $\varepsilon \sim N(0, \sigma^2_\varepsilon)$. Parameter estimates suggested that diameter and volume growth were significantly greater under the Removal treatment ($P >$ 0.05) but declined with increasing local SS (Table 4). Individual tree height growth also declined with increasing SS but did not differ significantly ($P > 0.05$) between treatments (Table 2). Diameter, height, and volume growth also declined with increasing Pandora moth DEF and increasing BAL in trees larger than the subject tree (BAL). Diameter, height, and volume growth began to decline substantially when mean SS exceeded approximately 1,000 kPa. Above this level, the models predict rapidly declining growth rates, becoming negligible at 4,000–5,000 kPa (Figures 1–3). A residual plot of observed minus predicted volume growth indicates the theoretical model fits actual conditions well (Figure 4).

Table 3. Potential predictor variables for regression analysis of individual tree growth response to SS.

Variable	Description
TRT	Treatment (removal, no removal)
dbh	dbh in 1991 (in.)
HT	Height in 1991 (ft)
CR	Crown ratio in 1991
PDF	Percent defoliation
VOL	Initial volume in 1991 (total ft^3)
TPA	Trees per acre
BAPA	BBAL(ft^2/ac) Basal area per acre
SDI	Stand density index
CCF	Crown competition factor
BAL	BAL in trees with larger dbh (ft^2/ac)
CCFL	Crown completion factor in larger dbh
DistNearest	Distance (ft) to closest tree
DiaNearest	Diameter (in.) of closest tree (1991)
NoDist	Number of trees within search radius
AvgDia	Average diameter of trees within search radius (in.)
MARTINEK	Martin and Ek (1984)
ARNEY	Arney (1973)
CC-H66	Crown closure at 66% of height of subject tree for competitors taller than a vertical angle of 50° (Biging and Dobbertin)
CC-H75	Crown closure at 75% of height of subject tree competitors taller than a vertical angle of 50° (Biging and Dobbertin)
SS	Average SS at 0–12 in. (kPa)

Discussion

Soil compaction results from a complex interaction between SS, density, and porosity, thereby influencing the ability of roots to penetrate the soil. Aeration and moisture and nutrient availability generally deteriorate with compaction, so all of these factors may

Table 4. Parameter estimates for diameter, height, and volume growth models (Equations 2, 3, and 4).

Variable	Parameter	Parameter Estimate	Parameter Std. Error
Diameter growth			
Intercept	β_0	1.92750	0.92600
TRT	β_1	0.57470	0.11680
dbh	β_2	−0.74090	0.31830
DEF	β_3	−0.01707	0.00341
SS	β_4	−0.83650	0.02854
BAL	β_5	−0.00987	0.00221
Height growth			
Intercept	β_6	1.52630	0.25270
DEF	β_7	−0.01848	0.00412
SS	β_8	−0.08447	0.02390
Volume growth			
Intercept	β_9	−1.4368	0.8106
TRT	β_{10}	0.3309	0.1018
dbh	β_{11}	1.2041	0.2775
DEF	β_{12}	−0.0178	0.0030
SS	β_{13}	−0.0910	0.0249
BAL	β_{14}	−0.0061	0.0019

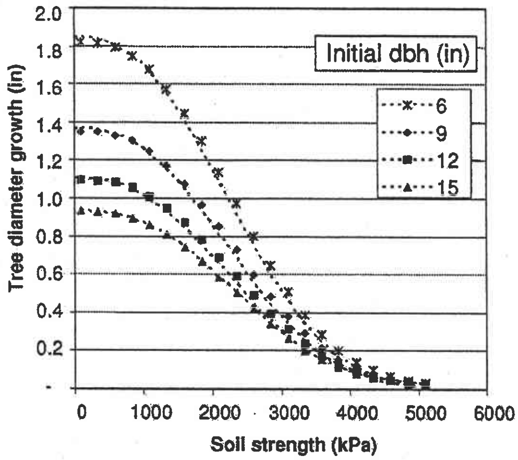

Figure 1. Predicted 5-year individual tree diameter growth response to increasing SS for a tree with initial dbh of 6, 9, 12, and 15 in.

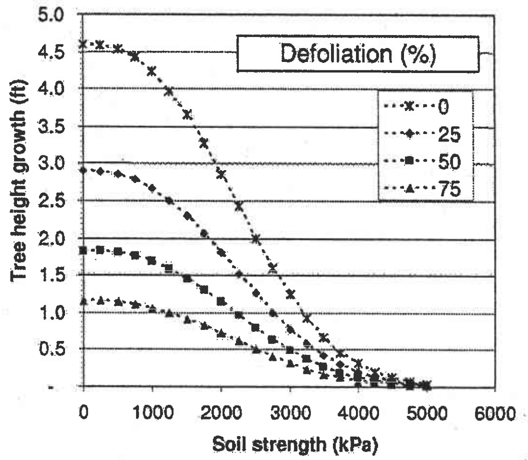

Figure 2. Predicted 5-year individual tree height growth response to increasing SS for a tree with 0, 25, 50, and 75% Pandora moth DEF.

have influenced the tree growth measured in this study. However, because only SS was measured in this study as an indicator, it is not possible to fully identify the mechanisms causing the observed growth patterns. Likewise, because change in soil condition could not be estimated in this retrospective study, the functional relationship between harvest treatments and observed SS remains uncertain.

The lack of a treatment effect on plot-level stem volume growth was surprising given the difference in apparent SS between Removal and No Removal plots. This insensitivity of plot volume growth was underscored by the inconsistent average plot diameter and height growth responses to Removal plots (Table 2). It is important to recognize, however, that initial stand density was not introduced as a covariate in the plot-level ANOVAs because of the small sample size. Because differences in plot attributes inevitably arise due to natural variability in the sampled population, corrections for these differences through the use of covariates would be expected to increase the power of the statistical tests.

The mixed-effects model tested the growth responses of individual trees to both the plot-level treatment and the local-level

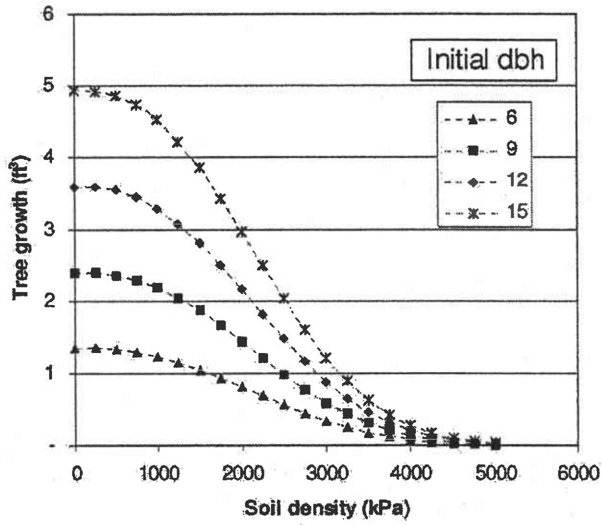

Figure 3. Predicted 5-year individual tree cubic foot volume growth response to increasing SS for a tree with initial dbh of 6, 9, 12, and 15 in..

SS, after removing the random effects of site and fixed effects of initial dbh, Pandora moth DEF, and competition from larger trees. Increasing SS within a local zone of influence (30-ft radius) had a significantly negative effect on individual tree growth ($P > 0.05$). The combined plot-level and tree-level results suggested the possibility that the spatial distribution of compacted soils (e.g., skid trails) relative to residual trees may be important for controlling adverse effects on tree growth. Trees experiencing high SSs clearly showed reduced growth, but the lack of a statistically significant growth loss at the plot level may indicate that relatively few trees experienced extreme SS conditions, despite the fact that the average SS was greater on Removal plots. As previously mentioned, this possibility has to be weighed against differences in initial stand density. One unknown factor that could have complicated the LTSP results was possible elevation of SS by previous railroad logging.

After the effect of local SS was accounted for, the Removal treatment was associated with greater individual tree growth. This result suggested that the Removal treatment could have imposed other effects beyond those relating to SS. For example, whole tree removal may have avoided nutrient sequestration by decomposing organisms in material left on site under the No Removal treatment. The fresh woody material, in particular, could have immobilized nitrogen due to the high carbon-to-nitrogen ratio characterizing bark and wood.

Many silvicultural studies would benefit from concurrent monitoring of soil compaction. Assessment of compaction would help separate growth effects attributable to manipulation of vegetation structure from those that are inadvertently produced by compaction and other soil disturbances. In at least one study, soil analysis showed a strong correlation between tree spacing and soil variables, to the extent that spacing effects were confounded with soil differences (Miller et al. 2004).

Decisions about preferred harvest practices and acceptable limits for soil impacts must consider site-specific factors such as condition of the soil before harvest, soil type, forest type, and amount of residual slash to buffer equipment (Page-Dumroese et al. 2006). Good land stewardship is needed to sustain long-term site productivity and intensive forest management practices but the economic costs of protective management practices must allow the forest industry to remain competitive in the global economy (Cline et al.

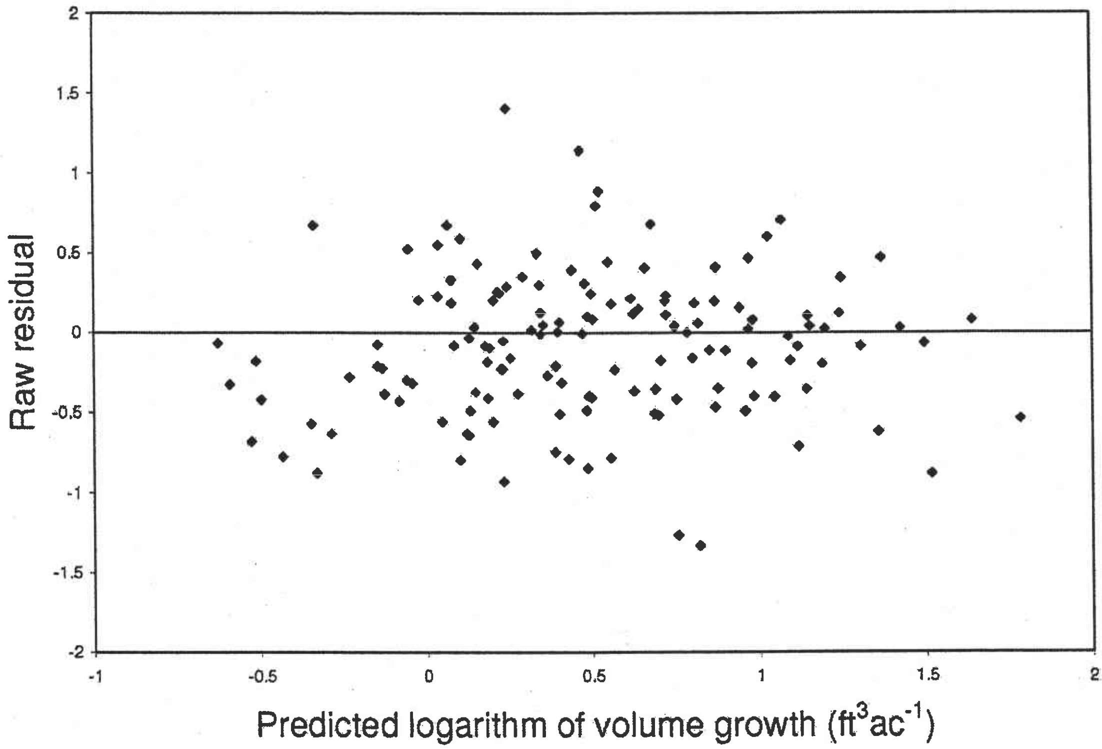

Figure 4. Residuals from individual tree volume growth model (Equation 4).

2006). However, taking measures to protect the soil does not necessarily increase costs because harvesting practices such as designated skid trails and low-impact harvesting equipment that can substantially reduce site disturbance also can be economically efficient and cost-effective (Bradshaw 1979, Garland 1993).

Because soil compaction can adversely affect long-term site productivity, some organizations and agencies have attempted to mitigate possible losses in productivity by establishing threshold standards for site disturbance. For example, in 1978 the Forest Service developed the widely adopted policy that a 15% increase in soil bulk density of ash-derived soils represents detrimental compaction and that this level of disturbance should not exceed 20% of the total (gross) harvested area, including permanent roads (USDA Forest Service 1998). The 44% greater SS found in the Removal plots suggested that this standard may have been exceeded, assuming a corresponding increase in bulk density. However, the lack of pretreatment SS measurement limits the degree to which definitive statements can be made about the direct effects of the treatments on SS and subsequent tree growth. Likewise, the limited geographic scope restricts application of the results to ponderosa pine growing in the volcanic ash soils of central Oregon. Long-term tree performance, reliably measured over a wide range of soil types and climatic conditions, is needed to reduce the uncertainty about the actual consequences of soil compaction. (Miller and Anderson 2002).

Conclusion

This study establishes the use of SS measurements as a potential tool for monitoring impacts of harvesting operations on tree growth. Based on data from three sites with volcanic ash soils in central Oregon, diameter, height, and volume growth of individual ponderosa pine trees declined with increasing local SS (i.e., within a 30-ft radius of influence), but plot-level growth did not differ between treatments associated with significant differences in SS. This study was limited by factors such as the relatively short growth period since treatment (5 years), three separate DEF events by the Pandora moth, and the lack of preharvest soil measurements. Later, follow-up on tree growth and SS would add significantly to our current knowledge of impacts of and recovery from soil disturbance. However, the results from this study do support previous research indicating that ponderosa pine productivity declines with elevated SS, regardless of its cause.

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