Ground-Based Forest Harvesting Effects on Soil Physical Properties and Douglas-Fir Growth

Adrian Ares,* Thomas A. Terry, Richard E. Miller, Harry W. Anderson, and Barry L. Flaming

ABSTRACT

Soil properties and forest productivity can be affected by heavy equipment used for harvest and site preparation but these impacts vary greatly with site conditions and operational practices. We assessed the effects of ground-based logging on soil physical properties and subsequent Douglas-fir [*Pseudotsuga menziesii* (Mirb) Franco] growth on a highly productive site receiving vegetation control in coastal Washington. We also tested the effectiveness of tillage in maintaining or enhancing site productivity. On average, about half of the area of ground-based harvested plots was affected by vehicular traffic. Sixty-three percent of the trees were planted on microsites with some degree of soil disturbance. Soil bulk density at the 0- to 30-cm depth increased from 0.63 to 0.82 Mg m^{-3} in the most compacted portions of traffic lanes. The area-weighted increase in soil bulk density in the 0- to 30-cm depth was 27%. Soil strength in traffic lanes increased at all depths < 55 cm but never exceeded 1300 kPa. Tillage to the 60-cm depth returned the soil to its initial strength condition. Volumetric soil water content in compacted traffic lanes was greater than that in non-compacted soil. Total soil porosity decreased 10 to 13% with compaction, while available water holding capacity increased. In compacted soil, macropore space was reduced 40 to 52%. The study revealed no detrimental effects on tree height and diameter from soil compaction at age 4. At stand age 3, a tree volume index was actually greater for trees planted on traffic lanes than for those on non-disturbed soil.

MAINTAINING LONG-TERM site productivity is an essential requirement for sustainable forest management. This goal can be compromised in managed stands if the use of heavy equipment for harvest and site preparation causes soil degradation and reduces tree growth (Wert and Thomas, 1981; Murphy, 1983; Froehlich et al., 1986; Conlin and van den Driessche, 1996). The most common effect on soils from ground-based forest operations is increased compaction (Steinbrenner and Gessel, 1955; Hatchell et al., 1970), usually indexed by bulk density or soil strength measurements (Greacen and Sands, 1980; Powers et al., 1998). Soil compaction has been found to reduce infiltration (Startsev and McNabb, 2000), saturated hydraulic conductivity (Purser and Cundy, 1992), sorptivity (Malmer and Grip, 1990), pore-size distribution and volume (Lenhard, 1986; Huang et al., 1996), redox potential (Herbauts et al., 1996), N mineralization (Zabowski et al.,

1994), and microbial number, biomass, and activity (Smeltzer et al., 1986; Dick et al., 1988; Torbet and Wood, 1992). Each of these effects can potentially reduce tree growth. In contrast, soil compaction can increase soil water holding capacity (Gomez et al., 2002b), unsaturated water flow (Sands et al., 1979), root contact with soil (Bhadoria, 1986), and N uptake (Gomez et al., 2002a), and may therefore result in conditions being more favorable for tree growth.

Recent studies have revealed a large degree of site-specificity both in soil and tree growth responses to soil compaction (Brais, 2001; Gomez et al., 2002b; Smith, 2003). These research results have promoted new insights on the effects of soil compaction on forest productivity in different soil types, and demonstrated the importance of having site-specific soil-quality assessments in forests. Moreover, there is still limited information on the relationships between soil compaction/disturbance and tree responses. Also, compaction is not the only type of soil disturbance resulting from harvesting activities. Soil mixing, puddling, and rutting can cause disruption of water flow and other effects. Topsoil can also be displaced if stumps are bladed to make access for skidding or forwarding equipment. It is therefore important to characterize disturbance so that compaction is differentiated from detrimental impacts on soils such as topsoil removal or disrupted soil drainage (Miller et al., 1989; Heninger et al., 1997). Generalizations about negative effects of harvest-related soil disturbance on tree growth may be in error because these impacts depend on their type and severity, and on soil properties and climatic conditions (Heninger et al., 2002).

These issues are relevant for the Pacific Northwest, a highly productive timber production region of the USA where heavy equipment is commonly used for site preparation and timber harvest. The region contains large areas of forest soils with inherently high organic C content, and relatively low soil bulk density that apparently mitigate some of the impacts on forest site productivity from intensive management. Supporting this view, 8-yr stem diameter and height growth, and survival of Douglas-fir on Inceptisols in coastal Washington were similar on non-tilled and tilled skid trails, and on nontrafficked areas in spite of the fact that bulk density on skid trails was 41 to 52% greater than in non-trail areas after logging (Miller et al., 1996). For sites with less soil organic matter, greater soil clay content,

A. Ares, Weyerhaeuser Co., 2730 Pacific Blvd. Albany, OR 97322; T.A. Terry, Weyerhaeuser Co., 505 N. Pearl, Centralia, WA 98531; R.E. Miller and H.W. Anderson, USDA Forest Service, Pacific Northwest Research Station, Olympia Forestry Sciences Laboratory, 3625 93rd Avenue SW, Olympia, WA 98512; B.L. Flaming, ENSR International, 9521 Willows Rd. NE, Redmond, WA 98052. Received 7 Oct. 2004. *Corresponding author (adrian.ares@weyerhaeuser.com).

Abbreviations: AWC, available water content; D_b, bulk density; DBH, stem diameter at 1.3 m above ground; DC, disturbance class; MV, macropore volume; r_p, pore radius; SVOL, volume index; TH, total height; ΔP, pressure difference across an air–water interface at equilibrium; θ, volumetric soil water content; θ_r, residual volumetric soil water content; θ_s, volumetric soil water content at saturation; ψ, soil water potential; σ, surface tension of water.

and more severe drought stress than in coastal Washington, impacts of soil compaction on early growth of Douglas-fir were negative but effects on annual growth rates were temporary. Thus, Douglas-fir height growth on non-tilled and tilled skid trails on Ultisols in Oregon Cascades averaged 24% less on non-tilled skid trails than on tilled trails in Year 4 after planting but differences in annual growth decreased to 6% in Year 7, and by age 8 to 10 year growth rates were similar (Heninger et al., 2002). Ten years after planting trees in 15-cm deep skid-trail ruts were 10% shorter on average with 29% less volume than those on undisturbed areas (Heninger et al., 2002).

Many studies in the Pacific Northwest and elsewhere have assessed tree growth and soil response in logged sites using the "after-the-fact" retrospective approach described by Powers (1989), which may not allow to ascertain the original type, degree, and extent of disturbance. In addition, tree growth may have been unknowingly and differentially affected by plant competition, disease, herbivory and other factors. Tree growth impacts are also sometimes measured for short periods of time and these data are then incorrectly used to project long-term effects. For these reasons, the retrospective approach was not used in our research.

In this study, we examine harvesting effects on soil properties and tree growth on a highly productive site intensively managed for Douglas-fir production in coastal Washington. This is a long-term, replicated experiment in which imposed disturbance reflects field operational conditions as closely as possible, and the confounding effects of competition to trees by vegetation, big game browse, and unknown site history have been removed. In addition, the experimental site has homogenous soil and topographic conditions, and relatively low levels of tree root-rot diseases such as *Armillaria* or *Phellinus*. This study is an affiliate installation to the U.S. Forest Service Long-Term Soil Productivity research program that encompasses numerous sites across the USA and Canada (Powers and Fiddler, 1997).

The objectives of this investigation were to (i) assess soil disturbance after ground and cable-based logging; (ii) determine the impacts of soil disturbance and compaction on soil properties and tree growth, and the effectiveness of tillage in maintaining or enhancing site productivity; and (iii) widen the knowledge base for refining site preparation and harvesting standards for soil disturbance and best management guidelines for intensively managed Douglas-fir sites.

MATERIALS AND METHODS

The Fall River site is in the Coastal Range of Washington State at 46°43′ N lat. and 123°25′ W long., approximately 60 km southwest of Olympia (Fig. 1). The climate is maritime with wet, mild winters and warm, dry summers. Mean annual precipitation is 2260 mm, mostly as rain. Mean annual air temperature is 9.2°C with monthly means of 2.6°C in January and 16.0°C in August. During the study period, the highest annual rainfall was in 2003 (1928 mm) compared with 1608 mm in 2001, and 1388 mm in 2002. In 2001, 42% of the annual rainfall occurred from April to September with 103 mm re-
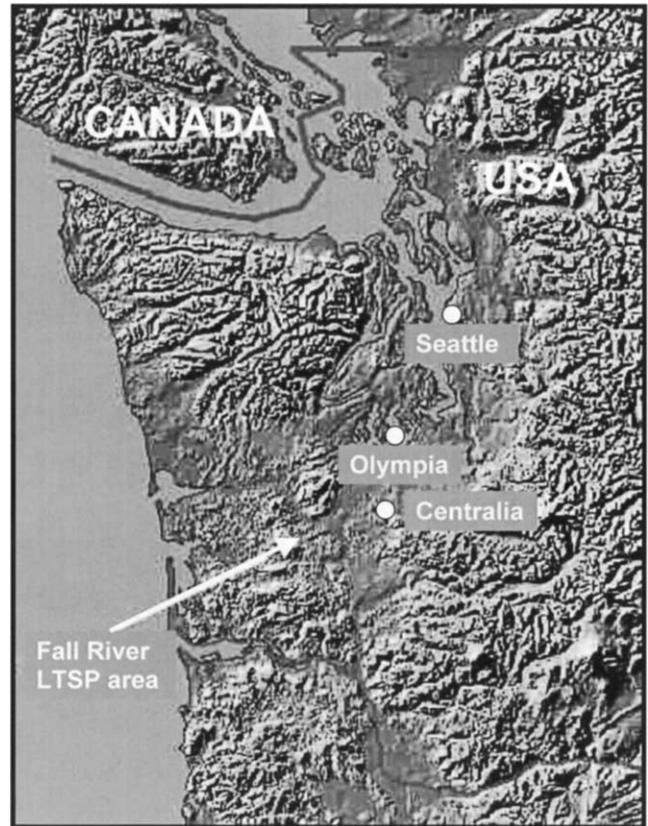

Fig. 1. Location of the Fall River study area in coastal Washington, USA.

corded for July and August. In contrast, 24% of the rainfall occurred during this period in 2002 with only 13.7 mm in July and August. In 2003, 33% of the rainfall fell during April to September with 20 mm in July and August.

The experimental site is on gentle slopes (<10%) facing west with elevation ranging between 305 and 362 m. The soil is a medial over clayey, ferrihydritic over parasesquic, mesic Typic Fulvudand (Soil Survey Staff, 1992) of the Boistfort series developed from weathered Miocene basalt and influenced by volcanic ash in the upper horizons (Steinbrenner and Gehrke, 1973; Logan, 1987). The modal sequence of horizons is A/AB/B/C. The soil is deep, well-drained, and mostly stone-free, and has low bulk density, high organic C content and high water-holding capacity (Table 1). Total soil N to 1.5-m depth ranges from 12 214 to 14 716 kg ha^{-1} (R. Harrison, unpublished data, 2004). The site quality class for Douglas-fir is I to II+ with a site index (i.e., mean dominant height at breast-height age 50; King, 1966) of 42 m.

The site is within the western hemlock [*Tsuga heterophylla* (Raf.) Sarg.] vegetation zone (Franklin and Dyrness, 1973). A preharvest vegetation survey indicated that the plant association community was western hemlock/western sword fern *(Polystichum munitum* (Kaulf.) C. Presl.)/redwood sorrel (*Oxalis oregana* Nutt). The old-growth stand previously occupying the site was cable yarded in 1952–1953 followed by broadcast burning and planting of Douglas-fir. Aerial photographs taken after harvest showed no evidence of significant soil compaction or other major soil disturbance within the study area. The Douglas-fir stand was precommercially thinned in 1971, and fertilized four times between 1970 and 1995 with a total of 820 kg N ha^{-1} as urea.

The Fall River study was installed, except for vegetation control treatments, from April to July of 1999 to examine the

Table 1. Soil characteristics at the Fall River study site in Coastal Washington.†

Horizon	Depth	D_b	AWC	MV	Sand	Silt	Clay	pH	C	N	P	K	Ca	Mg
	cm	Mg m^{-3}	— m^3 m^{-3} —			%			— % —			mg kg^{-1}		
A	0–16	0.59	0.34	0.43	13.0	52.4	34.6	5.0	9.6	0.4	12.5	111	243	46
AB	16–44	0.72	0.33	0.36	10.3	28.0	61.7	5.1	4.3	0.2	6.0	51	25	7
2B$_w$1	44–88	0.99	0.21	0.32	12.5	49.6	37.9	5.0	1.0	0.1	2.5	61	87	39
2B$_w$2	88–152+	1.14	0.16	0.20	15.4	45.8	38.8	5.0	0.6	0.1	2.7	41	100	78

† Values for D_b (Bulk density), AWC (Available water capacity at −10- to −1500-kPa tensions), MV (Macropore volume), pH, and elements are means from data collected in soil pits in each of the four blocks of the study. Values for textural classes are from composited samples from the four blocks.

effects of ground-based harvesting, organic matter retention, vegetation control and fertilization on soil characteristics and growth of Douglas-fir. The whole study contains 12 treatments replicated four times in a randomized complete block design. Treatment plots are 30 m by 85 m (0.25 ha), with an internal 15 m by 70 m (0.10 ha) measurement plot. In this paper, we report harvesting effects on soil quality and tree growth for three treatments: (i) bole-only removal with no soil compaction, (ii) bole-only removal with soil compaction, and (iii) bole-only removal with soil compaction plus tillage. The bole-only removal harvest followed conventional merchantability standards of 3-m log length and 8- to 13-cm small-end top diameter. Logging slash was scattered uniformly across each plot during the log-forwarding operation.

All harvested trees were directionally hand-felled between May and July of 1999 so that all tree tops remained within the plot. In non-compacted plots, logs were cable-removed with a CAT 330L (Caterpillar, Peoria, IL) two-drum shovel yarder, and a CAT tail-hold tractor to minimize site disturbance. In compacted plots, trees were yarded in May 1999 with a CAT 330L shovel with 70-cm wide pads. The soil water content at time of yarding was near field capacity. Eight equally spaced traffic lanes were flagged in each plot to be trafficked to make soil disturbance comparable across blocks. Every other lane was trafficked twice to more closely simulate traffic patterns that operationally occur when both a feller-buncher and a shovel yarder are used during harvesting. Thorough soil tillage to the 60-cm depth on tilled plots was accomplished on the areas trafficked by the shovel with a small CAT 322BL excavator shovel fitted with a PSM bucket with two 70-cm-long tillage tines.

Plots were planted with 1 + 1 Douglas-fir seedlings on a 2.5 by 2.5 m spacing (1600 trees ha^{-1}) in March 2000. Seedlings were produced from a mixed seed lot of 23 first-generation half-sib families. Only seedlings between 5 and 10 mm in caliper, and 35 and 51 cm in height were shovel planted. Planters were instructed to plant seedlings within 30 cm of pin-flags placed on a 2.5 m by 2.5 m spacing grid so trees would be planted in the full range of microsites represented in each treatment and each plot would have the same planting density. The study area was fenced to eliminate deer and elk browsing. All treatments included weed control using ground-applied herbicides in the four growing seasons after planting to eliminate the confounding effects that soil disturbance and compaction can have on vegetation communities and competition pressure (Dyck and Cole, 1994).

We followed a quantitative approach to assess soil disturbance that visually characterizes five classes developed by W. Scott (for details, see Heninger et al., 2002). We encountered three soil disturbance conditions: Class 0 (DC0)–no soil disturbance because the soil has not been subjected to vehicular traffic, Class 1 (DC1)–soil compaction by vehicular traffic without puddling of soil structure or rutting, and Class 2 (DC2)–churning and mixing of the topsoil with the forest floor and slash with severe alteration of topsoil structure. The subsoil may or may not be compacted. Additionally, we included Class 6 (DC6)–presence of berms of soil and slash

resulting from the turning and churning motion of the shovel tracks. There were no disturbance Class 3 (churning and mixing into the B horizon), disturbance Class 4 (topsoil displacement or removal), or disturbance Class 5 (drainage blocked or impeded).

In August 1999, soil bulk density samples were taken in all plots before tillage with a 31.2-mm diam. punch-tube volumetric sampler (Clements Associates, Newton, IA) at the 0- to 10-, 10- to 20-, and 20- to 30-cm depths in 13 sampling spots randomly located on each disturbance class in the plots. Class 0 disturbance was sampled in non-compacted plots while DC1 and DC2 were sampled within compacted plots. Paired comparisons of bulk density values obtained with this sampler and with an 808-cm^3 hammer-driven sampler did not differ ($P = 0.65$) in a complementary field test (Ares and Terry, unpublished data, 2004). Samples with significant amounts of sound or decayed wood material were discarded and replaced with new samples. Samples were then oven-dried at 105°C for determinations of bulk density, and soil gravimetric and volumetric water content. No coarse fragments were present.

In August 2000, we coded soil disturbance conditions within the compacted plots at the point where each measurement tree was planted using the classes described above. Where the code was DC2, the rut depth from the original soil level was recorded. Around every other measurement tree, we recorded the percentage of each disturbance class in a tree-centered 2.5 by 2.5 m square area. We calculated the percentage of ground area and the tree frequency in each soil disturbance class.

Soil strength was measured in August 2001, the driest period of the year, in eight locations per plot with a cone penetromer (DELMI, Shafter, CA) having a 30° angle cone tip of 2.02 cm in diameter and shaft length adjustable to about 90 cm. We sampled at this time because soil strength values were likely around the maximum values for the year. Additional penetrometer readings were planned to be taken during the soil drying stage—early to late summer—the following year if results indicated that soil strength values were limiting root growth. Eight to twelve penetrometer reading measurements were taken at 2-cm intervals to the 60-cm depth on each non-compacted, compacted, and compacted and tilled plots. Sample points within non-compacted plots were randomly located within each quartile of the tree measurement plots. In compacted plots, four readings were taken in each DC1 and DC2 disturbance classes while in tilled plots we recorded soil strength in the tilled harvest equipment trails. Readings within compacted and tilled plots were taken as close as possible to a randomly located point within the tree measurement plot with the desired soil disturbance condition. Cone index values were read using a scale template aid over the penetrometer cards. High-spike values created when roots or buried wood were hit by the penetrometer were noted on the cards in the field and those measurements were discarded from the dataset.

To determine soil porosity and water retention curves, we randomly collected non-disturbed soil cores on non-compacted, compacted, and compacted and tilled plots with 68.7-

cm^3 cylinder rings centered at 5- and 15-cm depths to characterize the 0- to 10- and 10- to 20-cm depths, respectively. In compacted, and compacted and tilled plots, sampling was restricted to traffic lanes with DC2 soil disturbance. Four cores per depth were taken in all plots of two blocks in 2001, and six cores per depth were obtained in the remaining two blocks in 2002. Samples at the two depths were taken at different sampling points and therefore were independent. The samples were located halfway to the north between a randomly selected tree and the next tree (or to the east, south, or west if the north position was occupied by a stump or other non-representative condition). Soil water retention curves and particle density were determined at the Soil Physics Laboratory of Oregon State University. Total porosity was determined by both the gravimetric method with water saturation (Flint and Flint, 2002), and the particle density method (Black and Hartge, 1984) in 2001, but only by the first method in 2002. Correlation between data from these two methods in 2001 was used to estimate total porosity by the particle density method in 2002. Total porosity reported in the paper is based on the particle density method estimates because during saturation there may have been some soil sample swelling causing a slight bias in the total porosity estimate.

Pore-size distribution was determined by the water-desorption method (Danielson and Sutherland, 1986). The effective pore diameter dividing water-filled and drained pores was calculated from the following function:

$$\Delta P = 2\sigma r_p^{-1} \qquad [1]$$

where ΔP is the pressure difference across an air–water interface at equilibrium (Pa), σ is the surface tension of water at ambient temperature (J m^{-2}), and r_p is the pore radius (m). We calculated macroporosity as the difference in volumetric water content between saturation and -10 kPa, where effective pore diameter equals 58 μm (Soil Science Society of America, 1997). Saturation was assumed to be when total pore space, as calculated from the particle density method, was filled with water. Pores larger than 58 μm would be air-filled at -10-kPa tension and defined as macro and mesopores (Soil Science Society of America, 1997).

Gravimetric and volumetric water contents were determined after equilibrating the soil with water at tensions of -6, -10, -80, -200, and -1500 kPa. Water retention was determined with a ceramic-plate system at tensions from -6 to -200 kPa. After equilibrating at each tension on the ceramic plate, the soil cores were weighted and transferred to a plate with the next greater tension. After being subjected to the -200-kPa tension, cores were weighed, dried at 105°C, and then reweighed. For the -1500-kPa tension, a membrane pressure system was used.

We estimated available water content (AWC) for volumetric water contents between -6 and -1500 kPa, and between -10 and -1500 kPa. We also calculated AWC between -10 and -200 kPa, a range that may better reflect water availability affecting tree growth than that for wider tension intervals. Volumetric soil water content (θ in %) was related to soil water tension (ψ in kPa) by using a three-parameter equation (Van Genuchten, 1980):

$$\theta = \theta_s[1/1 + (\alpha\psi)^n]^{1 - 1/n} \qquad [2]$$

where θ_s = soil volumetric water content at saturation (%), and α and n are equation parameters. The α parameter is proportional to the inverse of ψ at the midpoint between θ_s and the residual volumetric water content (θ_r), while n indicates the steepness of the water-release curve (Hodnett and Tomasella, 2002). The θ_r term was excluded from the equation because the data indicated that soil volumetric water content in compacted and non-compacted soil converged at large negative values of ψ.

In the field, soil water content was measured during the growing season in 2001 and 2002 with a Hydrosense CS620 probe (Campbell Scientific Inc., Logan, UT) that gives integrative measures for the 0- to 20-cm depth. Five measurements per plot in 2001 and eight in 2002 were taken approximately monthly from May 2001 to October 2002 on the buffer zone of each plot as part of a related experiment on woody biomass decomposition. A locally developed calibration function was used to convert Hydrosense readings to volumetric soil water values.

Instantaneous measurements of soil temperature were taken monthly between 0700 and 1100 h from April 2000 to July 2002 at the 20-cm depth in compacted and noncompacted plots with ELE International moisture-temperature cells (Soiltest, WoodDale, IL) calibrated for temperature accuracy. Soil temperature was also recorded continuously and averaged hourly during July 2002 at 5-cm depth on shovel traffic lanes and adjacent non-disturbed areas with iButton digital temperature loggers (Maxim/Dallas Semiconductor, Dallas, TX).

Trees within measurement plots were measured immediately after planting and yearly after the first four growing seasons. Measurements included total height (TH), stem basal diameter (BD) measured at a permanently marked location 15 cm above ground level in growing seasons 1 through 3, and stem diameter at 1.3 m above ground (DBH) in growing seasons 2, 3, and 4. Height measurements were done with a telescopic pole and stem diameters were measured with a diameter tape. A stem volume index (SVOL) was calculated as $(BD)^2$ TH.

Harvesting effects on bulk density and soil strength were analyzed as a mixed model of repeated measures data with soil disturbance and soil depth as fixed effects, and block as a random effect (Littell et al., 1996). In mixed models, the overall error associated with the model is allocated properly to the error term and the random block factor, and allows for accurate calculation of probability values to draw inferences on soil disturbance, depth, and soil disturbance $\times$ depth effects. In addition, a repeated measures analysis was appropriate because measurements of bulk density and soil strength were done at different depths at the same sampling point, and, therefore, sampling errors were not independent. Measurements taken at adjacent depths are expected to be more correlated than measurements taken some distance apart. The covariance structures associated with the within-subject factor (i.e., depth) were selected by choosing those with the lowest value for the Bayesian Criterion and Akaike's Information Criterion. The first-order autoregressive heterogeneous covariance structure provided the lowest values for both criteria.

The arc-sine square-root transformation was used for data in percent. A mixed-model approach was also used to test for soil disturbance-effects on tree size and growth in Years 0 to 4. Comparison of treatment means was made using one degree of freedom orthogonal contrasts. Procedure MIXED in SAS 8.2 (SAS Institute, 1999) that estimates variance components using restricted maximum likelihood methods was used for the statistical analyses. Coefficients of the van Genuchten equation (Van Genuchten, 1980) were calculated using procedure NLIN in SAS. An $\alpha = 0.05$ was used in all statistical analyses for determining significance.

RESULTS

Soil Disturbance, Bulk Density, and Soil Strength

On average, about half of the area of ground-harvested (compacted) plots was affected by vehicular traf-
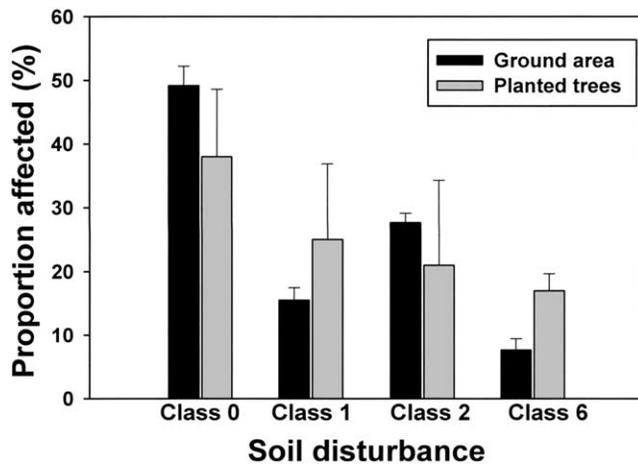
Fig. 2. Area in each disturbance class and proportion of tree seedlings planted on each disturbance class at Fall River. Class 0 = No soil disturbance, Class 1 = Soil compaction preserving topsoil structure, Class 2 = Soil compaction altering topsoil structure, Class 6 = Presence of berms of soil and slash. Values are means ± one standard error.
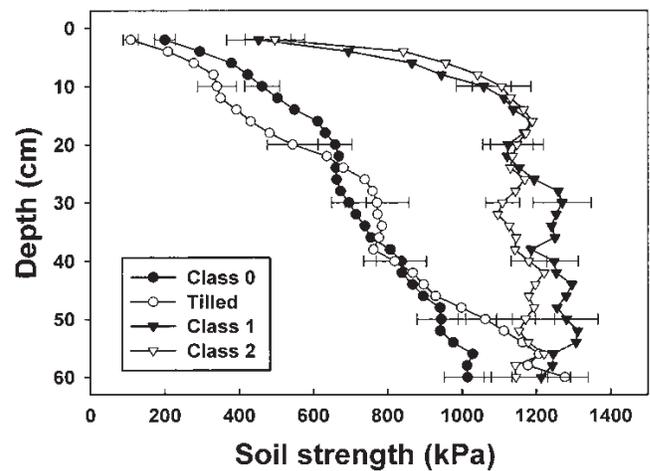

Fig. 3. Soil strength by soil disturbance class and tilled soil 14 to 17 mo after forest harvest at Fall River. Values are means with standard errors indicated for some depths. Class 0 = No soil disturbance, Class 1 = Soil compaction preserving topsoil structure, Class 2 = Soil compaction altering topsoil structure.

fic (Fig. 2). Ground areas with DC1, DC2, and DC6 conditions in compacted plots averaged 15.5, 27.7, and 7.7%, respectively, with the remaining portion of compacted plots being non-disturbed. Sixty-three percent of the trees within the measurement plots of the compacted treatment were located on some degree of soil disturbance. Rut depths were generally shallow averaging 2.5 cm for DC1 and 12.6 cm for DC2.

There were proportionally more trees planted in DC6 and DC1 microsites in compacted plots than expected based on the occurrence of these microsites in the soil disturbance survey (Fig. 2). Planters may have preferred DC6 and DC1 areas over DC0 and DC2 microsites when given the option to plant seedlings within 30 cm of the pin-flags. Also, planters could have avoided DC0 areas in close proximity to stumps where large lateral roots precluded appropriate planting.

Soil bulk density increased with both soil disturbance ($P < 0.001$) and depth ($P < 0.001$), but the soil disturbance × depth interaction was not significant ($P = 0.080$) (Table 2). Relative to the non-disturbed soil condition, soil bulk density at the 0- to 10-cm depth increased 23.2% for DC1 and 37.5% for DC2 in compacted plots. At depths of 10 to 20 and 20 to 30 cm, the increases in soil bulk density were similar for DC1 and DC2; 18.5 and 19.1% for DC1, and 27.7 and 26.5% for DC2, re-

spectively. Weighted by the ground area affected by soil disturbance, bulk density in the 0- to 30-cm soil depth for ground-harvested plots was 27% greater than for non-compacted plots.

Soil strength significantly increased with soil disturbance ($P < 0.001$) and depth ($P < 0.001$). Also, soil strength varied differently with depth as reflected by the significant soil disturbance × depth interaction ($P < 0.001$) (Fig. 3). Changes in soil strength with depth were similar for DC1 and DC2 while tillage returned the soil to its initial strength condition. The data suggested that the tillage effect took place up to the 50-cm depth. Differences in soil strength between DCO and the tillage treatment were not significant ($P = 0.11$) for the 52- to 60-cm depth range. Compaction extended to 54-cm depth in DC1 and to 48-cm depth in DC2 as indicated by the significant differences in soil strength between soils with these two disturbance classes and DC0 ($P < 0.05$).

Soil Porosity, Available Plant Water, and Soil Water Release

Changes in total porosity with compaction were relatively minor. On compacted soil, total porosity at the 0- to 10-cm depth decreased by 10% compared with non-compacted soil, and by 13% at the 10- to 20-cm depth (Table 3). Total porosity of compacted and tilled

Table 2. Bulk density (Mg m^{-3}) as related to soil disturbance and soil depth 3 to 4 mo after forest harvest at the Fall River study site.

Soil depth	Soil disturbance class		
	0	1	2
cm			
0–10	0.56 (0.010) a a†	0.69 (0.012) a b	0.77 (0.017) a c
10–20	0.65 (0.010) b a	0.77 (0.013) b b	0.83 (0.015) b c
20–30	0.68 (0.014) c a	0.81 (0.017) c b	0.86 (0.016) c c

† Values are means ± one standard error in parentheses. Means followed by the same letter are not significantly different at $P ≤ 0.05$. The first letter after each mean refers to comparisons between depths and the second letter to comparison among soil disturbance classes.

Table 3. Total soil porosity in non-compacted, compacted and, compacted and tilled soils at the Fall River study area in coastal Washington.

Depth	Total soil porosity, m^3 m^{-3}		
	Non-compacted	Compacted	Compacted and tilled
cm			
0–10	0.69 (0.009) a a†	0.62 (0.010) a b	0.67 (0.015) a a
10–20	0.68 (0.007) a a	0.59 (0.012) a b	0.65 (0.012) a a

† Values are means ± one standard error in parentheses. Means followed by the same letter are not significantly different at $P ≤ 0.05$. The first letter after a mean refers to comparisons between depths and the second letter to comparisons among treatments.

Table 4. Macropore volume and available water capacity in non-compacted, compacted, and compacted and tilled soils at the Fall River study area in coastal Washington.

	Depth	Macropore volume, $m^3 \, m^{-3}$		Available water capacity, $m^3 \, m^{-3}$		
		−6 kPa	−10 kPa	−6 to −1500 kPa	−10 to −1500 kPa	−10 to −200 kPa
	cm					
Non-compacted	0–10	0.28 (0.001) a†	0.39 (0.002) a	0.33 (0.002) b	0.22 (0.002) b	0.08 (0.009) c
Compacted		0.17 (0.002) b	0.24 (0.002) b	0.41 (0.002) a	0.35 (0.002) a	0.16 (0.007) a
Compacted and tilled		0.27 (0.001) a	0.35 (0.002) a	0.36 (0.002) ab	0.29 (0.001) a	0.11 (0.017) b
Non-compacted	10–20	0.23 (0.001) a	0.36 (0.001) a	0.35 (0.002) a	0.25 (0.002) c	0.06 (0.002) c
Compacted		0.14 (0.002) b	0.19 (0.002) b	0.38 (0.002) a	0.34 (0.002) a	0.13 (0.010) a
Compacted and tilled		0.27 (0.001) a	0.30 (0.002) a	0.37 (0.002) a	0.30 (0.001) b	0.11 (0.010) b

† Values are means ± one standard error in parentheses. Means followed by the same letter are not significantly different at P 0.05 among treatments for a given depth.

soil did not differ from the undisturbed condition. The depth × treatment interaction was not significant ($P = 0.68$).

At −6 and −10 kPa soil water potential, macropore volume was significantly reduced in compacted soil compared with non-compacted, and compacted and tilled soil, both at the 0- to 10, and 10- to 20- depths (Table 4). Compaction reduced macropore volume at −10 kPa soil water potential by 40% at the 0-to 10-cm depth, and by 48% at the 10- to 20-cm depth. Tillage of compacted soil recovered macropore volume to within 83–88% of non-compacted soil.

Compaction increased AWC at the 0- to 10-cm depth by 24 to 59% of the non-compacted soil. At both the 0- to 10-cm and the 0- to 20-cm depths, AWC of the non-compacted soil was lower than that of the compacted and tilled soil at −10 to −1500 and −10 to −200 kPa water potentials (Table 4). If water potential at field water capacity was −10 kPa, AWC on non-compacted soils averaged 0.22 $m^3 \, m^{-3}$ at the 0- to 10-cm depth, and 0.35 $m^3 \, m^{-3}$ for compacted soil. At the 10- to 20-cm depth, AWC at −10 to −1500 kPa water potential was higher in compacted soil than in non-compacted, and compacted and tilled soil. The increase in AWC from the −10 to −1500 kPa to the −6 to −1500 kPa interval was greater in non-compacted than in compacted soil (Table 4) reflecting differences in pore-size distribution.

Soil water retention curves indicated that compacted soil consistently retained more water at −10 to −200 kPa water potentials than non-compacted, or compacted and tilled soil ($P < 0.05$) (Fig. 4). The Van Genuchten function explained 97% or more of the variation in volumetric soil water content (Table 5). Saturated volumetric water content was significantly higher for non-compacted soil than for compacted soil at both the 0- to 10-cm and 10- to 20-cm depths ($P < 0.05$). The α parameter did not differ between compacted and non-compacted soil probably because of the wide intervals of confidence for α in non-compacted soils. The slope of the water retention curve indicated by the *n* parameter was somewhat steeper in compacted than in non-compacted soil at the 10- to 20-cm depth (Table 5, Fig. 4).

Field Soil Water and Temperature

Volumetric soil water in DC1 and DC2 compacted soils was higher or equal than that in non-compacted soils when sampled at mid-month throughout the measurement period. Compared with non-compacted soils, values were significantly higher ($P < 0.05$) in compacted soils in June, July, September, and December of 2001, and in January, August, and September of 2002 (Fig. 5).

Soil temperature, measured once a month, was remarkably similar between compacted and non-compacted areas both at the 5-cm and at 0- to 20-cm depths (data not shown). In July 2002, mean daily temperature at the 0- to 5-cm depth was 16.8°C for both compacted and non-compacted soil. Hourly mean temperatures for compacted and non-compacted soil during July 2002 did not differ ($P = 0.96$).

Douglas-fir Mortality and Growth

At planting, trees had similar TH ($P = 0.65$) and BD ($P = 0.24$). Tree mortality in Year 4 was 3.4, 4.5, and
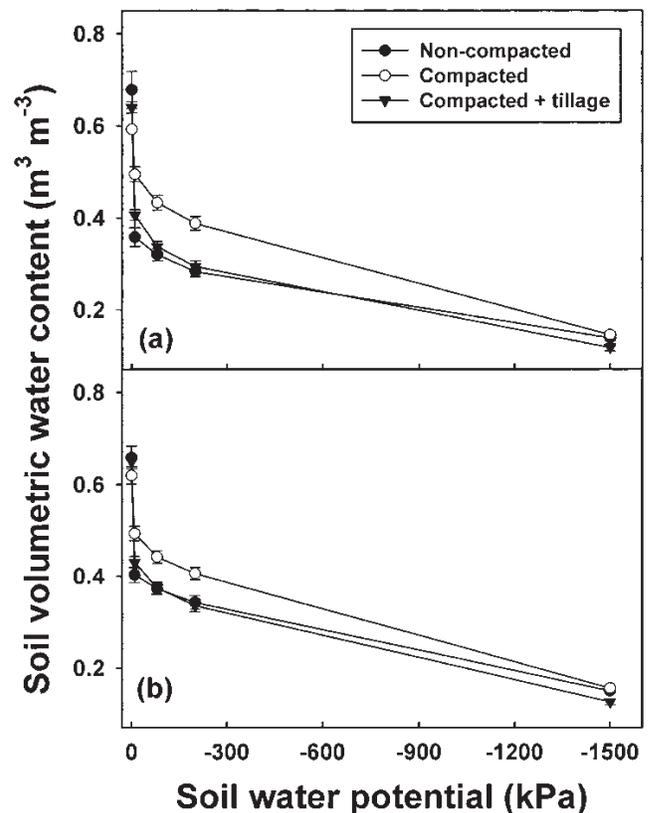
Fig. 4. Water retention curves for non-compacted, compacted, and compacted and tilled soil at the (a) 0- to 10-cm, and (b) the 10- to 20-cm depth at Fall River. Values are means ± one standard error.

Table 5. Coefficients of van Genuchten's equation; $\theta = \theta_s[1/1 + (\alpha\psi)^n]^{1 - 1/n}$ where θ = Volumetric soil water content ($m^3\ m^{-3}$), θ_s = Volumetric soil water content at saturation ($m^3\ m^{-3}$), and ψ = Soil water potential (kPa), for compacted and non-compacted soil at Fall River.

Treatment	Depth, cm	θ_s	α	n
Non-compacted	0–10	0.68 a†	2.23 a	1.16 a
Compacted		0.63 b	0.17 a	1.19 a
Non-compacted	10–20	0.68 a	2.24 a	1.14 a
Compacted		0.57 b	0.03 a	1.30 b

† Values followed by the same letter are not significantly different at P 0.05 between treatments for a given depth.

4.8% for compacted, non-compacted and, compacted and tillage treatments, respectively, and did not significantly differ among treatments. There were no significant differences in mean TH, BD, and SVOL for trees growing on non-compacted, compacted, and compacted and tilled treatments at Years 1 to 4 (Table 6). In Year 3, mean DBH was greater for trees in compacted, and compacted and tilled treatments than that for non-compacted. Within compacted plots, mean TH, BD, DBH, and SVOL were in general similar for trees growing on DC0, DC1, DC2, and DC6 except in Year 3 when trees growing in DC1 compacted areas had greater BD than those growing on DC0 non-compacted areas (Table 7). In year 3, SVOL in the compacted treatment was also greater for trees growing on DC1 and DC2 areas within the compacted treatment than those growing on non-compacted DC0 soil.

DISCUSSION

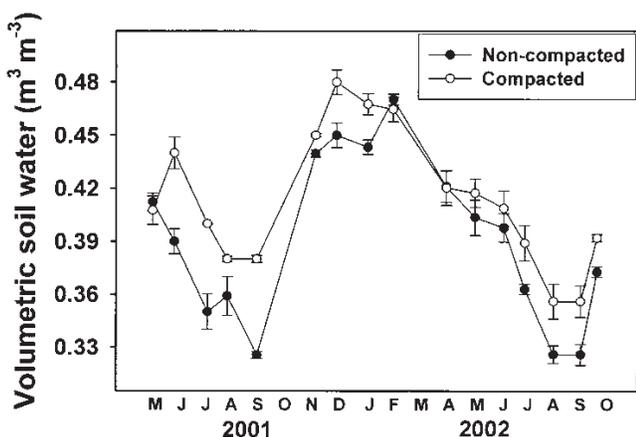### Soil Disturbance and Physical Properties

Site impacts from ground-based forest harvest depend on equipment type, operational timing, execution expertise, soil moisture conditions, and soil characteristics (Wingate-Hill and Jakobsen, 1982; McNabb and Boersma, 1993; Heninger et al., 1997). At the Fall River study, bole-only ground-harvest of a 46-yr-old Douglas–fir stand caused soil disturbance in about half of the harvested area and modified soil physical characteristics. Equipment traffic was applied when soil water contents were

Fig. 5. Volumetric soil water content during 2001 and 2002 at Fall River for DC2 compacted and DC0 non-compacted areas. Values are means ± one standard error.

at or somewhat drier than field water capacity, which is considered to correspond to a given soil water potential within the −6 to −50 kPa range (Cullen et al., 1991; Da Silva et al., 1994; Soil Survey Laboratory, 1995). Traffic increased soil bulk density of the A and AB horizons with little or no puddling. Andisols are less compressible than other denser soils because of their high shear strength (McNabb and Boersma, 1993). In a study in three Coastal Washington sites that are similar to the Fall River area (i.e., high soil organic matter content, low bulk density, loam to clay soil textures), yarding equipment produced more severe soil disturbance (up to DC4) than that at Fall River. This was because of the type of equipment used and operations occurring on soils between saturation and field water capacity (Miller et al., 1996). In that study, bulk density in the 0- to 8-cm depth of primary skid trails was 41 to 52% greater than in non-disturbed areas.

Spodosols of Vancouver Island, BC were differently affected by increasing passes of both a rubber-tired skidder with low ground pressure tires and a grapple skidder with conventional tires and chains, but disturbance depended more on soil water content at trafficking time than on other soil characteristics (Senyk and Craigdallie, 1997). In their study, a gravelly loamy sand soil of the Honeymoon series had high water content at time of trafficking and significant puddling occurred. In contrast, significant rutting but not puddling was observed in a silt loam to loam soil of the Snuggery series that was relatively dry when trafficked. Bulk density of the Honeymoon series soil of Vancouver Island increased to 1.4 Mg m^{-3} after 30 to 40 equipment turns but total soil porosity did not drop below 50% (Senyk and Craigdallie, 1997).

Soil strength at Fall River also increased after vehicle trafficking to about 50-cm depth but it remained well below the critical threshold for tree root growth considered to be around 2000 to 3000 kPa depending on tree species and soil conditions (Sands et al., 1979; Greacen and Sands, 1980). In northern Idaho, compaction increased soil strength to more than 2500 kPa in a Fragixeralf developed from volcanic ash, but shoot growth of 1-yr-old Douglas-fir seedlings was not affected (Page-Dumroese et al., 1998). Soil strength of a Hapludand and a Paleohumult in coastal Washington reached maximums of about 2500 and 3200 kPa at the 10- to 20-cm depth corresponding to fine-soil bulk densities of about 0.7 and 0.8 Mg m^{-3} (Miller et al., 2001). In trafficked areas at Fall River, mean soil strength by depth increment never exceeded 1300 kPa. Tillage with an excavator restored soil strength to a condition similar to that initially but this practice is deemed unnecessary for this site.

Decreases in total porosity at Fall River of 10 and 13% from initial porosities of 0.68 and 0.69 $m^3\ m^{-3}$ at the 0- to 10-cm, and 10- to 20-cm depths, respectively, were similar to the 9 and 14% reductions at the 0- to 15- and 15- to 30-cm depths from initial porosities of 0.68 and 0.66 $m^3\ m^{-3}$ for a loam soil in Northern California (Gomez et al., 2002b). Macropore volume at −10 kPa in Fall River dropped 40 to 52% with compaction con-

firming that macropore volume is a more sensitive indicator of soil changes than total porosity.

Water retention and AWC were increased by soil compaction. Compacted soil retained more water than non-compacted soil likely because compression converted larger pores to smaller ones, especially in the upper part of the soil profile. In a study with a silty clay loam, compaction decreased macroporosity (pores > 60-μm diam.) by more than 50% but pores < 6-μm diam. were unaffected by compaction (Bullock et al., 1985). At the Vancouver Island, BC study (Senyk and Craigdallie, 1997), water retention increased in compacted soil leading to saturation and increased seedling mortality in areas where soil drainage was blocked on rutted skid trails. Standing water was never observed in traffic lanes on compacted plots during the winter rainy season at Fall River indicating that water infiltration was not severely limited.

Douglas-Fir Early Growth

Despite noticeable effects on soil physical properties from ground-based harvest, stem diameter, height and a volume index of Douglas-fir were not reduced by soil disturbance or compaction. Values for these growth indicators were even greater for trees on disturbed soil than for those on non-disturbed soil in Year 3. Clearly, bulk density, soil strength, and macroporosity did not reach levels in compacted areas that reduced tree growth. Including compacted soils, observed bulk density of 0.56 to 0.86 Mg m^{-3} at Fall River was within the 0.70 to 1.15 Mg m^{-3} range for which Douglas-fir seedling growth was not affected on the eastern Cascade Mountains of Washington State (Zabowski et al., 2000). In other studies, Douglas-fir root growth decreased or ceased at soil bulk densities from 0.9 Mg m^{-3} for clay loams to 1.8 Mg m^{-3} for sandy loams although shoot growth was not generally affected both in field (Forristall and Gessel, 1955) and pot experiments (Minore et al., 1969; Heilman, 1981; Singer, 1981).

The greater plant-water availability in compacted soil compared with the undisturbed soil suggests that increased soil water mediated the growth increase of Douglas-fir measured at Year 3 on compacted soil. Soil water, however, could have been retained at more negative tensions in compacted soil, and become less available than in non-compacted soil during portions of the growing season. This was difficult to evaluate in this study because measurements of field volumetric water content integrated for the 0- to 20-cm depth (including the litter layer) were taken monthly within the plot buffers while soil water retention curves were derived from samples collected within the measurement plots and centered at the 5- and 15-cm depths. Also, the soil water potential at which growth of Douglas-fir seedlings or saplings start to decline is uncertain, and so was the lapse of time during which compacted and non-compacted soil would have reached soil water status limiting for Douglas-fir growth. Photosynthesis rates of 2- to 3-month-old Douglas-fir seedlings slowly declined with soil water potential decreasing to −100 kPa and

Table 6. Douglas-fir height, stem diameter, and volume index (SVOL) at the end of four growing seasons in non-compacted, compacted†, and compacted and tilled treatments in coastal Washington.

	Year 1			Year 2			Year 3			Year 4		
	Control	Compacted	Compacted and tilled	Control	Compacted	Compacted and tilled	Control	Compacted	Compacted and tilled	Control	Compacted	Compacted and tilled
Total height, cm	44.3 a	44.0 a	44.3 a	91.9 a	94.5 a	95.8 a	152.7 a	155.2 a	158.7 a	245.8 a	249.3 a	256.1 a
Basal diameter, mm	6.5 a	6.6 a	–	16.8 a	17.0 a	17.0 a	31.8 a	32.2 a	33.1 a	57.9‡ a	58.4‡ a	58.7‡ a
DBH, mm	–	–	–	5.5 a	5.9 a	4.9 a	9.2 b	10.1 a	10.2 a	23.8 a	24.0 a	25.2 a
SVOL index, cm^3	21.2 a	21.8 a	–	308 a	319 a	326 a	1753 a	1837 a	1968 a	8972 a	9037 a	9455 a
Trees with measurable DBH, %	–	–	–	5.1 a	6.7 a	8.5 a	76.4 a	77.0 a	78.5 a	97.7 a	98.6 a	98.1 a

† Means are for all trees in the compacted plots irregardless of the soil disturbance class of the microsite where they were growing.
‡ Calculated from DBH-basal diameter relationship. Means followed by the same letter are not significantly different at $P \geq 0.05$ among treatments for given year and tree variable.

Table 7. Mean Douglas-fir height, stem diameter and volume index (SVOL) by soil disturbance class within the compacted treatment (ground-based harvest), and by year since treatment in coastal Washington.

	Year 1				Year 2				Year 3				Year 4			
	DC0	DC1	DC2	DC6	DC0	DC1	DC2	DC6	DC0	DC1	DC2	DC6	DC0	DC1	DC2	DC6
Total height, cm	45.1 a	43.9 a	44.9 a	43.7 a	95.5 a	96.1 a	97.1 a	96.6 a	151.2 a	157.4 a	151.2 a	158.2 a	246.8 a	253.0 a	251.1 a	253.8 a
Basal diameter, mm	6.4 a	6.5 a	6.3 a	6.3 a	17.1 a	17.4 a	17.1 a	16.9 a	31.0 b	33.5 a	31.3 b	32.7 ab	56.5† a	58.1† a	58.0† a	58.1† a
DBH, mm	–	–	–	–	–	–	–	–	9.7 b	10.8 a	10.3 ab	9.7 b	23.1 a	24.6 a	24.4 a	24.5 a
SVOL index, cm³	20.6 a	20.3 a	19.4 a	19.1 a	314 a	335 a	327 a	304 a	1638 b	2050 a	2012 a	1827 ab	8463 a	9225 a	9027 a	9112 a
Trees with measurable DBH, %	–	–	–	–	4.7 a	8.4 a	3.6 a	4.2 a	73.5 ab	76.1 ab	70.1 ab	87.5 a	99.2 a	98.7 a	100.0 a	99.0 a

† Calculated from DBH-basal diameter relationship. Means followed by the same letter are not significantly different at P 0.05 among treatments for a given year and tree variable.

decreased sharply below that water potential (Zavitkovski and Ferrell, 1968). Growth of conifer seedlings was considered to cease at soil water potential of −500 kPa (Spittlehouse and Childs, 1990). Additional work needs to be conducted to confirm at what soil water potentials Douglas-fir growth begins to be limited in Coastal Washington soils.

Available water held between −10 and −500 kPa may be more useful to characterize water availability and relate it to tree growth than the routinely calculated AWC between −10 and −1500 kPa for soils that likely never reach a soil water potential of −1500 kPa or other largely negative potentials that reduce seedling survival. The potential beneficial effects of other factors on tree growth such as increased N uptake (Gomez et al., 2002b; Kranabetter and Sanborn, 2003) or CO_2 concentrations (Conlin and van den Driessche, 1996) found in compacted soils cannot be ruled out as a potential beneficial effect on tree growth at Fall River. In fact, CO_2 concentrations were markedly greater in compacted than in non-compacted soil in an ancillary study at Fall River (M. Jurgensen, personal communication, 2002).

The tree growth advantage on traffic lanes did not continue at age 4 most likely because tree roots are likely growing out of the compacted track areas and penetrating deeper into the soil profile. At Age 3, mean root lateral spread from the tree trunk was 111 cm for trees growing on the 70-cm wide equipment tracks at Fall River, and did not differ from trees on non-compacted soil (C. Harrington, personal communication. 2004). A similar effect may probably explain why height growth of trees growing on skid-trails and non-compacted areas became similar after trees reached about 1.4 m in height in western Oregon (Heninger et al., 2002).

Root growth of Douglas fir is considered limited at soil temperatures less than 10°C with optimum growth occurring at 20°C (Lopushinsky and Max, 1990). At Fall River, soil temperature was higher than 10°C from early May to early October, and did not differ between compacted and non-compacted areas.

Soil Quality Thresholds for Best Management Practices

Critical threshold values for a wide range of soils are difficult to estimate because data are rather limited (Powers et al., 1998). At Fall River, no negative effects on tree growth were observed although the area compacted was greater than 15% and the soil bulk density increase exceeded 20%. These values are the recommended admissible increases over non-disturbed conditions for Andisols in the Pacific Northwest (Powers et al., 1998). The suggested threshold values are too conservative for the Boistfort soil at the Fall River study site. The reductions in total porosity and macroporosity observed in this study were marginally greater than the >10 and >50% reductions considered detrimental to soil quality (Powers et al., 1998). On the other hand, macroporosity did not decrease below 14% when at least 10% of total soil volume is considered necessary for plant growth (Grable and Siemer, 1968).

Andisols have good physical properties such as low bulk density, high water-holding capacity, good tilth, and stable aggregation, and constitute an excellent rooting media (Kimble et al., 2000). At Fall River, these advantageous soil physical characteristics confer the site the capacity to sustain harvest impacts without decreasing tree growth. The unique properties of Andisols have been only partially considered in soil quality standards and guidelines for sustainable forest productivity. As more data become available, soil quality standards for Andisols should be refined to better differentiate them from other soil types.

CONCLUSIONS

The study indicates that ground-based harvesting altered soil physical properties on a highly productive forest site of coastal Washington, but the extent of disturbance was not detrimental for early growth of planted coastal Douglas-fir. Given the relatively fine texture of the soil at Fall River, negative impacts on tree growth could have been expected. The high organic matter content, low bulk density, and low compressibility of the Boistfort soil, however, likely contributed to buffer the harvest impacts and made this soil conducive for intensive forest management and ground-based harvesting systems.

Although both soil bulk density and soil strength were increased, they did not reach levels that reduced Douglas-fir growth. There was some evidence in this study that compaction could actually be beneficial as early tree growth at age 3 was greater on compacted soil compared with compacted soil. Increased available water in the −10- to −200-kPa range on compacted traffic lanes may explain this increased growth.

Consequences from heavy machinery use such as in-

creased soil strength and bulk density can be ameliorated by tillage but this practice is deemed unnecessary on the tested site. Limiting soil disturbance to Classes 1 and 2 appears to be a sound recommendation for Andisols of coastal Washington. The long-term nature of this study will address possible changes in soil characteristics and tree growth responses with time as well as their interactions with climatic conditions.

REFERENCES

Bhadoria, P.B.S. 1986. Transport of anions towards root as influenced by soil compaction. Plant Soil 208:9–19.

Blake, G.R., and K.H. Hartge. 1986. Bulk density. p. 363–375. In A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Brais, S. 2001. Persistence of soil compaction and effects on seedling growth in northwestern Quebec. Soil Sci. Soc. Am. J. 65:1263–1271.

Bullock, P., A.C.D. Newman, and A.J. Thomasson. 1985. Porosity aspects of the regeneration of soil structure after compaction. Soil Til. Res. 5:325–341.

Conlin, T.S.S., and R. van den Driessche. 1996. Short-term effects of soil compaction on growth of Pinus contorta seedlings. Can. J. For. Res. 26:727–739.

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

Da Silva, A.P., B.D. Kay, and E. Perfect. 1994. Characterization of the least limiting water range of soils. Soil Sci. Soc. Am. J. 58:1775–1781.

Danielson, R.E. and P.L. Sutherland. 1986. Porosity. p. 443–461. In A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. No. 9. ASA and SSSA, Madison, WI.

Dick, R.P., D.D. Myrold, and E.A. Kerle. 1988. Microbial biomass and soil enzyme activities in compacted and rehabilitated skid trail soils. Soil Sci. Soc. Am. J. 52:512–516.

Dyck, W.J., and D.W. Cole. 1994. Strategies for determining consequences of harvesting and associated practices on long-term productivity. p. 13–40. In W.J. Dyck et al. (ed.). Impacts of forest harvesting on long-term site productivity. Chapman & Hall, London.

Flint, L.E., and A.L. Flint. 2002. Porosity. p. 241–254. In J.H. Dane and G.C. Topp (ed.). Methods of Soil Analysis. Part 4. SSSA Book Series No. 5. SSSA, Madison, WI.

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

Franklin, J.F., and C.T. Dyrness. 1973. Natural vegetation of Oregon and Washington. USDA For. Serv. Gen. Tech. Rep. PNW-8. U.S. Forest Service, Portland, OR.

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

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

Gomez, A., R.F. Powers, M.J. Singer, and W.R. Horwath. 2002b. Soil compaction effects on growth of young ponderosa pine following litter removal in California's Sierra Nevada. Soil Sci. Soc. Am. J. 66:1334–1343.

Grable, A.R., and E.G. Siemer. 1968. Effects of bulk density, aggregate size, and soil water suction on oxygen diffusion, redox potentials and elongation of corn roots. Soil Sci. Soc. Am. Proc. 32:180–186.

Greacen, E.L., and R. Sands. 1980. Compaction of forest soils: A review. Aust. J. Soil Res. 18:163–189.

Hatchell, G.E., C.W. Ralston, and R.R. Foil. 1970. Soil disturbances in logging: Effects on soil characteristics and growth of loblolly pine in the Atlantic Coastal Plain. J. For. 68:772–775.

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

Heninger, R., W. Scott, A. Dobkowski, R. Miller, H. Anderson, and S. Duke. 2002. Soil disturbance and 10-year growth response of coast Douglas-fir on non-tilled and tilled skid trails in the Oregon Cascades. Can. J. For. Res. 32:233–246.

Heninger, R.L., T.A. Terry, A. Dobkowski, and W. Scott. 1997. Managing for site productivity: Weyerhaeuser's Forestry Perspective. Biomass and Bioenergy 13:255–267.

Herbauts, J., J. El Bayad, and W. Gruber. 1996. Influence of logging traffic on the hydromorphic degradation of acid forest soils developed on lessic loam in middle Belgium. For. Ecol. Manage. 87:193–207.

Hodnett, M.G., and J. Tomasella. 2002. Marked differences between van Genuchten soil water-retention parameters for temperate and tropical soils: A new water-retention pedo-transfer function developed for tropical soils. Geoderma 108:155–180.

Huang, J., S.T. Lacey, and P.J. Ryan. 1996. Impact of forest harvesting on the hydraulic properties of surface soil. Soil Sci. 161: 79–86.

Kimble, J.M., C.L. Ping, M.E. Sumner, and L.P. Wilding. 2000. Classification of Soils: Andisols. p. 209–223. In M.E. Sumner (ed.) Handbook of soil science, CRC Press, New York.

King, J. 1966. Site index curves for Douglas-fir in the Pacific Northwest. Weyerhaeuser Forestry Paper No. 8. Weyerhaeuser Co., Forestry Research Center, Centralia, WA.

Kranabetter, J.M., and P. Sanborn. 2003. Short-term effects of forest soil compaction and site organic matter removal on mineralizable soil nitrogen in Central British Columbia. University of British Columbia LTSPS Research Note. Smithers, BC, Canada.

Lenhard, R.J. 1986. Changes in void distribution and volume during compaction of a forest soil. Soil Sci. Soc. Am. J. 50:462–464.

Littell, R.C., G.A. Milliken, W.W. Strout, and R.D. Wolfinger. 1996. SAS System for Mixed Models. SAS Institute Inc., Cary, NC.

Logan, R.L. 1987. Geologic map of the Chehalis River and Westport Quadrangles, Washington. Washington Division of Geology and Earth Resources. Open File Report 87–8.

Lopushinsky, W., and T.A. Max. 1990. Effect of soil temperature on root and shoot growth and on budburst timing in conifer seedling transplants. New Forest 4:107–124.

Malmer, A., and H. Grip. 1990. Soil disturbance and loss of infiltrability caused by mechanized and manual extraction of tropical rainforest in Sabah, Malaysia. For. Ecol. Manage. 38:1–12.

McNabb, D.H., and L. Boersma. 1993. Evaluation of the relationship between compressibility and shear strength of Andisols. Soil Sci. Soc. Am. J. 57:923–929.

Miller, R.E., J. Hazard, and S. Howes. 2001. Precision, accuracy, and efficiency of four tools for measuring soil bulk density or strength. Res. Pap. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Miller, R.E., W. Scott, and J.W. Hazard. 1996. Soil compaction and conifer growth after tractor yarding at three coastal Washington locations. Can. J. For. Res. 26:225–236.

Miller, R.E., W.I. Stein, R.L. Heninger, W. Scott, S.N. Little, and D.J. Goheen. 1989. Maintaining and improving site productivity in the Douglas-fir region. p. 98–136. In D.A. Perry et al. (ed.) Maintaining the long-term productivity of Pacific Northwest Ecosystems. Timber Press, Portland, OR.

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

Murphy, G.E. 1983. Pinus radiata survival, growth and form 4 years after planting off and on skidtrails. N.Z. J. For. 28:184–193.

Page-Dumroese, D.S., A.E. Harvey, M.F. Jurgensen, and M.P. Amaranthus. 1998. Impacts of soil compaction and tree stump removal on soil properties and outplanted seedlings in northern Idaho, USA. Can. J. Soil Sci. 78:29–34.

Powers, R.F. 1989. Maintaining long-term forest productivity in the Pacific Northwest: Defining the issues. p. 3–16. In D.A. Perry et al. (ed.). Maintaining the long-term productivity of Pacific Northwest forest ecosystems. Timber Press, Portland, OR.

Powers, R.F. and G.O. Fiddler. 1997. The North American long-term soil productivity study: Progress through the first five years. p. 88–102. Proceedings 18th Annual Forest Vegetation Management Conference. Redding, CA.

Powers, R.F., A.E. Tiarks, and J.R. Boyle. 1998. Assessing soil quality: practicable standards for sustainable forest productivity in the United States. p. 53–80. In M.B. Adams et al. (ed.). The contribution of soil science to the development of and implementation of

criteria and indicators of sustainable forest management. SSSA Spec. Pub. No. 53. SSSA, Madison, WI.

Purser, M.D., and T.W. Cundy. 1992. Changes in soil physical properties due to cable yarding and their hydrologic implications. West. J. Appl. For. 7:36–39.

Sands, R., E.L. Greacen, and G.J. Gerard. 1979. Compaction of sandy soils in radiata pine forests. I. A penetrometer study. Aust. J. Soil. Res. 17:101–113.

SAS Institute. 1999. SAS user's guide: Statistics. Version 8. SAS Institute, Cary, NC.

Senyk, J.P., and D. Craigdallie. 1997. Ground-based wet weather yarding operations in Coastal British Columbia: Effects of soil properties and seedling growth. Information Report BC-X-372, Pacific Forestry Center, Victoria, B.C.

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

Smeltzer, D.L.K., D.R. Bergdahl, and J.R. Donnelly. 1986. Forest ecosystem responses to artificially induced soil compaction. II. Selected soil microorganism populations. Can. J. For. Res. 16:870–872.

Smith, C.W. 2003. Does soil compaction on harvesting extraction roads affect long-term productivity of Eucalyptus plantations in Zululand, South Africa? S. Afr. For. J. 199:41–53.

Soil Science Society of America. 1997. Glossary of soil science terms: Soil Science Society of America. SSSA, Madison, WI.

Soil Survey Laboratory. 1995. SSL information manual. USDA Natural Resources Conservation Services. SS Investigative Report no. 45, Version 1.0. Lincoln, NB.

Soil Survey Staff. 1992. Keys to soil taxonomy. 5th ed. SMSS Tech. Monogr. No. 19. Pocahontas Press, Inc., Blacksburg, VA.

Spittlehouse, D.L. and S.W. Childs. 1990. Evaluating the seedling moisture environment after site preparation. p. 80–94. Proc. 7th North American Forest Soils Conference.

Startsev, A.D., and D.H. McNabb. 2000. Effects of skidding on forest soil infiltration in west-central Alberta. Can. J. For. Res. 80:617–624.

Steinbrenner, E.C., and F.E. Gehrke. 1973. Soil survey of the McDonald Tree Farm. Weyerhaeuser Company, Tacoma, WA.

Steinbrenner, E.C., and S.P. Gessel. 1955. The effect of tractor logging on physical properties of some forest soils in southwestern Washington. Soil Sci. Soc. Am. Proc. 19:372–376.

Torbet, H.A., and C.W. Wood. 1992. Effects of soil compaction and water-filled pore space on soil microbial activity and N losses. Commun. Soil. Sci. Plant Anal. 23:1321–1331.

Van Genuchten, M.T. 1980. A closed-form equation for predicting the hydraulic conductance of unsaturated soils. Soil Sci. Soc. Am. J. 44:892–898.

Wert, S., and B.R. Thomas. 1981. Effects of skid roads on diameter, height, and volume growth in Douglas-fir. Soil Sci. Soc. Am. J. 45:629–632.

Wingate-Hill, R. and B.F. Jakobsen. 1982. Increased mechanization and soil damage in forests–a review. N. Z. J. For. Sci. 12:380–393.

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

Zabowski, D., M.F. Skinner, and P.T. Rygiewickz. 1994. Timber harvesting and long-term productivity: Weathering processes and soil disturbance. For. Ecol. Manage. 66:55–68.

Zavitkovski, J. and W.K. Ferrell. 1968. Effect of drought upon rates of photosynthesis, respiration, and transpiration of seedlings of two ecotypes of Douglas-fir (*Pseudotsuga menziesii*). Bot. Gaz. 129:346–350.