Soil disturbance and 10-year growth response of coast Douglas-fir on nontilled and tilled skid trails in the Oregon Cascades

Ronald Heninger, William Scott, Alex Dobkowski, Richard Miller, Harry Anderson, and Steve Duke

Abstract: We (*i*) quantified effects of skidder yarding on soil properties and seedling growth in a portion of western Oregon, (*ii*) determined if tilling skid trails improved tree growth, and (*iii*) compared results with those from an earlier investigation in coastal Washington. Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) seedlings were hand planted at eight recent clearcuts in skid ruts in either nontilled or tilled trails, in adjacent soil berms, and in adjacent logged-only portions. Four and 5 years after skidding, rut depths averaged 15 cm below the original soil surface; mean fine-soil bulk density (0–30 cm depth) below ruts of nontilled trails exceeded that on logged-only portions by 14%. Height growth on nontilled trails averaged 24% less than on logged-only portions in year 4 after planting and decreased to 6% less in year 7. For years 8–10, mean height growth was similar for all treatments. Reduced height growth lasted for about 7 years compared with 2 years for coastal Washington. Ten years after planting, trees in skid-trail ruts averaged 10% shorter with 29% less volume than those on logged-only portions. Tillage improved height and volume growth to equal that on logged-only portions. Generalizations about negative effects of skid trails on tree growth have limited geographic scope.

Résumé : Nous avons (*i*) mesuré les effets du débardage par téléphérage sur les propriétés du sol et la croissance de jeunes arbres dans une partie de l'ouest de l'Oregon, (*ii*) déterminé si le fait de labourer légèrement le sol dans les ornières améliore la croissance des arbres et (*iii*) comparé nos résultats avec une expérience précédente réalisée dans la région côtière de l'état de Washington. Des semis de douglas de Menzies (*Pseudotsuga menziesii* (Mirb.) Franco) ont été plantés manuellement sur le site de huit coupes à blanc récentes, dans des ornières labourées ou non, dans les talus adjacents et dans des coupes adjacentes. Quatre et 5 ans après le débardage, la profondeur des ornières atteignait en moyenne 15 cm sous la surface initiale du sol; la densité moyenne du sol (0 à 30 cm de profondeur) sous les ornières non labourées était 14% plus élevée que celle des zones qui avaient seulement été coupées. La croissance en hauteur des arbres dans les ornières non labourées était, en moyenne, inférieure de 24% à celle observée dans les zones qui avaient seulement été coupées 4 ans après la plantation et la différence n'était plus que de 6% inférieur après 7 ans. Entre la huitième et la dixième année, la croissance moyenne en hauteur des arbres était similaire pour tous les traitements. La réduction de croissance a duré environ 7 ans comparativement à seulement 2 ans dans la région côtière de l'état de Washington. Dix ans après la plantation, les arbres qui avaient poussé dans les ornières étaient 10% plus petits et avaient un volume inférieur de 29% aux arbres dans les zones qui avaient seulement été coupées. Le labourage a amélioré la croissance en hauteur et en volume des arbres au point d'égaler celle dans les zones qui avaient seulement été coupées. Les généralisations concernant les effets négatifs du débardage par téléphérage sur la croissance des arbres ont une portée géographique limitée.

Introduction

Ground-based machinery used for felling and yarding trees or preparing sites for planting disturbs soil and creates visible patterns of disturbance. Soil disturbance can reduce tree performance, contribute to stream sedimentation, or visually suggest poor stewardship. Soil disturbances range from compacting, to churning and incorporating organic de-

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R. Heninger. Weyerhaeuser Co., Oregon Forestry Research Field Station, P.O. Box 275, Springfield, OR 97477, U.S.A.
W. Scott and S. Duke. Weyerhaeuser Technology Center, Tacoma, WA 98477, U.S.A.
A. Dobkowski. Washington Forestry Research Field Station, P.O. Box 188, Longview, WA 98632, U.S.A.
R. Miller[1] **and H. Anderson.** USDA Forest Service, Pacific Northwest Research Station, Forestry Sciences Laboratory, 3625 93rd Avenue SW, Olympia, WA 98512, U.S.A.

[1] Corresponding author (e-mail: millersoils@aol.com).

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bris, to removing and mixing topsoil with subsoil, and to displacing topsoil from narrow ruts or wider areas.[2] Compaction reduces amount and continuity of macropores. Churning or puddling soil also reduces macroporosity by rearranging soil particles (Bodman and Rubin 1948). These reductions in volume and continuity of large pores reduce infiltration rates (Greacen and Sands 1980), slow saturated water flux (Warkentin 1971), reduce gaseous flux (Grable 1971; Cannell 1977), increase thermal conductivity and diffusivity (Willis and Raney 1971), and increase soil resistance to root penetration (Sands et al. 1979).

Consequences of soil disturbance to subsequent tree growth and stand yields are less researched and predictable (Greacen and Sands 1980; Wronski and Murphy 1994). Although trees planted on skid trails and landings are subjected to the most severely disturbed soil (Froehlich and McNabb 1984; Helms and Hipkin 1986), altered soil properties do not always result in poorer survival or tree growth (Greacen and Sands 1980; Firth and Murphy 1989; Miller et al. 1996; Senyk and Craigdallie 1997*b*). In some coarse-textured soils, seedling performance can be better on compacted than on undisturbed soil (Powers et al. 1999). Site-to-site differences in climatic stress also weaken generalizations about tree performance on disturbed soil. We can assume a priori that performance of most tree species encountering unfavorable soil conditions is more limited in stressful climates than in nonstressful climates.

Predictions based on growth of young seedlings are uncertain. The duration of reduced growth of seedlings is especially uncertain, because soil properties change naturally and tree roots eventually exploit more favorable soil conditions nearby. Although height or height growth of seedlings or young trees is a commonly used measure of tree performance (Froehlich and McNabb 1984), we assert that short-term height growth is a weak indicator of long-term stand growth per unit area. Other factors can confound interpretations of early growth response to degraded soil properties. For example, vegetation succession on disturbed soils often differs in species and density from that on nondisturbed soils (Halpern 1988). Differences in vegetative competition can favor tree growth on skid trails in some situations but hinder it in others. Skidder and forwarder trails could become big-game pathways, thus increasing risk that animal browse will reduce seedling growth and size on skid trails.

To better assess impacts of soil disturbance on sustainable forest production and to evaluate mitigative options, Weyerhaeuser Co.'s Western Timberlands Research section investigated tree growth on soils disturbed by ground-based yarding. Initially, we measured consequences of soil disturbance caused by ground-based yarding on survival and growth of planted Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and other coniferous species planted at three locations along coastal Washington (Miller et al. 1996). That research indicated no measurable growth losses at 8 and 18 years after planting in skid trails, despite increases in soil bulk density exceeding 40%. To expand that research, we used a similar study design in western Oregon, where climate and native soil conditions are less favorable for seedling performance.

Our objectives were to (*i*) quantify impacts of skidder yarding on soil properties, tree survival, and growth at Weyerhaeuser Co. ownership in the Oregon Cascade Range; (*ii*) determine if tillage recovers soil properties and tree growth to that of undisturbed soil; and (*iii*) compare results with those from coastal Washington sites. We report several measures of soil disturbance and tree growth through 10 years after planting.

Methods

Study areas

Eight study areas were located in the foothills on the west side of the Cascade Range near Springfield, Oreg. The areas ranged between 43°35′ and 44°05′N and between 122°40′ and 123°06′W. The areas were selected to represent typical clearcuts of 50- to 70-year-old stands of coast Douglas-fir on Weyerhaeuser's Springfield and Cottage Grove Tree Farms. Elevations of study sites ranged from 300 to 820 m. The climate is Mediterranean with cool winters and warm, dry summers. Annual precipitation as rain and snow ranges from 1020 to 2290 mm, generally with increasing amounts at higher elevations. Precipitation occurs mostly from mid-October through May (Patching 1987). Intervening coastal mountains partially block this study area from the moisture and moderating temperatures of maritime airflows from the west.

According to maps prepared by Patching (1987), soil series were Bellpine silty clay loam, Honeygrove silty clay loam, and Peavine silty clay loam. According to U.S. taxonomy (Soil Survey Staff 1975), each of these series is in the fine, mixed, active mesic family of their respective subgroup: Bellpine (Xeric Haplohumults), Honeygrove (Typic Palehumults), and Peavine (Typic Haplohumults). These soils (Ultisol Order) do not exist in Canada, so there is no Canadian equivalent classification (C. Tarnocai, personal communication).[3] These soils formed in fine-textured colluvial and residual materials mostly from sedimentary rock types (Table 1). The three series have 25- to 30-cm deep, moderately fine-textured topsoils (A horizons). Subsoils (B horizons) are fine textured (silty clay or clay at the 40- to 50-cm depth). When these soils are saturated, permeability is moderately slow. Modal site index for these soils range from 30 to 37 m for Douglas-fir at 50-year breast height age (Patching 1987). The three soil series were rated as high to very high risk for soil disturbance from ground-based yarding on wet soil (Heninger et al. 1999). Periods of high to very high risk usually occur for 8 or more months of the year near Springfield.

Seven of these eight locations were harvested and yarded in wet, winter conditions. Yarding was accomplished with unspecified combinations of tracked and rubber-tired skidders. After yarding, portions of selected skid trails were

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[2] Definitions of terms used in this article can be found in Helms (1998), Dunster and Dunster (1996), or Soil Science Society of America (1997).

[3] E-mail dated July 12, 2001, to Richard Miller. On file with R. Miller, Forestry Sciences Laboratory, 3625 93rd Avenue SW, Olympia, WA 98512, U.S.A.

Table 1. Soil series, elevation, season, and year of logging, planting, and soil sampling by location in the Oregon Cascades.

Location				Harvested		Growing season	
No.	Name	Soil series (as mapped)	Elevation (m)	Year	Soil*	Planted[†]	Soil sampled[‡]
1	Ewing Creek	Bellpine	300	1986	Wet	1987	5
2	1031 Big River	Peavine	410	1986	Wet	1987	5
3	Quaglia	Bellpine	340	1986	Wet	1987	5
4	Gettings Creek	Honeygrove	760	1986	Wet	1987	5
5	Reservoir	Bellpine	340	1987	Wet	1988	4
6	Laurel Mountain	Peavine	820	1987	Wet	1988	4
7	Baxter Spur	Honeygrove	390	1987	Wet	1988	4
8	Greenhouse	Peavine	480	1987	Dry	1988	4

*Soil moisture when yarded.

[†] Seedlings were planted in January through March (before the growing season of the indicated year).

[‡] Years after harvest (bulk density sampled in summer 1992).

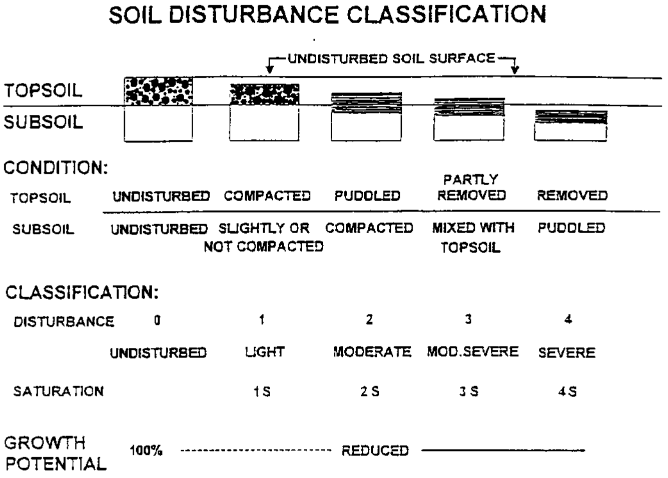
tilled at seven of the eight locations with a crawler tractor equipped with rear-mounted, rock-ripping tines spaced 1.1 m apart. The eighth site was tilled by a winged-ripper (Andrus and Froehlich 1983) pulled by a crawler tractor. Before either tool was used on deeply rutted trails (ruts deeper than about 30 cm), adjacent berms were first pushed into the ruts by a front-mounted blade, then the trails were cross-tilled to about 40 cm deep.

Soil disturbance classification

We used a qualitative classification of soil disturbance that visually characterizes five classes of soil disturbance (Fig. 1). The classes represent a continuum of increased soil disturbance with increased traffic of heavy machinery and logs (Scott et al. 1979). The classes are assumed to relate to tree growth.

In this classification, nondisturbed soil is class 0 (DC0). As machines move, topsoil can be compacted without destroying soil structure (DC1). Depending on depth of topsoil (A horizons), the subsoil is not compacted or only slightly compacted. As traffic continues on wet soils, topsoil is churned and mixed with the forest floor and slash; class 2 (DC2) results. Structure of the topsoil is severely altered, and the subsoil (B horizons) may or may not be compacted, depending mainly on depth of topsoil. Macropores and channels are reduced and disconnected to the depth of churning and compaction. Continued traffic can result in class 3 (DC3) where topsoil is partly removed (displaced in lateral berms) and mixed into the subsoil; subsoil is compacted, puddled, or both. Forest floor and slash often are mixed into the soil. In class 4 (DC4), all topsoil is displaced in side berms or completely removed by blading, and the subsoil is exposed and either compacted or puddled. Excessive blading, trafficking, dragging logs, and turning machines are common causes of DC4 disturbance, especially on soils with shallow (thin) topsoil. Even light disturbance can disrupt surface or subsurface water flow by reducing macropores and can cause the soil to be saturated for extended periods. Such saturation often results in seedling mortality. For example, seedlings of coast Douglas-fir usually die after roots are subjected to saturated soil for about 10 days (Minore 1968, 1970). Soils with a slowly draining or impermeable soil horizon close to the surface are especially susceptible to DC5 (as currently coded), because downward movement of water is limited.

Fig. 1. Weyerhaeuser system for classifying soil disturbance in the Pacific Northwest. Topsoil, A horizons; subsoil, B horizons. Subclass "S" (saturation) applies to any class 1–4 disturbance that causes the soil to be saturated for 10 or more days. Adapted from Miller et al. (1989).



Plot establishment

At each location, segments of readily identified skid trails were selected as potential experimental blocks. These segments appeared to have uniform severity of disturbance within 60 m or more of length. This selection criterion was assessed by systematically classifying potential skid-trail segments for severity of soil disturbance (Fig. 1). Adjacent logged-only portions near each segment were identified to represent DC0; these portions had no visual indications of vehicular disturbance. Primary (major) skid trails usually were classed as DC2 and DC3. The most severe disturbance occurred on or near landings. Three to five experimental blocks were established at each location. Each block straddled a 40–60 m long segment of skid trail (at least 80% having the same disturbance class). Note that the blocks were representative of primary skid trails but not of all skid trails in these clearcuts. The 40–60 m long segments were halved, and one half was randomly assigned for tillage. Areas immediately adjoining both sides of the skid trails were designated as soil berms, and nearby areas with no visible evidence of machine traffic were considered control or logged only.

The year after harvesting the mature stands, up to 60 Douglas-fir seedlings (1–1) were hand planted in each treatment area (plot). These seedlings originated from seed collected in three local seed zones. The number of plots totaled 115 because a berm plot was not installed in one block. Of the 115 plots, only 4 had as few as 20 seedlings planted. Within nontilled and tilled skid trails, trees were planted in two rows corresponding to the original ruts. When planted, roots of seedlings on nontilled skid trails were confined to compacted soil below these ruts, thus worst-case conditions. Seedlings were spaced 1.5–2.0 m apart within rows and 1.0–1.5 m between rows. To maintain the same spacing, seedlings also were planted beside skid trails, usually on soil berms. Adjacent logged-only areas were planted at the same spacing.

In the first and second growing seasons after planting, herbicides were applied by helicopter as an operational treatment to each study location to reduce competition from *Ribes* spp., grasses, and forbs. We concluded from visual observations that these applications uniformly controlled the targeted species in each study area. This control reduced the potentially confounding effects of differing vegetational competition among the experimental blocks and treatment plots.

Treatments

Four treatments can be compared at each location: (*i*) nontilled (nontreated) skid trails (NT), (*ii*) tilled skid trails (T; occasionally topsoil respreading plus tillage), (*iii*) soil berms (B), and (*iv*) adjacent logged-only areas (LO; nondisturbed). A total of 29 blocks, each with four treatment plots, were installed over 2 years (1987 and 1988).

Soil sampling and analyses

Rut depth and bulk density determinations

Soils were sampled either 4 or 5 years after yarding. Two transects were installed across each NT and T plot in 20 of the 29 blocks (Table 2). Transects were 10 and 20 m from the end of each plot that was closer to the landing. For both transects, berm height and rut depth (above and below the prelogging soil surface) and their widths were recorded. Bulk density (BD) samples were extracted below both ruts (by decimetre sampling intervals to 40 cm). Soils were collected with a continuous, volumetric sampler (Altanasiu and Beutelspacher 1961); each 10-cm interval in the sampling tube contained 116.4 cm^3 of soil. At LO plots, corresponding BD samples were extracted to the 50-cm depth at four points and combined in the field by 10-cm intervals. Soil samples from LO plots had two purposes: (*i*) to characterize BD, carbon (C), and nitrogen (N) of nondisturbed soil and (*ii*) to estimate preharvest BD at corresponding depths in the original profile of T and NT plots. No soil samples were taken in berms.

Table 2. Number of experimental blocks for analyses of soil and tree growth by location and disturbance class (DC).

Location		Soil analysis*			Tree growth analysis*		
No.	Name	DC2	DC3	All	DC2	DC3	All
1	Ewing Creek	2	—	2	3	—	3
2	1031 Big River	—	2	2	1	2	3
3	Quaglia	—	2	2	1	2	3
4	Gettings Creek	2	—	2	3	—	3
5	Reservoir	2	2	4	2	2	4
6	Laurel Mountain	—	2	2	—	3	3
7	Baxter Spur	2	—	2	3	2	5
8	Greenhouse	2	2	4	3	2	5
All		10	10	20	16	13	29

Note: With one exception, each block has four treatment plots.
*Disturbance classes are defined in the text.

Soil processing

Samples were air-dried, then sieved through a 2-mm screen. Volume of gravel and coarse organic matter retained on the sieve was calculated from their ovendry masses and their mean particle density of 2.40 Mg·m^{-3} (measured from water displacement of gravel from each location) and 0.40 Mg·m^{-3} (assumed to be Douglas-fir wood). Thus, adjusted BD is fine-soil BD that may be compared between gravelly and nongravelly horizons or soils.

Particle-size determinations

Percentages of sand, silt, and clay in the <2-mm soil fraction were determined by hydrometer. The procedure closely followed Grigal (1973) except that (*i*) the soil was previously dried at 105°C (to determine BD) and (*ii*) an 8-h reading was taken to estimate clay percentage. Soil texture classes were assigned using 40-s and 8-h readings of the hydrometer.

Carbon and nitrogen analysis

Subsamples of the <2-mm soil fraction from LO plots (0- to 10-cm and 40- to 50-cm depths) and NT plots (0- to 10-cm depth only) were ground by mortar and pestle to pass a 0.042-mm mesh. Nitrogen was estimated from ammonium concentration (Technicon autoanalyzer[4]) in samples digested by the micro-Kjeldahl procedure (Nelson and Sommers 1980). Total C (organic and inorganic) was determined by dry combustion (Carlo Erba NA 1500).

Tree measurements

Seedling condition was recorded after planting and annually through the third growing season. Damaged or unhealthy seedlings were coded only for the agent most likely to kill the seedling. Seedling height (cm) and stem diameter (mm) were measured annually after the third growing season until age 7 (locations 1–4) or 8, then at age 10 (all locations). Stem diameter initially was measured at 30 cm above

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[4] The use of trade or firm names is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

the soil, then at breast height (1.4 m) when attained. Total bole volume (dm^3) from tip to soil level was estimated by assuming a conical form and using tree height and outside-bark diameter at 140 cm above the soil.

Statistical analysis

We used three types of analyses in this study. The experimental design for tree performance was a randomized complete block. Each location had three or more blocks, each corresponding to a 40- to 60-m-long segment of skid trail, adjacent berm, and logged-only areas (Table 2). Neither these blocks nor the four plots that sampled treatment areas (NT, T, B, and LO) had a fixed area. Individual plots are the experimental unit for analyzing treatment effects on tree growth. For these analyses, there were 29 blocks among eight locations. Although we didn't explicitly incorporate sites in the analysis, the site-to-site variability is included in the term called "blocks". The blocks, which are segments of skid trails, are independent in the sense required by the analysis, which is that the treatments in one block have no effect on any other block. The number of blocks does vary from site to site, but this does not affect the independence.

A second type of analysis was used for soil characteristics measured at 20 blocks. Treatment plots (from the randomized complete block design for growth variables) were sampled at four depths for soil measurements. The result is a split-plot design with treatments (NT, T, and LO) as the whole-plot treatment and soil depth as the subplot treatment.

Analysis of variance (ANOVA) ($P \leq 0.10$) was the basis for statistical inferences. When treatment means were significantly different and the interaction term was not, means were separated by Bonferroni, multiple-comparison procedures. SAS version 6.03 (SAS Institute Inc. 1988) was used for statistical calculations.

Finally, when an effect was not statistically significant, power analysis was conducted to indicate whether the lack of difference was real or the result of the study being inadequate to detect it. The power value given here is the probability of getting a significant result with this study if (*i*) the true means equaled the observed means, (*ii*) the true variability equaled what we observed, and (*iii*) the test is done at a significance level of 0.10. A power macro provided by Latour (1992) was used.

Results

Soil texture

Surface textures for all sites ranged from fine loamy to very fine (18–40% clay in the 0- to 10-cm depth; Soil Survey Staff 1975). Subsoil textures (in the 40- to 50-cm soil depth) were characterized as fine to very fine (32 to 80% clay). In BD samples, maximum gravel percentages (by volume) among the control plots ranged between 2 and 14% in the surface (0- to 10-cm depth) and between 2 and 26% in the subsoil (40- to 50-cm depth). Coarse organic matter (roots, wood) was usually less than 1% of core volume (maximum was 5%).

Table 3. (A) Results of the split-plot analysis of variance to test for the effects of treatment on fine-soil bulk density (Mg·m^{-3}) in year 4 or 5 after logging and (B) mean values by treatment and soil depth.

(A) Analysis of variance.

Source of variation	Description	df	MS	*P*
Main plot				
Block (B)		19	0.1166	$\leq$0.001
Treatment (T)[*]	(NT, T, LO)	2	0.2676	$\leq$0.001
Error 1	B × T	38	0.0206	—
Subtotal	(20 × 3) – 1	59		
Split plot				
Soil depth (S)		3	0.3988	$\leq$0.001
S × T		6	0.0361	0.006
Error 2		171	0.0115	—
Total	(20 × 3 × 4) –1	239		

(B) Mean values by treatment and depth.

Soil depth (cm)	Nontilled	Tilled	Logged only	Mean
0–10	0.844	0.742	0.690	0.759
10–20	1.032	0.870	0.876	0.926
20–30	0.994	0.870	0.942	0.935
30–40	0.908	0.884	0.885	0.892
Mean 0–40[†]	0.945*a*	0.841*b*	0.848*b*	
Mean 0–30	0.957	0.827	0.836	

Note: Soil bulk density is mean of four samples per treatment in each block.

[*] Soil bulk density was not measured in berm areas.

[†] Means within a row followed by the same letter are not significantly different based on Bonferroni tests ($P \leq 0.10$).

Rut depth and soil bulk density

Based on four measurements per NT plot (two transects × two ruts), mean rut depth (below the original soil surface and 4 or 5 years after logging) averaged 15 cm and ranged between 3 and 34 cm among 20 plots at eight locations. Rut depth averaged 30 cm or more in 3 of the 20 plots. Rut depth was not measured in 9 of the 29 experimental blocks. Neither rut depth nor disturbance class seemed related to percentage of slope or steepness of skid trails at these locations. Deep and shallow ruts occurred on both flat and steeper terrain. Volumetric coarse-fragment content in these soils was low and, therefore, unlikely to affect rut depth or soil resistance to traffic. We did not attempt to relate rut depth to (*i*) soil moisture status (only one unit was yarded on dry soil) or (*ii*) tracked versus wheeled equipment (both types used interchangeably without documentation).

In year 4 or 5 after logging, fine-soil BD in LO plots averaged 0.690 Mg·m^{-3} in the 0- to 10-cm depth, increasing to 0.885 Mg·m^{-3} in the 30- to 40-cm depth (Table 3). Tilled and LO plots had similar profiles of BD. Average BD in the 0- to 40-cm depth differed significantly among the NT, T, and LO treatments; BD in NT plots exceeded that in T and LO plots (Table 3). The split-plot ANOVA detected a significant treatment × soil depth interaction that reflected the especially large increases (22%) in BD at the 0- to 20-cm depth below NT ruts compared with that in T and LO plots (Table 3).

In the 0- to 30-cm depth (upper rooting zone for planted seedlings), NT DC2 and DC3 skid trails averaged 0.957 Mg·m^{-3} compared with 0.836 Mg·m^{-3} for LO portions. This residual increase in BD averaged 14%.

Table 4. Percentages and content of carbon (C) and nitrogen (N) by soil depth and treatment at 20 blocks.

	Percent (by mass)			C	N
Treatment	C	N	C/N	(t/ha)	(kg/ha)
0–10 cm					
Nontilled	4.99 (0.37)	0.225 (0.012)	22.0 (1.0)	41.1 (4.5)	1880 (101)
Logged only	7.16 (0.58)	0.279 (0.019)	25.7 (1.5)	46.1 (3.5)	1810 (115)
Difference					
NT – LO	–2.17	–0.054	–3.7	–5.0	70
*P**	0.003	0.008	0.056	0.262	0.614
40–50 cm					
Logged only	1.30 (0.12)	0.074 (0.001)	17.3 (0.9)	10.7 (1.0)	620 (50)
Difference[†]					
Depth	–5.86	–0.205	–8.4	–35.4	–1190
*P**	≤0.001	≤0.001	≤0.001	≤0.001	≤0.001

Note: Values for percentages and content are means with SEs given in parentheses. Carbon and nitrogen were determined only in samples from transect 1 of nontilled plots (0- to 10-cm depth only) and from four sample points in each logged-only plot (0- to 10-cm and 40- to 50-cm depths).

*Based on paired *t* tests

[†] Difference (between depths in logged-only plots) is the value for the 40- to 50-cm depth minus the value for 0- to 10-cm depth.

Table 5. (A) Results of analysis of variance to test for the effects of treatment on Douglas-fir survival at years 2 and 10 after planting at eight locations and (B) means and SEs for survival.

(A) Analysis of variance.

		Survival in year 2		Survival in year 10	
Source of variation	df	MS	*P*	MS	*P*
Block (B)	28	207.7	≤0.001	298.3	≤0.001
Treatment (T)	3	625.5	≤0.001	843.2	≤0.001
Error (B × T)	83	80.3	—	86.4	—
Total	114	—	—	—	—

(B) Means and SEs.

Treatment	Survival in year 2	Survival in year 10
Nontilled	86.4 (1.64)*b*	84.1 (1.75)*b*
Tilled	94.9 (1.04)*a*	93.3 (1.17)*a*
Berm	87.9 (1.83)*b*	85.6 (2.14)*b*
Logged only	84.1 (2.92)*b*	80.5 (3.23)*b*

Note: Means within a column followed by the same letter are not significantly different based on Bonferroni tests (*P* = 0.10).

Carbon and nitrogen relationship

In nondisturbed soil of LO plots, concentration and content of C decreased markedly between the 0- to 10-cm and 40- to 50-cm depths (Table 4). The concentration of C in the surface 0- to 10-cm depth averaged 7.16 ± 0.60% (mean ± SE) and, at the 40- to 50-cm depth, averaged only 1.30 ± 0.10%. In the corresponding 0- to 10-cm depth below ruts in NT skid trails, C concentration averaged 4.99% and C content averaged 41 $t{\cdot}ha^{-1}$ below NT ruts, compared with 46 $t{\cdot}ha^{-1}$ for LO portions. Note that no samples were collected in the 40- to 50-cm depth in NT skid trails.

Nitrogen concentration and content also decreased markedly between the 0- to 10-cm and 40- to 50-cm depths in LO plots. Nitrogen in the LO plots averaged 0.28% at the surface and 0.07% at 40–50 cm. Below NT skid trail ruts, N concentration averaged 0.22%, but greater BD resulted in slightly more N in the surface 0- to 10-cm depth than in LO portions (1880 vs. 1810 $kg\ N{\cdot}ha^{-1}$; Table 4).

Seedling survival

A few seedlings died in the first growing season; these were not replaced. Most seedling mortality occurred by the end of the second growing season after planting. Between years 2 and 10, survival percentages changed slightly (Table 5). Ten-year survival on T skid trails (93%) averaged significantly greater than that on NT skid trails, B, and LO portions (80–86%). Cause of seedling mortality was usually uncertain and, hence, coded as unknown. Severe animal browse and frost damage was noted for some dead seedlings.

Height growth and mean height

Mean annual height growth on NT plots was less than on LO plots for the first 7 years after planting. The growth deficit averaged 24% in year 4 but decreased to 6% in year 7. Growth differences were statistically significant, although the significance levels decreased from *P* = 0.001 in year 4 to *P* = 0.012 in year 7 (Table 6). Annual losses in height growth (NT – LO) averaged 11 cm in year 4 and declined to 5 cm in year 7. Subsequent annual height growth (mean of years 8 through 10) did not differ between trees on NT skid trails and control areas. Averaged for the eight locations, trees on NT skid trails required 4.7 years to attain breast height (1.4 m) compared with 4.0 years on T, B, and LO portions (Fig. 2).

Mean height through 10 years after planting at most locations was least on NT plots and was similar on T, B, and LO plots. Based on pooled data from all eight locations (29 blocks total), seedlings planted in NT skid trail ruts averaged 5.79 m tall, or 0.61 m (10%) shorter at year 10 than seedlings planted in LO, B, and T portions (*P* = 0.001; Table 7). Tillage improved average 10-year height by 11% over that on NT skid trails. Recent 3-year periodic annual height growth averaged 92–95 $cm{\cdot}year^{-1}$ among the four treatments (Table 7), and differences were nonsignificant (*P* = 0.180, power = 0.55, given a type 1 error rate or α of 0.10). Thus,

Table 6. (A) Results of analyses of variance to test for the effects of nontilled skid trails on mean annual height growth (cm) in specified year after planting at eight locations and (B) means and SEs for the years.

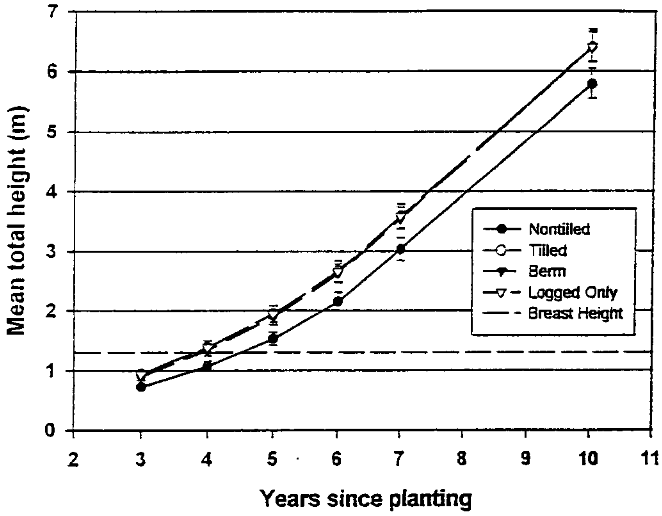
(A) Analysis of variance.

		Year 4		Year 5		Year 6		Year 7		Years 8–10	
Source of variation	df	MS	*P*	MS	*P*	MS	*P*	MS	*P*	MS	*P*
Block (B)	28	904.8	≤0.001	514.7	≤0.001	1211.4	≤0.001	474.6	≤0.001	307.2	≤0.001
Treatment (T)	1	1677.3	≤0.001	1264.1	0.002	1000	0.002	413.2	0.012	57.5	0.180
Error (B × T)	28	47.3	—	55.9	—	85.4	—	57.8	—	30.4	—
Total	57	—	—	—	—	—	—	—	—	—	—

(B) Means and SEs.

	Annual height growth (cm)				
Treatment	Year 4	Year 5	Year 6	Year 7	Years 8–10
Nontilled	33.5 (3.8)	45.5 (3.3)	62.8 (5.1)	87.0 (3.3)	91.9 (2.5)
Logged only	44.3 (4.3)	54.8 (3.0)	71.1 (4.3)	92.3 (2.8)	93.9 (2.3)
Loss (cm)	10.8	9.3	8.3	5.3	2.0
Loss (%)	24.3	17.0	11.7	5.8	2.1
Tilled	45.0 (4.4)	55.9 (3.3)	72.3 (4.7)	91.9 (3.1)	93.9 (2.6)
Berm	43.4 (4.0)	55.3 (2.9)	73.0 (4.4)	92.1 (2.9)	94.9 (2.4)

Fig. 2. Mean total heights and standard errors through year 10 at eight locations in Oregon by year and treatment.



given the variability in this trial, we had a 55% chance of getting a significant test result if the differences among the true means were the same as our observed means (2–3 cm or 2–3% of mean LO growth).

Mean tree volume and recent volume growth

Averaged over the eight locations, mean 10-year bole volume on the NT plots was 14.1 dm^3 per tree compared with 18.7 to 19.9 dm^3 per tree for T, B, and LO control treatments (Table 8). Thus, volume per tree averaged 29% less on NT compared with LO; the difference was statistically significant ($P = 0.001$). This percentage of reduction in volume exceeded the percentage of reduction in height (10%) and diameter at breast height (DBH) (14%). Tilling primary skid trails at these locations increased mean bole volume to that of LO plots.

Table 7. (A) Results of analyses of variance to test for effects of treatment on mean height after year 10 and mean periodic annual height growth in years 8–10 after planting at eight locations and (B) means and SEs for height and growth.

(A) Analysis of variance.

		10-year height (m)		Height growth (cm)	
Source of variation	df	MS	*P*	MS	*P*
Block (B)	28	7.23	≤0.001	617.24	≤0.001
Treatment (T)	3	2.63	≤0.001	40.73	0.180
Error (B × T)	83	0.126	—	24.44	—
Total	114	—	—	—	—

(B) Means and SEs.

Treatment	10-year height (m)	Height growth (cm)
Nontilled	5.79 (0.25)*b*	91.9 (2.49)*a*
Tilled	6.41 (0.28)*a*	93.9 (2.60)*a*
Berm	6.40 (0.25)*a*	94.9 (2.43)*a*
Logged only	6.40 (0.26)*a*	93.9 (2.34)*a*

Note: Means within a column followed by the same letter are not significantly different based on Bonferroni tests ($P \leq 0.10$).

Recent 3-year change in mean tree volume (years 8–10) averaged 3.62 $dm^3 \cdot year^{-1}$ on NT skid trails compared with 4.61 to 5.01 $dm^3 \cdot year^{-1}$ on T, B, and LO areas (Table 8). This 28% lower rate of change in mean tree volume on NT skid trails compared with LO areas was statistically significant ($P \leq 0.001$).

Discussion

The most severe disturbance from harvesting these 50- to 70-year-old stands occurred on primary skid trails and landings, where equipment traffic was most frequent. These areas occupied about 10–20% of the total clear-cut areas. We

Table 8. (A) Results of analyses of variance to test for effects of treatment on tree volume after year 10 and periodic annual growth in years 8–10 after planting at eight locations and (B) means and SEs for growth and volume.

(A) Analysis of variance.

Source of variation	df	Volume after year 10 (dm^3)		Annual volume growth (dm^3)	
		MS	*P*	MS	*P*
Block (B)	28	300.8	≤0.001	17.90	≤0.001
Treatment (T)	3	151.8	≤0.001	10.39	0.001
Error (B × T)	83	6.8	—	0.50	—
Total	114	—	—	—	—

(B) Means and SEs.

Treatment	Volume after year 10 (dm^3)	Annual volume growth (dm^3)
Nontilled	12.5 (1.5)*b*	3.62 (0.38)*b*
Tilled	16.8 (1.8)*a*	4.61 (0.42)*a*
Berm	16.7 (1.6)*a*	4.75 (0.40)*a*
Logged only	17.6 (1.8)*a*	5.01 (0.45)*a*

Note: Means within a column followed by the same letter are not significantly different based on Bonferroni tests ($P \leq 0.10$).

focused our measurements of soil disturbance and subsequent performance of planted Douglas-fir on and near primary skid trails, assuming that effects there would be stronger than on the more extensive secondary and tertiary skid trails.

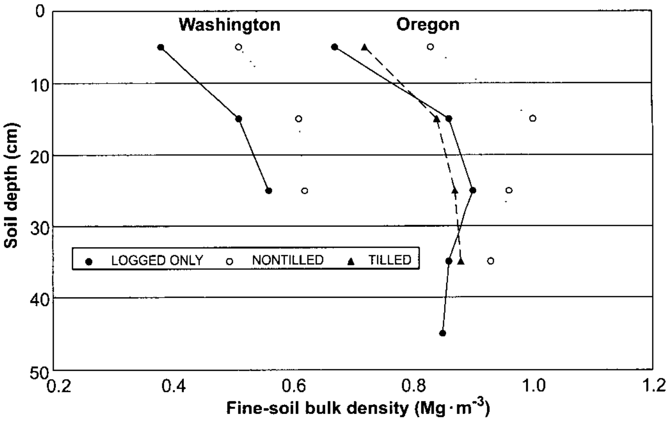
Soil disturbance on skid trails

Classification

We used visual criteria developed by Weyerhaeuser Co. to classify soil disturbance on skid trails (Fig. 1). This classification was designed so that harvest managers, equipment operators, and foresters could easily recognize and control the amount of soil disturbance from ground-based operations, regardless of equipment type. The classification has proved (*i*) to be easy to understand and use in the field, (*ii*) to be applicable to a wide range of soil conditions and equipment types, and (*iii*) not to require measuring soil physical properties. After this Weyerhaeuser soil disturbance classification was developed for the Pacific Northwest, others reported qualitative systems to classify soil disturbance in the southeastern Coastal Plain (Miller and Sirois 1986) and the U.S. Southeast in general (Kluender and Stokes 1992). Those classifications also include some recognition of litter layer disturbance, mixing of litter and mineral layers, obvious soil compression, and ruts caused by traffic. Visually determined soil disturbance classes are closely related to quantitative soil and site properties in the Coastal Plain of South Carolina (Aust et al. 1998).

Rubber-tired and tracked skidders on primary skid trails at our Cascade locations affected the A horizon by churning soil and by admixing organic debris. In some skid trail segments, however, this class 2 disturbance increased to DC3, because some topsoil was removed or mixed with subsoil.

Fig. 3. Mean fine-soil bulk density in logged-only portions and in ruts on nontilled and tilled skid trails, by depth and location.



Rut depth

Four and 5 years after yarding, ruts from skidders and logs were clearly evident. Rut depth averaged 15 cm on primary skid trails among 20 experimental blocks. Rut depth can be used as a measure of severity of traffic or soil disturbance; it can be used as a continuous variable in statistical testing; the deeper the rut, presumably the more severely soil was disturbed. In contrast, the Weyerhaeuser classification system assumes that the ecological significance of rut depth depends on topsoil thickness (or depth to B horizon). Soils with a thin topsoil (A and A–B horizons), therefore, are more likely to be classified as severely disturbed (DC3 and DC4) than are soils with a thick topsoil (Fig. 1).

Bulk density

At our Oregon sites and 4 or 5 years after yarding, fine-soil BD in the 0- to 30-cm planting depth on DC2 and DC3 skid trails averaged 14% greater than that on adjacent LO portions. Because natural processes occurring between yarding and our measurements in year 4 or 5 probably ameliorated original soil conditions, differences in BD at planting could only have been greater. Our ANOVA indicated that mean BD in the 0- to 40-cm depths was significantly greater in NT than in LO plots, which had no visual indications of soil disturbance. A significant treatment × soil depth interaction also existed; BD was notably greater at the 0- to 10-cm and 10- to 20-cm depths on NT skid trails. Tilled plots, however, averaged similar BD to the 40-cm depth as the LO areas. Thus, tillage changed mean BD to that of undisturbed soil.

In coastal Washington clearcuts and 8 years after yarding (Miller et al. 1996), mean BD of NT skid trails still exceeded that of adjacent LO portions by 20% in the 0- to 30-cm depth (Fig. 3). Soils at these three sites were Andisols (Udands suborder) with deep, stone-free, silt loam A horizons.

We suspected that greater BD below ruts could be explained, in part, by our sampling depth being lower in the original profile, where BD is inherently greater. We exam-

Table 9. Summary of mean relative differences in seedling performance, by tree variables and treatment comparisons; pools all soil disturbance classes at eight locations (29 blocks).

	Relative percentage difference by comparisons*			
Tree variable	(NT – LO)/LO	(T – NT)/NT	(T – LO)/LO	(B – LO)/LO
Survival percentage (year 2)	2	9	11	4
Survival percentage (year 10)[†]	4	11	16	6
Incidence of terminal damage from browse (mean of years 2 + 3)[‡]	3	2	5	0
Mean total height (year 10)	–10	11	0.2	0
Height growth (mean of years 8, 9, and 10)	–2	2	0	1
Mean DBH (year 10)	–14	15	–2	–0.4
Mean bole volume (year 10)	–29	32	–6	–5
Change in mean tree volume (mean of years 8, 9, and 10)	–28	27	–8	–5

*NT, nontilled; T, tilled; B, berm; LO, logged only.

[†]Difference between percentage of survival in each treatment.

[‡]Difference between percentage of damaged trees in each treatment.

ined this in Oregon by assuming that the bottom of the rut (mean rut depth 15 cm) approximated the start of the corresponding sampling depth in the preharvest soil profile. Thus, the 0- to 10-cm sampling depth below a 15 cm deep rut would correspond to the 15- to 25-cm depth in preharvest profiles and in nearby LO portions. With this assumption, the mean BD, hence compaction below ruts, was greater to about the 40-cm depth in the original profile. Similarly, we adjusted our sampling depths on tilled plots by 7.5 cm (one-half the overall average rut depth), because deep ruts were at least partially filled before or during tillage. Respreading topsoil and tilling apparently reduced BD in the upper 30 cm of the original profile.

Although our reconstructed trends of BD in these plots are uncertain, the concept should be noted by those attempting to infer duration of increased BD on skid trails by retrospectively comparing BD on skid trails with BD on nearby LO areas (e.g., Wert and Thomas 1981). We think that retrospective comparisons are invalid where lower density surface soil was displaced during harvest. Such DC3 and DC4 disturbance is most likely in more easily identified primary skid trails and landings, where retrospective measurements are usually made.

Tree performance

Tree survival

Percentage of trees surviving two growing seasons after planting averaged slightly greater in ruts of NT skid trails than in nearby LO portions (Table 9). This was surprising given the strong evidence of topsoil displacement and mixing with more clayey subsoils, and increased BD where trees were planted. Causes of seedling mortality were usually uncertain, but animal browse and frost were suspected. Others (Youngberg 1959; Miller et al. 1996) also report that survival of Douglas-fir planted on primary skid trails in clearcuts is similar to that on LO portions. For naturally seeded stands, however, Steinbrenner and Gessel (1955) and Wert and Thomas (1981) report about 20% less stocking on skid trails compared with off-skid trail areas. This difference in results seems readily explained by greater inherent influence of unfavorable soil and microclimate on survival of newly germinated, volunteer seedlings than of planted 2- to 3-year-old seedlings.

Tilling skid trails, after filling deep ruts with soil from nearby berms, resulted in an additional 9% in 2-year survival to that on NT portions, and an additional 11% to that on LO plots (Table 9). We infer a beneficial effect of this remedial treatment and assume these remedial actions improved planting quality, made clayey subsoils more accessible to seedling roots, and reduced vegetative competition.

Attained height and height growth

Mean tree heights at planting were similar among the four treatments. Subsequent differences in mean height resulted from (*i*) treatment effects on soil conditions, (*ii*) slight changes in sample size (mortality), and (*iii*) effects from competing vegetation and animals. Despite our using herbicides to provide some control of vegetation in the early years after planting, vegetative competition and animal browsing may have differed among the treatments. Because these indirect effects (aftereffects) of treatment on seedling performance could not be separated from the direct effects of changed soil properties, differences in mean height or other growth parameters were assumed to be the net of direct effects and these aftereffects of treatment.

Shorter trees on NT skid trails represent an accumulation of small deficits in annual growth (Table 6). Because we first remeasured height in the third growing season after planting, earliest growth reductions are unknown. After seedlings exceeded about 1.4 m in height, annual height growth was increasingly similar among treatments. On T plots, annual height growth in most years averaged 1 or 2 cm more than on LO plots. Thus, tillage (preceded by respreading berms into deep ruts) recovered the height growth potential of the site.

The number of years for seedlings to attain breast height or free-to-grow size has implications for meeting "green-up" standards in regulations or stewardship commitments. These standards preclude harvest of neighboring stands for a specified time or until seedlings attain a specified size. On NT skid trails of our Oregon locations, trees averaged 4.7 years to attain breast height compared with 4.0 years on T skid trails, B, and LO areas. Thus, regeneration lag in NT skid trails averaged nearly 1 year. One can derive similar information about regeneration lag from an earlier investigation of the effects of tractor logging on productivity in a 32-year-old, naturally regenerated Douglas-fir stand near Drain, Oreg. (Wert and Thomas 1981). Skid-trail trees (natural regeneration) were shorter and needed 4.1 years longer to reach breast height than those growing in undisturbed areas. In contrast, our data showed a mean delay of only 0.7 year for our planted skid-trail trees. We surmise that roots of both volunteer and planted trees on NT skid trails eventually access nearby nondisturbed soil and that exploiting this better soil improves height growth.

Duration of reduced height growth and yield projections

Effects of skid-trail disturbance on seedling height growth can be of short duration. Slower annual height growth on our NT skid trails lasted for about 7 years after planting (averaged over the eight locations; Table 6). We reason that maximum differences in tree heights between NT skid trails and those on LO plots has already occurred and that height differences at age 10 likely will either be maintained or decrease with time. In either case, the percentage of difference or loss will become smaller as total tree height increases. In contrast, at the three Washington sites, height growth was slightly reduced only in the first 2 years after planting (Miller et al. 1996). After 7, 8, and 18 years, however, there were no differences in total tree height among NT, T, and LO treatments. Tree height at 18 years averaged 16 m, reflecting the favorable soil and climate at these coastal locations.

Other researchers also report that early growth losses on skid trails (Thompson et al. 1990; Senyk and Smith 1991) and skid roads (Smith and Wass 1976) dissipate with time after planting and that projections based on measurements taken in young plantations could overestimate actual growth reductions expected at harvest. Several explanations have been advanced for this implied recovery of growth on disturbed soil versus that on adjacent nondisturbed areas. These include increasingly greater vegetative competition on nondistubed soil, natural amelioration of disturbed soils, and root growth into more favorable physical and nutritional conditions adjacent to skid trails or skid roads (Senyk and Craigdallie 1997*a*). We affirm that the longer the period of observation, the more reliable the interpretation of the consequences of soil disturbance and tree performance. We agree that the future significance of early reductions in seedling height or volume growth to eventual yield per hectare is problematic, especially when tree survival is not greatly reduced by soil disturbance.

Relation of Douglas-fir root and height growth to bulk density

Bulk density that stops or reduces root growth seems to differ with soil texture, tree species, and experimental conditions. Sandy loams with artificially created bulk density of 1.59 $\mathrm{Mg \cdot m^{-3}}$ stopped root penetration of potted 2-year-old Douglas-fir but had no effect on shoot dry mass (Minore et al. 1969). In a sandy loam soil artificially compacted from initial 0.59 $\mathrm{Mg \cdot m^{-3}}$ to 0.84 and 1.02 $\mathrm{Mg \cdot m^{-3}}$, root length of 8-week-old Douglas-fir and especially western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) seedlings was more greatly reduced at the 1.02 $\mathrm{Mg \cdot m^{-3}}$ bulk density than was top length (Pearse 1958). In artificially compacted cores of sandy loam to loam textured soils, root-limiting BD was 1.7–1.8 $\mathrm{Mg \cdot m^{-3}}$ for Douglas-fir seedlings (Heilman 1981). Seedling height growth, however, was not affected at these root-limiting densities. Similarly, Singer (1981) reports that BDs ranging from 1.06 to 1.35 $\mathrm{Mg \cdot m^{-3}}$ for sandy loam and from 0.9 to 1.1 $\mathrm{Mg \cdot m^{-3}}$ for clay loam reduced root growth but not shoot growth of 2-year-old Douglas-fir. Thus, these investigators suggest a wide range for root-limiting BD and that top growth is less responsive than root growth to increased soil bulk density.

Bulk density in NT DC2 and DC3 skid trails in our Oregon study areas averaged 0.66 to 1.22 $\mathrm{Mg \cdot m^{-3}}$ in the 0- to 30-cm depth compared with 0.54 to 1.00 $\mathrm{Mg \cdot m^{-3}}$ in LO portions. Nontilled DC1 through DC4 skid trails at our three Washington locations immediately after yarding had BDs in the surface 23 cm ranging from 0.72 to 0.90 $\mathrm{Mg \cdot m^{-3}}$ compared with 0.51 to 0.66 $\mathrm{Mg \cdot m^{-3}}$ in LO portions. Thus, most of our skid trails did not approach root-limiting BDs for Douglas-fir as reported in the literature.

Relation of height growth to changes in bulk density

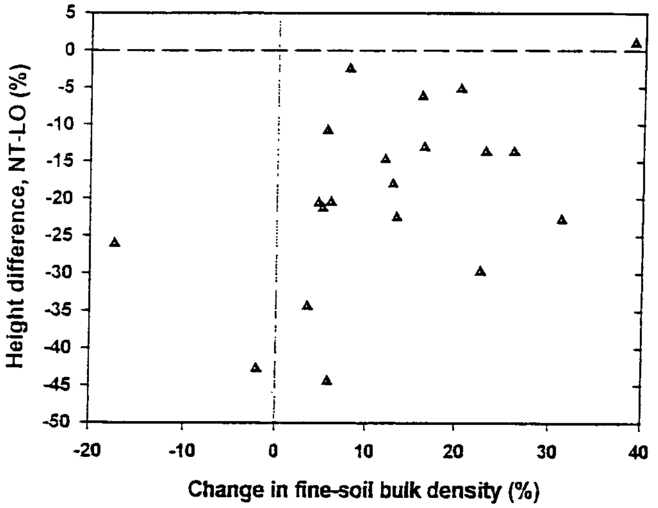
Percentage of increase in BD is often used as an index of potential decline in soil productivity. For example, by combining growth data from several locations, for several coniferous species including Douglas-fir, and for various periods after harvest, Froehlich and McNabb (1984) display a close linear relation between percentage of reduction in tree height and percentage of increase in soil BD. This generalized relation, however, is fundamentally flawed for at least two reasons.

(1) A percentage of change in BD depends strongly on initial BD of the soil. Thus, a measured 50% increase from a preharvest BD of 0.50 $\mathrm{Mg \cdot m^{-3}}$ would have much less significance to rooting environment than the same percentage of increase from an initial BD of 1.0 $\mathrm{Mg \cdot m^{-3}}$ where both soils have similar textures.

(2) A percentage of difference in tree height on compacted soil versus on noncompacted soil (control) depends on the height of control trees. A percentage of reduction in height, therefore, will decline as control trees become older and taller.

Our current Oregon and earlier Washington studies do not support the empirical relation reported by Froehlich and McNabb (1984). At our Oregon locations, maximum increase in BD did not maximize reductions in tree height even through year 7, after which growth was similar on NT and LO plots (Fig. 4). In fact, the correlation coefficient (r = 0.49) indicated increased 7-year height with increasing percentage change in BD (P = 0.003). Among the 20 blocks where BD was measured, there is a great deal of variability in this relation; for example at about a 5% increase in BD, height reductions range between 0 and 45%. Results at our three coastal Washington locations also fail to support generalizations about percentage of change in BD and tree growth (Miller et al. 1996). Despite a 47% increase in BD (0–23 cm depth) immediately after yarding at these locations, Douglas-fir survival, height, and volume through year 8 and

Fig. 4. Relation of mean percent height difference (NT – LO) at year 7 and mean percent change in fine-soil bulk density of the 0- to 40-cm depth (r = 0.49, P = 0.03).



year 18 after planting were not significantly different among NT, T, and LO plots (Miller et al. 1996). Preharvest BD in the 0- to 23-cm depth at the Washington locations ranged from about 0.50 to 0.60 Mg·m^{-3}; therefore, a 47% increase in BD would, have less effect on soil porosity and resistance than at the Springfield study sites where preharvest BD in the 0- to 20-cm depth was about 0.85 Mg·m^{-3}. We affirm that the importance of absolute or percentage of change in BD to tree growth at a given site depends on other soil properties and other growth-determining environmental factors, including moisture-nutrient stresses and competing vegetation. We suggest that percent increase in soil BD is not a reliable indicator of height-growth impacts when used across a wide range of climates and soils with different textures, mineralogy, and organic matter contents.

Site-to-site differences in soil disturbance and tree response

Our eight locations in western Oregon are considered high to very high risk for soil disturbance by ground-based yarding equipment on wet soil (Heninger et al. 1999). All but one of these locations were harvested and yarded in wet, winter conditions when the soil was near field water capacity. Soil disturbance on primary skid trail was either DC2 or DC3. Soils at the three Washington locations (Labar silt loam and Willipa silt loam; Typic Hapludands and Aquic Fulvudands, respectively) are considered moderate to high risk for disturbance (Scott et al. 1998). These Washington sites were yarded in the wet season with tracked equipment. Soil disturbance was somewhat less (mostly DC1 and DC2; ranging from DC1 to DC4 among 12 experimental blocks), in part because the A horizon was thicker (depth to the silt loam subsoil averaged 30–46 cm).

Douglas-fir planted on NT skid trails at our locations in the Oregon Cascade Range show greater and more sustained reductions in height and volume than the Douglas-fir planted at three locations along coastal Washington. The difference in tree performance could have several explanations.

Soil texture

A major difference exists in subsoil texture between the Oregon and coastal Washington sites. Subsoil textures near Springfield, Oreg., were fine to very fine texture with 32–80% clay in the 40- to 50-cm depth. This B horizon was well developed and, when dry, was strongly resistant to a cone penetrometer (2.5–5.1 MPa; data on file at the Forestry Sciences Laboratory, Olympia, WA 98512, U.S.A.). In contrast, subsoils at the Washington sites were sandy to fine-loamy with 12–40% clay; cone resistance in dry soil (summer) ranged between 1.2 and 1.4 MPa. We suspect that the more clayey texture and stronger resistance to penetration of subsoils at the Oregon Cascade sites are more limiting to rooting volume. Hence, compaction and puddling of the surface soil (also thinner) would have more growth-limiting effects than that at the coastal Washington sites.

Organic matter and nitrogen relations

Carbon and total N were analyzed to characterize the study sites and to indicate organic matter and N status for seedling roots. On LO plots in Oregon, average percentage, amounts, and ratios of C and N in the 0- to 10-cm depths indicate favorable status for seedling growth at all locations. Amounts of C and N in the 40- to 50-cm depth (upper B horizon), however, averaged 18 and 27%, respectively, of the amounts in the 0- to 10-cm depth. The lesser decline in N than in C content with soil depth suggests that much N at these lower depths could be fixed in clays rather than in soil organic matter.

In contrast to the sharp decline in soil C and N content with soil depth at the Oregon locations, soils at the three coastal Washington locations retain large amounts of C and N deeper in the profile; means and their standard errors (in parentheses) follow:

Nutrient (by depth, cm)	Cascades, Oregon	Coast, Washington
C (t·ha^{-1})		
0–10	46.1 (3.5)	43.8 (4.7)
40–50	10.7 (1.0)	33.9 (2.2)
N (kg·ha^{-1})		
0–10	1810 (115)	2100 (172)
40–50	623 (50)	1980 (94)

In summary, compared with our coastal Washington locations, locations near Springfield have (*i*) less favorable soil conditions for growth and root penetration (less organic matter and N, more strongly developed and more clayey subsoil) and (*ii*) greater moisture stress during the growing season because of a Mediterranean versus coastal climate. We suspect that seedlings near Springfield are more stressed by soil disturbance, because other environmental factors are less favorable than along coastal Washington. Reduced height growth after planting, consequently, lasted for about 7 years compared with 2 years along coastal Washington.

Bole volume versus height as dependent variables

Lipsey (1990) recommends a dependent variable that (*i*) displays a wide range of responsiveness to treatment, (*ii*) can be measured precisely (minimal measurement error), and (*iii*) shows small within-group variation in response (subject heterogeneity is small).

Choice of dependent variable to express effects of treatment also can be based on practical considerations. For example, differences in seedling height indicate the relative risk of animal browse and brush competition. Differences in tree height, however, are less indicative of overall tree size and growth potential than are differences in bole volume, which integrates effects of treatment on both diameter and height. For example, at year 10 after planting our Oregon sites, bole volume of individual trees on NT skid trails averaged 29% less than that of trees planted in LO areas, but reductions in tree height averaged only 10%. From this we infer that volume is a more responsive variable than height because percentage differences in volume ((NT – LO)/LO) were about three times those in tree height.

Management implications

Results from our studies add considerable knowledge about impacts of ground-based harvest systems on tree growth. Because these studies have been monitored for a sufficient period, some general conclusions about the magnitude of these impacts can be formulated. These field trials demonstrate that soil disturbance (DC1 through weak DC3) from ground-based yarding slightly reduced Douglas-fir height growth for 2 years after planting (coastal Washington) or about 7 years after planting (Oregon Cascades). Early growth losses on NT skid trails in the Oregon Cascades resulted in smaller trees at year 10 after planting; heights averaged 10% (0.61 m) shorter than on LO portions. Although recent height growth was similar for the four treatments, recent volume growth (in years 8, 9, and 10) averaged 28% less. Mean tree volume at year 10 after planting averaged 29% less on NT skid trails than in LO portions. We suspect that the height differences at age 10 will either be maintained or decrease with time. Future differences in individual tree volumes among the treatment is more uncertain, in part because volume is affected by stand density more than is height. In contrast, both tree height and volume on primary skid trails at our coastal Washington sites were not different from those in adjacent LO portions.

Tillage of skid trails fully ameliorated growth losses at the eight Oregon locations but proved ineffective (unnecessary) along coastal Washington. On NT skid trails in our Oregon sites, planting seedlings beside skid trails (in soil berms) instead of in ruts proved to be a practical means to avoid growth losses.

Our contrasting results from these trials demonstrate that generalities about the negative effects of skid trails on subsequent tree growth may have limited geographic scope and application. The consequences of soil disturbance to growth for one soil and climatic type should not be extrapolated to other soils and climatic types. We agree with Greacen and Sands (1980, p. 183): "Compaction of forest soils and the effects on current and long-term productivity depends in a complex way on various interacting factors such as climate, soil properties and management practices." This view is consistent with that of Senyk and Craigdallie (1997*a*, p. 15) "...many soil and climatic factors acting together affect seedling performance following clearcutting and ground skidding."

Severe soil compaction and soil displacement of most forest soils will have some undesirable effects on soil organisms (Dick et al. 1988) and tree growth and could contribute to stream sedimentation or visually suggest poor stewardship. The magnitude and duration of these effects, however, remain difficult to predict. We affirm that the consequences of soil disturbance for tree performance can be expected to differ from site to site; that a "treatment" × location interaction is the norm. If so, then concurrent quantification of the linkage between soil disturbance and tree response must occur at numerous locations and in a mensurationally and statistically valid manner. This linkage should be known before monitoring standards are set or a general prescription for remedial tillage is implemented.

Needed research

Issues about skid trails are becoming less relevant as logging equipment and methods change. Skid trails are less evident as felling, delimbing, and bucking are accomplished by machines, and yarding by forwarders and tracked shovels. This recent shift in harvest methods results in a more diffuse traffic pattern and more variable intensities and widths of soil disturbance. Consequently, research will require innovative procedures to quantify soil disturbance and its linkage to tree growth and stand yields. To quantify the effects of differing widths and intensities of disturbance (DC1 through DC4) on subsequent growth, we recommend controlled-treatment trials, rather than attempting to obtain a balanced sampling of disturbance classes from operationally treated areas. To reduce the number of treatment combinations, these trials could test most treatments at the extreme end of the spectrum of soil disturbance, thereby measuring the consequences of worst-case situations. Measuring tree performance should be the main focus. Tree performance provides direct response (evidence) to the continuing concern for maintaining site productivity. Coincident measurement of soil properties and their change after disturbance or treatment can be useful to describe the experimental situation, and to relate tree performance to soil changes. Soil measurements could provide explanations for site-to-site differences in outcomes and could perhaps identify soil variables as surrogates for predicting tree response.

Conclusions

(1) Ground-based skidding at eight locations in the Oregon Cascades compacted, churned, or displaced surface soil to varying degrees of severity. Four and 5 years after harvest, bulk density below skid trail ruts still exceeded that of logged-only portions.

(2) Survival percentages for seedlings planted in skid trail ruts averaged slightly greater than for those planted on adjacent logged-only portions. Mean height growth, however, was slower for the first 7 years after planting but was similar thereafter. Total height after 10 years averaged 10% shorter (0.61 m or about 1 growth-year equivalent) than on logged-only portions. Both absolute and percentage differences in total height decreased with time. Ten-year bole volume of individual tree averaged 29% less on nontilled skid trails than on logged-only portions.

(3) Tillage (preceded by topsoil respreading into deep ruts on a few plots) recovered the potential for height and volume growth of these sites.

(4) Reductions in tree height were unrelated to percentage increases in soil bulk density in the 0- to 30-cm depth. This finding indicates the doubtful value of using percentage increases in bulk density after logging as an indicator of impaired forest sustainability.

(5) Generalizations about negative effects of skid trails on subsequent tree growth have limited geographic scope and application; site-specific predictions and prescriptions are warranted.

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