Soil compaction and conifer growth after tractor yarding at three coastal Washington locations

Richard E. Miller, William Scott, and John W. Hazard

Abstract: We measured soil density and tree growth after wet-season, ground-based yarding on fine-textured soils at three clear-cut sites. Four treatment conditions were sampled on or near four skid trails (replicates): nontilled and tilled primary skid trails, and adjacent slash-treated areas; the fourth treatment was secondary skid trails at two locations and a logged-only control at the third location. The 16 treatment plots were split into 4 subplots, each randomly assigned to a species – stock type and planted with 30 seedlings. Tree data through year 8 after planting were analyzed as a randomized block, split-plot design. Compared with nontrail areas, bulk density in the 0- to 8-cm depth on primary skid trails after logging averaged 41–52% greater. Eight years later, bulk density in the 0- to 30-cm depth of primary skid trails still exceeded that outside trails by about 20%, yet tree survival was similar except for western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) having poorer survival on nontilled trails at one location. Average tree height and volume of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*), Sitka spruce (*Picea sitchensis* (Bong.) Carr.), and hemlock (except height at one location) did not differ among treatments. Observed differences among treatment means were small. Power analyses indicated that 20% or larger differences in tree height or volume were detectable with 30–95% power.

Résumé : Les auteurs ont mesuré la densité du sol et la croissance des arbres après un débusquage terrestre durant la saison humide sur des sols de texture fine, sur trois parterres de coupe. Quatre conditions de traitement ont été échantillonnées sur ou à proximité de quatre sentiers de débusquage (réplicats) : sentiers de débusquage primaires labourés ou non, et superficies adjacentes traitées pour les débris de coupe; le quatrième traitement étant représenté par les sentiers secondaires sur deux stations et par un témoin uniquement soumis à la récolte à la troisième station. Les 16 parcelles ont été subdivisées en quatre sous-parcelles, auxquelles étaient attribués aléatoirement une espèce et un type de semis et reboisées à raison de 30 semis par sous-parcelle. Les données des plants jusqu'à 8 ans après la plantation ont été analysées comme un dispositif en blocs complets aléatoires avec parcelles subdivisées. La densité apparente de la couche de sol comprise entre 0 et 8 cm de profondeur sur les sentiers primaires était en moyenne supérieure de 41 à 52% après la coupe par rapport aux zones situées à l'extérieur des sentiers. Huit ans plus tard, la densité relative de la couche de 0–30 cm des sentiers primaires dépassait toujours de 20% celle des parcelles situées à l'extérieur des sentiers, mais la survie des plants était semblable, sauf pour la pruche de l'Ouest (*Tsuga heterophylla* (Raf.) Sarg.) dont la survie était plus faible sur les sentiers non labourés sur une station. La hauteur moyenne et le volume des tiges de Douglas taxifolié (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*), d'épinette de Sitka (*Picea sitchensis* (Bong.) Carr.) et de pruche (sauf sur une station) ne différaient pas entre les traitements. Les différences observées entre les traitements étaient faibles. Des analyses de puissance ont indiqué que des différences en volume ou en hauteur égales ou supérieures à 20% étaient décelables avec 30 à 95% de puissance.

[Traduit par la Rédaction]

Introduction

Sustained production of wood involves repeated cycles of harvest, regeneration, and stand tending. Heavy vehicles used for skidding logs and preparing sites for regeneration, however, displace and compact soil, and can reduce forest growth. Literature reviews (Greacen and Sands 1980; Froehlich and McNabb 1984) and their primary references clearly establish that heavy equipment compacts mineral soil, reducing infiltration rates and large-pore space for gas and water movement. The consequences of soil damage to subsequent tree growth and especially stand yields, however, are less researched and less predictable. Hence, land managers and loggers are less inclined than soil specialists to predict reduced tree or stand growth from observed or measured soil compaction.

Several reasons explain the skepticism and uncertainty about the practical significance of soil compaction to

Received September 28, 1994. Accepted August 21, 1995.

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forest growth: (1) Direct evidence about tree response, especially long-term response, is limited. (2) Some investigators fail to separate the various types of disturbance, often compositing them as "compaction" (Steinbrenner and Gessel 1955; Wert and Thomas 1981; Helms and Hipkin 1986). In fact, trees on primary skid trails and landings respond to a broad range of soil disturbance, including compaction, kneading, churning, rutting, and displacement of surface soil and even subsoil. (3) Effects of soil disturbance usually cannot be separated from those of other factors affecting tree growth. For example, vegetative succession on skid trails often differs in plant species and density from that on nearby non-skid-trail areas. Moreover, former skid trails are readily used by big game, thus increasing the risk that animal browse will reduce seedling growth and confound explanations for differences in tree growth. (4) Commonly used measures of tree growth fail to quantify the effects of soil disturbance on future yields. For example, height growth is the usual measure of tree performance. Short-term growth of individual trees is an uncertain indicator of long-term stand growth and yields per unit area. To evaluate effects of skid trails on stand yields on an area basis, two factors must be quantified: (1) tree growth on specified strata within the harvested area and (2) area extent of these strata compared with the total area (Wert and Thomas 1981).

Because of these issues, additional investigation of tree growth on compacted and displaced soil is needed to assess sustainable wood production and to prescribe mitigative measures. Land managers need quantitative data about tree and stand growth after soil disturbance so that costs of optional methods for yarding and site preparation can be evaluated against costs of remedial treatments or potential reductions in site productivity. To quantify such trade-offs, Froehlich (1977) urged the use of an empirical approach: measuring growth over a wide array of soil and climatic conditions over time.

We followed that empirical approach in western Washington and Oregon, and here report results from the oldest trials on moderately productive, loamy soils in coastal Washington. Results from other areas will be published later. First, we describe the effects of ground-based yarding on soil bulk density immediately after harvesting and after 8 years. Second, we document 7- or 8-year survival and growth of three conifer species after being planted on skid trails, with and without remedial tillage, and on intervening nontrail areas. Finally, we question the generalization (Froehlich and McNabb 1984) that percent change in soil bulk density in skid trails is a reliable indicator of change in height growth and soil productivity.

Methods

Study areas

This study was conducted at three locations after clear-cutting 70- to 80-year-old stands of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Sitka spruce (*Picea sitchensis* (Bong.) Carr.). These naturally regenerated stands followed an earlier clear-cut harvest of old-growth forests. Study areas were located on level topography in a 60 km long portion of the Washington coast near Willapa Bay. The Niawakum and Palix locations are within 2 km of each other. They are on terraces of marine sediments at 30–40 m elevation, within 1 km of salt water, and on Willapa silt loam (medial, mesic Andic Haplumbrept) (Pringle 1986). The Central Park location is on an alluvium-covered, glacial outwash terrace at 90 m elevation and about 15 km from salt water. The soil series is well-drained, LaBar silt loam (medial, mesic Typic Dysterandept). Both soils are probably equivalent to sombric Brunisols in the Canadian System of Soil Classification.

At all three locations, soils are deep, well-drained, nearly gravel-free loams to clay loams with low bulk density and much organic matter in the upper 50 cm (Table 1). These soil data are based on sampling at continuous 10-cm intervals to 50-cm depth. Each 10-cm increment contained 116.4 cm^3 of soil. Two such cores were extracted from each of four non-skid-trail plots per location, and total sample volume was composited before chemical analysis. Total carbon was determined by dry combustion (Carlo-Erba NA 1500) and nitrogen was determined from ammonium concentration (Technicon AutoAnalyzer) in samples digested by the micro-Kjeldahl process (Nelson and Sommers 1980). Bulk density is fine soil bulk density (net dry weight and volume of soil passing a 2-mm sieve after gravel and wood were removed). Percentage of sand, silt, and clay were determined by the hydrometer method on the <2-mm soil. The procedure closely followed that of Grigal (1973) using 40-s and 8-h readings of the hydrometer.

Site indices are about 34 m for hemlock and 37 m for coast Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) at 50-year breast-height age (Steinbrenner and Duncan 1969). The three areas have a marine climate with cool, wet winters and cool, dry summers (Phillips and Donaldson 1972). Annual precipitation averages about 2500 mm. Frequently in summer and fall, low clouds or fog form over the ocean, move inland at night, and disappear by the following noon (Phillips and Donaldson 1972). This occurrence reduces plant-moisture stress, which is common during the growing season in the Pacific Northwest.

Yarding occurred in the wet season with soil moisture visually estimated to vary between saturation and field moisture capacity. Machine operators selected skid-trail routes. At Niawakum and Palix, yarding was with low ground pressure, tracked, FMC (model 200 CA) equipment.[2] At Central Park, D-8 Caterpillar tractors were used. Yarding mixed and smeared organic matter and mineral soil by the combined action of machines and logs. Ruts were typical in primary skid trails but infrequent in lesser used, secondary skid trails. The incidence of displaced topsoil was more frequent at Central Park than at Niawakum and Palix. Based on type and degree of soil disturbance, four disturbance classes were recognized:

	Soil disturbance class			
Location	1	2	3	4
Topsoil	Compacted	Puddled	Partly removed	Removed
Subsoil	Slightly or not compacted	Compacted	Mixed with topsoil	Puddled

Portions of primary skid trails were tilled using a D-6 Caterpillar tractor equipped with a front-mounted brush rake. The

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[2] Mention of commercial products does not imply an endorsement of the U.S. Department of Agriculture.

Table 1. Mean soil characteristics by locations and soil depth.

Depth	Carbon		Nitrogen		BD*	Sand	Silt	Clay	
(cm)	%	t/ha	%	kg/ha	(Mg/m^3)	(%)	(%)	(%)	Texture
				Niawakum					
0–10	22.9	55.0	1.07	2 568	0.24	30	44	26	Loam
10–20	11.3	49.7	0.53	2 332	0.44	32	44	24	Loam
20–20	8.1	43.7	0.41	2 214	0.54	31	49	20	Silt loam
30–40	6.2	37.2	0.33	1 980	0.60	30	53	18	Silt loam
40–50	4.8	31.7	0.29	1 914	0.66	27	51	22	Silt loam
Total	—	217.0	—	11 008	—	—	—	—	
Mean	10.7	—	0.53	—	0.50	30	48	22	
				Palix					
0–10	14.0	44.8	0.68	2 176	0.32	32	48	21	Loam
10–20	10.7	46.0	0.54	2 322	0.43	22	59	19	Silt loam
20–30	8.6	42.1	0.46	2 254	0.49	29	50	22	Silt loam
30–40	6.7	40.9	0.36	2 196	0.61	26	59	15	Silt loam
40–50	5.6	37.5	0.32	2 144	0.67	27	54	19	Silt loam
Total	—	211.3	—	11 092	—	—	—	—	
Mean	9.1	—	0.47	—	0.50	27	54	19	
				Central Park					
0–10	14.0	35.0	0.67	1 675	0.25	32	36	32	Clay loam
10–20	8.6	37.8	0.47	2 068	0.44	37	37	26	Clay loam
20–30	6.8	36.0	0.37	1 961	0.53	36	43	21	Loam
30–40	5.2	30.2	0.32	1 856	0.58	38	41	21	Loam
40–50	4.6	35.9	0.27	2 106	0.78	29	46	25	Loam
Total	—	174.9	—	9 666	—	—	—	—	
Mean	7.8	—	0.42	—	0.52	34	41	25	

Note: Values are means of four off-skid-trail plots per location.
*BD, bulk density of fine soil (<2 mm).

rake was inserted 40–60 cm into the soil and then the tractor was moved forward 1–1.5 m. The machine was then backed so another segment of trail could be tilled in a similar manner. Logging slash was broadcast burned at Niawakum and Palix, but it was piled at Central Park using a D-6 tractor with a brush-rake attachment to minimize soil displacement. Although these piles were burned, no plots were located on burned areas. Portions of the Central Park area were neither piled nor burned; these were designated as logged-only controls. Similar control areas were not available at the other two locations.

Treatments

Variously treated portions of these clearcuts permitted comparison of four treatments at each location, but not the same four treatments at all locations. Tilled versus nontilled primary skid trails versus a logging slash treatment (either piled or broadcast burned) could be compared at all locations. The fourth treatment was secondary skid trails at Niawakum and Palix and a logged-only control (no slash treatment) at Central Park. Primary and secondary skid trails differed in usage during yarding; secondaries were generally lightly disturbed and invariably classified as class 1 disturbance instead of class 2 or 3, as usually found on primary skid trails. Tilled and nontilled portions were assigned randomly so that neither treatment was consistently nearer the landing, an area of greatest traffic and soil disturbance.

Plot establishment

The four treatment conditions were sampled by plots on or near four skid trails (replicates); this provided 16 treatment plots per location. Each treatment plot was split into four 4 × 11 m subplots, and each subplot was randomly assigned to one of four species – stock types: Douglas-fir (2-0), Douglas-fir (2-1), western hemlock (2-1) or Sitka spruce (2-0). Before the first growing season after logging (or second at Central Park), 30 seedlings were shovel planted in three rows of 10 trees each (1 × 1 m spacing). Within subplots on skid trails, seedlings in the outer rows were planted in the original tractor tracks; seedlings in the middle row were planted between the tracks, where soil was probably less compacted. The remainder of each study area was planted concurrently with one species of the same stock: Sitka spruce at Niawakum and Douglas-fir at Palix and Central Park. Seedling spacing was wider (3 × 3 m) than on the plots.

Experimental design

Data from the three locations were statistically analyzed separately because of differences in environment or treatments among the areas. Thus, statistical inference may not be made beyond the limits of these three areas. Because these areas are similar to many other areas in coastal Washington, however, we expect these results to be generally applicable to other such areas.

The four treatments compared were as follows:

Area	On skid trails	Off skid trails
Palix and Niawakum	Primary (class 2–3) ± tillage	Slash burned
	Secondary (class 1)	—
Central Park	Primary (class 2–4) ± tillage	Slash piled
	—	Logged only

Data were analyzed as a randomized block, split-plot design. Each whole-plot experimental unit (disturbance–tillage) had four split-plot treatments (species – stock type) initially sampled by 30 seedlings. The general format for the statistical analysis follows:

Source of variation	df
Blocks (i.e., replication)	3
Treatments (on and off skid trails)	3
Error *a*	9
Species – stock type	3
Treatment × species interaction	9
Error *b*	36
Total	63

This analysis of variance reflected the limitations imposed by the split-plot design. The main-plot analysis was that of a randomized blocks experiment with four treatments replicated in four blocks. Error *a* was used to test for differences among treatments. In the subplot analysis, the four species – stock types were replicated in each of the 16 main plots. Error *b* was used for testing species – stock type and their interaction with main treatments.

All tests of significance were made at $p \leq 0.05$; however, probability values are provided so readers can make their own interpretations. Tukey's multiple-comparison test (honestly significant difference procedure) was used to separate treatment means that were significantly different (Snedecor and Cochran 1967). In addition, a power analysis was performed on observed treatment means and on imposed 20% practical differences in response to treatments (Dixon and Massey 1957).

Bulk density measurement

Soil bulk density samples were taken immediately after yarding and 8 years later. Although the intent at both times was to characterize general conditions on and off skid trails, sampling intensity, tools, and calculations differed. For the first measurement, representative points were sampled on and off skid trails within each study area. At each sampling point, three 33-cm^3 cores were extracted and composited for each of two depths (0–8 and 15–23 cm).

For the 8-year measurement, a tube sampler extracted successive 100-cm^3 samples from 10-cm depth intervals at five locations per treatment. Sampling locations were designated on a map before fieldwork and systematically located about 3 m from plots to avoid soil disturbance that could affect tree growth. Thus, sampling at both first and second measurements was purposive, not random, yet represented conditions similar to those of the plots. Bulk density of tilled portions of skid trails is unknown, because tilled portions were not available at first measurement and because preliminary sampling at year 8 showed that voids and buried wood precluded a reliable estimate. Although soils were nearly gravel free, some core samples contained gravel and coarse organic matter. In the first sampling, these were not separated; hence, bulk density is total soil bulk density (uncorrected for >2-mm fractions). In the 8-year sampling, however, >2-mm fractions were separated so volumes of gravel and coarse organic matter were calculated from their dry weights and measured particle density (2.40 Mg·m^{-3} for gravel and 0.40 Mg·m^{-3} for organic matter). Adjusted bulk density thus derived is fine-soil bulk density.

Tree measurement

Height and condition of all trees were recorded at planting and in years 1, 2, and 8 (or 7 at Central Park) after planting. For 2-1 Douglas-fir subplots only, height measurements were continued for 10 additional years and after thinning to retain six trees per plot and similar spacing in surrounding buffers. Overbark stem diameter at 1.3 m height (DBH) was recorded at year 8 (Niawakum and Palix) or year 7 (Central Park). Total stem volume, including top and stump, was estimated from height and DBH assuming a conical stem form.

Results

Soil bulk density

In the year of logging

Wet-season, tractor yarding disturbed mineral soil. Skid-trail disturbance at Central Park ranged from removal of all topsoil and subsequent compaction of exposed subsoil near the landing (class 4) to puddling and compaction of the topsoil without much displacement (class 2). At Niawakum and Palix, disturbance on primary skid trails was limited to puddling and compaction of the topsoil with only small, discontinuous patches of displaced topsoil. Bulk density of the surface 23 cm of soil on primary skid trails was greater in class 2–2 skid trails than in class 1 skid trails and in nontrail areas (Table 2). Relative to nontrail portions, trails with class 2–3 disturbance had bulk density increases in the 0- to 8-cm depth averaging 50% at Niawakum, 52% at Palix, and 41% at Central Park. Bulk density in a skid trail (one of four replicates) with class 4 disturbance at Central Park averaged 86% greater than non-skid-trail areas where slash was piled.

Eight years after logging

At Niawakum and Central Park but not at Palix, fine-soil bulk density on primary skid trails with disturbance class 2–3 still exceeded that at corresponding depths at non-skid-trail locations (Table 3). Eight years after logging at Central Park, bulk density of the surface 30 cm on class 2–3 trails (puddled–compacted) averaged 31% and on class 4 skid trails (topsoil removed) averaged 47% greater than on scarified portions (Table 3). At Niawakum on class 2–3 trails, bulk density of the surface 30 cm averaged 30% more than on nontrail areas. At Palix, bulk density in primary skid trails averaged only 2% more than that in non-skid-trail areas. For some unknown reason, bulk density on class 1 trails at both Niawakum and Palix averaged 9–10% less than nontrail, broadcast-burned areas. For the 0- to 30-cm depth at the three areas, mean bulk density of primary skid trails still exceeded that in adjacent slash-treated areas by about 20%.

Table 2. Means and standard errors of gross soil bulk density ($\mathrm{Mg{\cdot}m^{-3}}$) immediately after logging, by depth, treatment, and location.

Depth (cm)	Disturbance class on skid trail*			Slash treatment	
	1	2–3	4[†]	Piled	None[‡]
			Niawakum (n = 4)[§]		
0–8	0.71 (0.04)	0.84 (0.03)	—	—	0.56 (0.05)
15–23	0.70 (0.04)	0.74 (0.01)	—	—	0.70 (0.04)
			Palix (n = 3 or 4)[§]		
0–8	0.55 (0.03)	0.76 (0.01)	—	—	0.50 (0.01)
15–23	0.58 (0.01)	0.68 (0.03)	—	—	0.52 (0.02)
			Central Park (n = 4)[§]		
0–8	—	0.83 (0.07)	1.10 (0.04)	0.59 (0.06)	—
15–23	—	0.98 (0.07)	1.16 (0.04)	0.72 (0.07)	—

*Class 1, compaction only; class 2, topsoil puddled, subsoil compacted; class 3, topsoil partly removed, topsoil mixed with subsoil; class 4, all topsoil removed, subsoil puddled. See text.

[†] Class 4 disturbance occurred only at Central Park on one of four skid trails (replicates).

[‡] Core samples collected before broadcast burning.

[§] n, number of sampling points in each sampling (treatment) stratum.

Table 3. Means and standard errors of net soil bulk density ($\mathrm{Mg{\cdot}m^{-3}}$) 8 years after harvest, by depth, treatment, and location.

Depth (cm)	Disturbance class on skid trail*			Slash treatment		
	1	2–3	4[†]	None	Piled[‡]	Burned
			Niawakum (n = 5)[§]			
0–10	0.30 (0.06)	0.54 (0.08)	—	—	—	0.28 (0.03)
10–20	0.44 (0.06)	0.64 (0.08)	—	—	—	0.52 (0.06)
20–30	0.53 (0.04)	0.63 (0.06)	—	—	—	0.59 (0.05)
			Palix (n = 5)[§]			
0–10	0.33 (0.05)	0.44 (0.04)	—	—	—	0.42 (0.03)
10–20	0.41 (0.08)	0.51 (0.03)	—	—	—	0.48 (0.05)
20–30	0.57 (0.05)	0.55 (0.02)	—	—	—	0.57 (0.06)
			Central Park (n = 5)[§]			
0–10	—	0.56 (0.04)	0.55 (0.06)	0.39 (0.03)	0.44 (0.04)	—
10–20	—	0.68 (0.12)	0.77 (0.06)	0.45 (0.03)	0.52 (0.08)	—
20–30	—	0.69 (0.11)	0.84 (0.06)	0.55 (0.03)	0.51 (0.04)	—

*See first footnote in Table 2.

[†] Class 4 disturbance occurred only at Central Park on one of four skid trails (replicates).

[‡] Piled but not burned.

[§] n, number of sampling points in each sampling (treatment) strata.

Soil structure was platey on class 3 disturbance (at all locations) and especially on class 4 at Central Park, in contrast with the friable, well-aggregated structure of undisturbed soil. No trends in bulk density were inferred from these data because potential comparisons of bulk density trends over time are confounded by differences in sampling intensity, tools, and locations used initially and in year 8. Clearly, however, trees in primary skid trails at the three locations were planted in compacted soil. Eight years after harvest, bulk density of the 0- to 30-cm depth on disturbance class 2–3 skid trails at Palix was similar to that on non-skid-trail areas, whereas at Niawakum and Central Park, bulk density averaged 30% greater than that on non-skid-trail portions.

Tree survival

Seedlings were planted in February 1977. A few died in the first growing season, but dead seedlings were not replaced.

Table 4. Significance levels (p) for main effects and their interaction, by tree attribute and location.

	Main effects, by location*								
	Treatment			Species–stock			Interaction		
Tree attribute	N	P	C	N	P	C	N	P	C
Survival (%)									
Year 2	0.42	0.04	0.48	0.01	0.05	0.06	0.01	0.48	0.43
Year 7 or 8	0.43	0.08	0.26	0.01	0.04	0.22	0.01	0.32	0.27
Height (m)									
Year 2[†]	0.14	0.14	0.01	0.01	0.01	0.01	0.01	0.84	0.13
Year 7 or 8[†]	0.67	0.05	0.50	0.01	0.01	0.01	0.33	0.04	0.42
Year 7 or 8[‡]	0.92	0.06	0.38	0.01	0.01	0.01	0.11	0.03	0.71
Volume (dm^3)									
Year 7 or 8[‡]	0.62	0.10	0.19	0.01	0.01	0.01	0.18	0.51	0.52

*N, Niawakum; P, Palix; C, Central Park.

[†] All survivors.

[‡] Six tallest trees per plot (1400/ha).

Some seedling losses were unrelated to treatment, and these occurred at Central Park on three subplots (spruce from theft, hemlock and Douglas-fir from motorcycle traffic) and at Niawakum on two Douglas-fir subplots (from elk trampling or from excess water in a depressional area). The 30-tree base for calculating survival percentage was reduced for these nontreatment losses.

Two years after planting

Averaged across all treatments and species – stock types, 2-year survival was high, averaging 90, 92, and 96%, respectively, at Niawakum, Palix, and Central Park. Niawakum was the only location showing an interaction between disturbance treatments and planting stock (Table 4). Although data are not displayed in tables, hemlock survival at Niawakum generally was poorer than that of other species and was especially poor (54%) on class 2–3 disturbance (mixing and puddling of topsoil and subsoil) unless these were tilled (98% survival). At Palix, 2-year survival of all species was generally poorer on class 2–3 disturbance. Survival at Central Park was uniformly high among all disturbance classes and species.

Seven or 8 years after planting

Despite slight declines in survival percentages in years 3–8 after planting, survival remained high, averaging 87, 91, and 92%, respectively, at Niawakum, Palix, and Central Park (Table 5). Niawakum was the only location with significant differences in survival among some treatments (Table 4), and this was restricted to hemlock on nontilled skid trails (48%; Table 5). Although survival at Palix remained poorest on class 2–3 trails (86%), differences among treatments were no longer significant ($p \le 0.08$); hemlock survival averaged less than that of other planting stock. Thus, with the exception of hemlock on nontilled trails at Niawakum, treatment did not affect percentage of trees surviving 7 or 8 years after planting. At both Niawakum and Palix, survival percentage of all species was high and more consistent on tilled plots (Table 5).

Average tree height

At planting, no differences in average tree height existed among the treatments for any species – stocks type. Subsequent differences in average heights resulted from (1) treatment effects on soil conditions; (2) slight changes (except for hemlock) in sample size (mortality); and (3) uncontrolled effects from competing vegetation, animals, and humans. Although treatment may have affected vegetative competition and animal browsing, these indirect effects or aftereffects of treatment could not be separated from direct effects on soil. Thus, any difference among treatments in average height or other growth parameters was assumed to be the net of direct effects and aftereffects of treatment.

Two-year height, all surviving seedlings

Only at Central Park was 2-year height generally related to treatment (Table 4); height of all species – stock types averaged greater on logged-only control plots (74 cm) than on other treatment plots (60–68 cm; data not shown). Compared with logged-only controls and pooled across species – stock types, reduction in 2-year height after planting at Central Park averaged 19% less for class 2–4 disturbance, 8% less for tilled skid trails, and 18% less for slash-piled portions. Niawakum was the only location showing an interaction between treatment and species – stock type (Table 4). Height growth of hemlock was more reduced by skid-trail disturbance than was that of other species; second-year height of hemlock at Niawakum was shortest on nontilled, primary skid trails (79 cm) and tallest in logged–burned plots (120 cm).

When based on sufficient sample size, mean height of undamaged, healthy seedlings seems a better index of soil conditions than height of all surviving seedlings, including browsed. This hypothesis is not supported by these data, however, because analysis of 2-year height of this nonbrowsed, healthy subset gave results similar to the foregoing analysis of all surviving trees.

Table 5. Percentage of seedlings surviving the seventh or eighth growing season, by species – stock type, treatment, and location.

		Treatment					
		Class 2–3*			Slash burned or piled		
Species	Stock type	Nontilled	Tilled	Class 1	No	Yes[†]	All
		Niawakum (8 years)					
Douglas-fir	2-0	88	97	72[†]	—	75[§]	83
	2-1	98	97	90	—	98	96
Hemlock	2-1	48	97	75	—	78	74
Spruce	2-0	96	94	93	—	87	93
	All[‖]	82*a*	96*a*	83*a*	—	85*a*	87
		Palix (8 years)					
Douglas-fir	2-0	82	92	86	—	84	86
	2-1	100	97	93	—	96	96
Hemlock	2-1	74	98	88	—	93	88
Spruce	2-0	87	92	96	—	92	92
	All[‖]	86*a*	95*a*	91*a*	—	92*a*	91
		Central Park (7 years)					
Douglas-fir	2-0	91	91	—	88	99	92
	2-1	86	93	—	94	98	93
Hemlock	2-1	80	85	—	92	97	88
Spruce	2-0	86	99	—	91	95	93
	All[‖]	86*a*	92*a*	97*a*	91*a*	—	92

[*] At Central Park, the values include a class 4 disturbance at one of the four replicates.

[†] Slash was piled but not burned at Central Park and broadcast burned at other locations.

[‡] Nearly all mortality was on one subplot in a depressional location.

[§] Most mortality from elk trampling.

[‖] Within a row, treatment means with the same letter are not significantly different ($p \leq 0.05$). The treatment × species–stock interaction was significant only at Niawakum.

Seven- or 8-year height, all surviving trees

Seven or 8 years after planting, Palix was the only location where disturbance reduced average height of surviving trees (Table 4), but the significant treatment by species interaction and the data indicate hemlock as the only species with reduced growth. Hemlock heights at Palix averaged 14% less on nontilled, primary skid trails than on nontrail, burned areas. Average heights of all species no longer differed among the four treatments at Niawakum ($p \leq 0.67$) and Central Park ($p \leq 0.50$); however, hemlock heights on nontilled primary skid trails at Niawakum averaged 17% less than on nontrail areas (Table 6). This difference was not statistically significant, presumably because of greater variability at Niawakum than at Palix. Shorter heights at Central Park are probably explained by measurement at year 7 instead of 8 after planting.

Seven- or 8-year height, six tallest trees per subplot

This subsampling corresponded to the tallest 1400 trees/ha, which is at least double the preferred crop tree density after precommercial thinning. These trees were well distributed within each subplot. As expected, average heights of this select subsample exceeded those of all surviving tree (Table 7). Inferences from statistical analyses (Table 4), however, were the same: only hemlock at Palix showed reduced height on skid trails.

Height trends

For Douglas-fir, Sitka spruce, and especially western hemlock planted in primary skid trails on each site, height growth frequently was retarded for one or two growing seasons when compared with seedlings growing on adjacent logged-only or site-prepared (broadcast-burned or piled) portions. By 7 or 8 years after planting, however, no measurable height differences could be detected between trees on severely disturbed portions of skid trails (disturbance classes 2–3 and 4) and nontrail trees, except for western hemlock at one location. Surprisingly, reductions in hemlock height growth occurred at Palix but not at Central Park, where increase in bulk density was greater.

Trees in secondary trails at Palix and Niawakum (class 1 disturbance) showed no loss in height growth throughout the 8-year period when compared with non-skid-trail areas (Table 6).

Extended trends of mean height of 2-1 Douglas-fir through 18 years after planting support earlier trends. All

Table 6. Average height (m) of all surviving trees 7 or 8 years after planting, by species – stock type, treatment, and location.

		Treatment					
		Class 2–3*			Slash burned or piled		
Species	Stock type	Nontilled	Tilled	Class 1	No	Yes†	All
		Niawakum (8 years)					
Douglas-fir	2-0	5.0	4.9	4.7	—	4.8	4.9
	2-1	5.6	5.6	5.6	—	5.6	5.6
Hemlock	2-1	4.8	5.0	5.0	—	5.8	5.1
Spruce	2-0	3.8	4.1	4.2	—	4.0	4.0
	All†	4.8*a*	4.9*a*	4.9*a*	—	5.1*a*	4.9
		Palix (8 years)					
Douglas-fir	2-0	5.4	5.6	5.1	—	5.3	5.3
	2-1	6.0	6.1	6.4	—	6.0	6.1
Hemlock	2-1	5.4	5.9	6.4	—	6.3	6.0
Spruce	2-0	4.4	4.9	4.6	—	4.2	4.5
	All‡	5.3*b*	5.6*a*	5.6*a*	—	5.5*a*	5.5
		Central Park (7 years)					
Douglas-fir	2-0	4.7	4.8	—	4.2	4.7	4.6
	2-1	5.0	5.3	—	5.0	5.1	5.1
Hemlock	2-1	3.9	3.8	—	4.1	3.6	3.8
Spruce	2-0	2.8	3.1	—	3.3	2.6	3.0
	All‡	4.1*a*	4.3*a*	—	4.2*a*	4.0*a*	4.1

*At Central Park, the values include a class 4 disturbance at one of the four replicates.

†Slash was piled but not burned at Central Park and broadcast burned at other locations.

‡Within a row, treatment means with the same letter are not significantly different ($p \le 0.05$). The treatment × species–stock interaction was significant only at Palix.

treatment means were within 1 m in all years; the largest standard errors of individual means ranged from 0.1 m (1978–1984) to 0.3 m (1988–1994) (Fig. 1). Mean 18-year heights among the four treatments did not differ at any location ($p \le 0.27$–0.84), indicating that height growth of this species was not affected by skid-trail disturbance or by subsequent tillage.

Average tree volume

Tree volume integrates past height and diameter growth. Because diameter growth is influenced strongly by stand density, average tree volume of surviving trees on these study plots could be influenced by tree to tree competition. This supposition was supported by statistical analyses showing that center-row trees frequently were significantly smaller than outer-row trees in average diameter, height, and volume. This difference presumably resulted from the initial 1 × 1 m spacing within plots, and wider spacing in surrounding buffers, which benefited outer-row trees. To reduce those stand-density effects, we used average volume of the six tallest trees per subplot (1400/ha) to assess treatment effects on tree volume.

No evidence of an interaction between treatment and species – stock type existed at any location ($p \le 0.18$–0.52; Table 4). Main effects of treatment are also nonsignificant ($p \le 0.10$–0.62), so average tree volume of all species at year 7 or 8 after planting did not differ among the four conditions sampled at each location (Table 7).

Discussion

Results at the three study areas were similar.

Soil bulk density

We infer that yarding increased bulk density on primary skid trails and that increased bulk density was evident 8 years later. In the 0- to 8-cm depth, bulk density initially averaged at least 40% more than on nontrail areas on which slash was broadcast burned or piled. When undisturbed, these soils have a gradient of increasing bulk density with depth, so some of the measured increases in bulk density on skid trails relates to sampling deeper in the original soil profile (Table 3).

Percent change in bulk density is often used as an index of change in soil productivity (Froehlich and McNabb 1984). Percent change in bulk density strongly depends on initial bulk density of the soil. The significance of a change in bulk density to plant growth at a given site, however, depends on other soil properties (for example, clay type and content) and on other growth-determining

Table 7. Average height and volume of the six tallest trees per subplot (1400/ha) in year 7 or 8 pooling all species – stock types, by location and treatment.

	Treatment						
	Class 2–3			Slash burned or piled			
Location	Non tilled	Tilled	Class 1	No	Yes*	All	MSE[†]
Height (m)							
Niawakum	5.9	6.1	6.1	—	6.1	6.0	0.936
Palix	6.3	6.7	6.6	—	6.4	6.5	0.121
Central Park	5.0	5.2	—	5.1	4.9	5.0	0.302
Volume (dm^3)							
Niawakum	7.2	7.3	7.3	—	8.2	7.6	7.480
Palix	8.5	10.3	10.0	—	8.7	9.5	4.500
Central Park	4.0	4.5	—	3.9	3.5	4.0	1.310

Note: Values for Niawakum and Palix are from year 8 and for Central Park, year 7.

*Slash was piled but not burned at Central Park and broadcast burned at other locations.

[†] Mean square error = error a = block × treatment interaction in the randomized block, split-plot design at each location.

environmental factors, including climatic stress and competing vegetation. For two noncoastal areas in western Oregon, Froehlich (1979) reports reductions in height growth (but not of survival) of planted Douglas-fir after small percent increases in soil bulk density. At Dunn Forest, where initial bulk density (0.92 $Mg \cdot m^{-3}$) was increased 10% to about the 15-cm depth, 5-year height growth on nonbrowsed Douglas-fir seedlings was 8 and 12% less on skid trails with 6 and 10 trips, respectively, than on non-skid-trail areas (average sample size = 48 planted seedlings/treatment). In Molalla Forest, a 9 and 14% increase in soil bulk density (0.87 $Mg \cdot m^{-3}$ initially) to about the 15-cm depth for 6 and 10 trips, respectively, resulted in a 17 and 27% decrease, respectively, in 4-year height growth (average sample size 50 planted seedlings/treatment). Bulk densities before yarding at these locations were about 0.90 $Mg \cdot m^{-3}$ compared with 0.50-0.60 at our locations; however, no information was provided about soil displacement that may have occurred.

Despite 40% or more increases in bulk density at our coastal locations, maximum bulk density recorded on skid trails was only 1.16 $Mg \cdot m^{-3}$ on a class 4 disturbance (Table 2). We did not investigate whether increases in bulk density, and reduced macropores we inferred from the associated platey structure, limited root growth in these fine-textured soils. Bulk density that limits roots seems to vary by soil texture, tree species, and experimental conditions. For pole-sized coastal Douglas-fir and western hemlock, Forristall and Gessel (1955) estimate that 1.25 $Mg \cdot m^{-3}$ is the upper limit of soil bulk density for root growth in sandy loam soil. For Douglas-fir seedlings in artificially compacted cores, Heilman (1981) suggests that root-limiting bulk density is 1.7–1.8 $Mg \cdot m^{-3}$ in sandy loam to loam-textured soils. Seedling height growth, however, was not affected at these root-limiting densities. Similarly, Singer (1981) reports that bulk densities ranging from 1.06 to 1.35 $Mg \cdot m^{-3}$ for sandy loam, and from 0.9 to 1.1 $Mg \cdot m^{-3}$ for clay loam, reduced root growth but not shoot growth of 2-year-old Douglas-fir. Minore et al. (1969) report that bulk density of 1.59 $Mg \cdot m^{-3}$ in sandy loam stops root penetration of potted 2-year-old Douglas-fir but has no significant effect on shoot dry weight. Moreover, roots of Douglas-fir penetrated soil columns that roots of western hemlock and Sitka spruce did not. Pearse (1958) compacted a sandy loam soil from 0.59 initially to 0.84 and 1.02 $Mg \cdot m^{-3}$ and sowed Douglas-fir and western hemlock. He notes that root length of 8-week-old Douglas-fir and, especially, hemlock seedlings was more greatly reduced at the 1.02 $Mg \cdot m^{-3}$ bulk density than was top length.

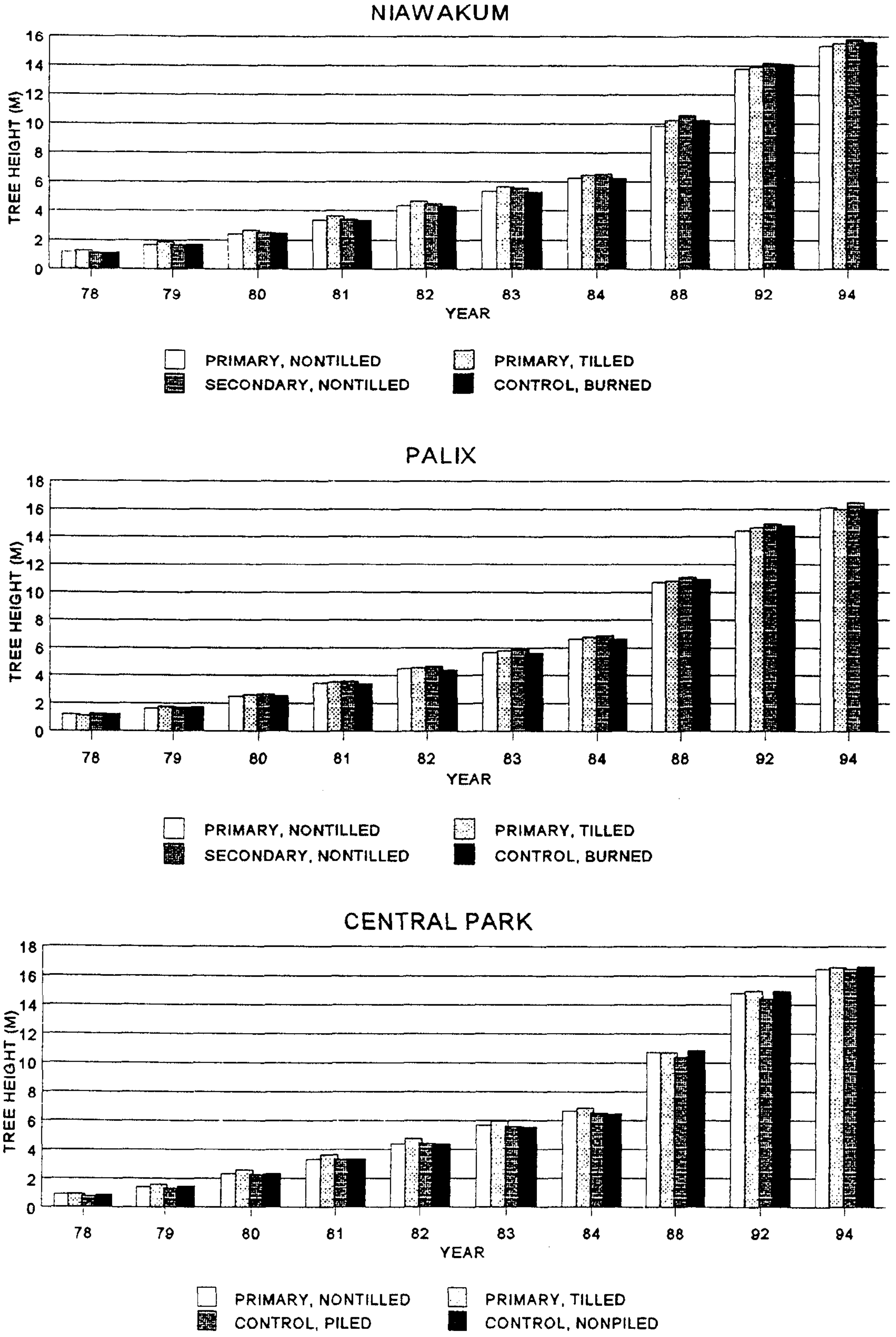
These short-term investigations with potted seedlings suggest that top growth is not as sensitive an indicator of soil compaction as is root growth, and that hemlock may be more sensitive than Douglas-fir to compaction. Our longer term field investigation of planted 2- to 3-year old conifers measured only aboveground growth. Height growth in the second year after planting was slightly reduced on primary skid trails at some locations. By year 8 and at one of three locations, hemlock was the only species remaining slightly shorter on nontilled skid trails.

Growth-limiting soil density indicates inadequate pore space and severe mechanical resistance to roots. Mechanical resistance, however, depends on water content and soil mineralogy (clay type and amount). Thus, a given change in soil bulk density can have different significance to root growth in dry versus wet soil. Drying or lack of it during the growing season could, therefore, produce a different growth response to a given change in bulk density. Thus, increased soil strength is more likely to limit root penetration in more xeric environments than in our study areas in coastal Washington.

Tree survival and growth

Of the three species tested, only hemlock showed poorer survival (at Niawakum at year 2) and height growth (at

Fig. 1. Trends of average height 18 years after planting 2-1 Douglas-fir at three locations, by treatment; each mean is the average of four replicated subplots and the tallest six trees per plot. The largest standard error of individual means ranged from 0.1 m (1978–1984) to 0.3 m (1980–1994).



Palix at year 8) on skid trails. Whether this result was a chance occurrence (our risk of type I error was $\alpha \leq 0.05$) or truly indicates less tolerance of this species for skid-trail environment is uncertain; however, tillage at Niawakum nearly doubled 2-year survival percentage of hemlock (54 vs. 98%). Thus suggests that (1) hemlock seedlings are more adversely affected by soil disturbance than are Douglas-fir and Sitka spruce and (2) tillage may be an effective rehabilitation treatment. For Douglas-fir, our results support Youngberg's (1959) opinion that survival of well-planted Douglas-fir in skid trails is of little concern on mesic Northwest sites.

Pooling all four stock types, we found no significant differences among treatment means for height or volume in any of the three areas. Treatment means for 7- or 8-year height varied less than 5% from the grand mean of all treatments, and corresponding means for volume varied less than 13% (Table 7). The background variation (mean square error (MSE)) was especially large at Niawakum compared with Palix, despite being mapped as same series. We suspect this greater variation is explained by the hummocky soil surface resulting from more prevalent windthrow in past stands.

Accepting the null hypothesis of no treatment differences does not preclude the possibility of committing a type II error (i.e., accepting the null hypothesis of no difference when, in fact, a difference actually exists). Because our observed effect size was so small, we calculated the probability of detecting a 20% reduction in mean tree size. We assumed a 20% reduction in mean height or volume was readily detectable by our measurement techniques and would have economic significance. Hence, a 20% difference was imposed on the nontilled treatment to simulate a practical difference (compared with control growth), and a power analysis was performed. At Palix and Central Park, the power to detect a 20% difference in height was moderate to high (60 and 95%, respectively). For height at Niawakum and for volume at all three areas, the power to detect a practical difference of 20% was low (30%), largely because of the large MSE (Table 7) and small degrees of freedom.

The observed means of height and volume showed very low dispersion, less than the theoretically imposed 20% difference. Yet difference among treatment means (or effect) is a major ingredient in the power of the test. This difference is divided by the background variation, MSE, to quantify the relative effect size. We believe our experimental design had sufficient power to detect height effects of a practical size at Palix and Central Park, if these had been present.

Several possible explanations are offered for the unexpected minimal effects of compaction and soil displacement on subsequent tree growth at our three locations: (1) Increased bulk densities did not result in soil strength that blocked root growth. (2) Soil degradation was offset by low climatic stress. (3) Seedling roots escaped skid trails. (4) Soil compaction and displacement on skid trails reduced vegetative competition more than slash burning or piling, and hence compensated for negative effects on soil properties. We do not know whether this occurred after the first year, when little difference in plant succession on skid trails and slash-treated portions was noted. (5) Disturbance on skid trails and piling or broadcast burning slash on non-skid-trail areas had equally damaging effects on seedling growth. This explanation could be checked only at Central Park, where a logged-only (control) treatment was available. The statistical analyses for that location reject explanation 5; compared with logging only, neither skid trails nor scarification at Central Park affected growth by year 7. Absence of a logged-only treatment at Niawakum and Palix precludes a similar treatment for those areas.

Our preferred explanation is that seedlings at these locations were not stressed by soil damage because other environmental conditions were so favorable. Soil organic matter in the 0- to 10-cm depth averages at least 20%. Moreover, the mesic coastal climate at these locations is likely to cause minimal evaporative stress on plants and to reduce soil strength. These favorable soil-moisture relations probably compensated for unfavorable soil compaction.

Implications for forest managers

Our research does not support generalization about the effects of skid trails on subsequent tree growth. 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." Initial severity of logging disturbance differs among yarding methods, operators, and from site to site. Critical variables include size and number of trees removed, type of equipment used, irregularity of terrain, content of soil moisture at time of traffic, and soil texture and organic matter. Our results at three coastal Washington sites demonstrate that generalities have limited geographic scope and application. With the exception of reduced hemlock survival at Niawakum and reduced hemlock height growth at Palix, planted seedlings of three different conifers attained similar size and numbers on compacted skid trails as they did on nearby portions of the clearcuts where slash was broadcast burned or piled. This indicates that soil displacement and compaction on skid trails from this second harvest will have no lasting effect on tree volume production at these coastal Washington locations.

For sustainable land management, prescription of treatment and equipment should be specific for each site and situation. For most soils and climates, soil displacement and deep compaction probably will have some undesirable effects on tree growth (Helms and Hipkin 1986; Clayton et al. 1987; Smith and Wass 1994) and soil organisms (Dick et al. 1988). The magnitude and duration of these effects, however, remain difficult to predict. Without well-designed, long-term studies at many locations to separate the potentially positive and negative effects of soil disturbance and skid trails on stand growth, however, uncertainty about the net effects of tractor logging on site productivity will continue.

Conclusions

(1) Ground-based skidding at these three clear-cut locations in coastal Washington displaced, churned, and compacted soil on primary skid trails. Eight years later,

soil bulk density on trails still exceeded that at non-skid-trail portions. Changes in bulk density since harvest could not be assessed, however, because sampling methods and tools differed.

(2) On primary skid trails, initial increases of 40% or greater in bulk density (to maximum of 1.2 $Mg \cdot m^{-3}$) did not affect 8-year survival and growth of planted Douglas-fir or Sitka spruce. Survival of western hemlock was reduced to about 50% at one location, and average 8-year height of hemlock at another location was 14% less than that on logged–burned portions. Western hemlock may be more susceptible to soil disturbance than Douglas-fir and Sitka spruce in coastal Washington.

(3) Tilling primary skid trails generally improved survival and early height growth, especially of hemlock. By year 7 or 8, however, average height of all surviving trees and the six tallest per plot was similar on tilled and nontilled skid trails, except for shorter hemlock on nontilled skid trails at one location.

(4) Although results at these study areas confirm some short-term growth reductions on skid trails as reported by other investigators, growth recovered so that by 7 or 8 years after planting, average tree height and volume of Douglas-fir, Sitka spruce, and hemlock (at two of the three locations) did not differ among treatments. With such small observed differences among treatment means, power to detect significant differences (or reject a null hypothesis) was low. To detect a theoretical 20% difference with the observed MSEs, power was about 30%, except for one comparison where the MSE was small. Thus, we expect that soil compaction and puddling on skid trails from this second harvest will have little or no long-term impact on forest yield at these locations.

(5) Percent change in soil bulk density is not a reliable predictor of growth or yield losses from logging disturbance on silt loam soils of coastal Washington. Initially favorable soil conditions and subsequently favorable climatic conditions can compensate for potentially negative effects of soil disturbance.

Acknowledgements

The authors gratefully acknowledge assistance in study establishment and data collection by Rick Leon, Rod Meade, and Marshall D. Murray; in data analysis by Jeralyn Snellgrove; and helpful technical reviews by Paul Adams, Bob L. Karr, Tim Max, Eugene Shoulders, William McKee, Tom Terry, Larry Morris, and two anonymous referees.

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