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Ground-Based Thinning on Steep Slopes in Western Oregon: Soil Exposure and Strength Effects

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Soil effects in vehicle trails were assessed on two cut-to-length thinning units that were very steep, averaging 65 and 58%, respectively. The thinnings in a young Douglas-fir forest included a harvester-cut, cable-yarded unit (harvester-cable) and a harvester-cut, forwarder-yarded (harvester-forwarder) unit. Steep vehicle trails covered 10% of the thinned area of harvester-forwarder and 15% of harvester-cable, and exposed soil occurred in 3% of the sample points in trail transects in harvester-cable and 7% of those in harvester-forwarder. After one harvester pass on harvester-cable, soil strength in vehicle tracks near the surface (25–200 mm) was 19–34% higher than that in undisturbed soil and 33–40% higher after a second vehicle (forwarder) pass on harvester-forwarder; the latter unit also showed 21% higher strength in the 225–300 mm layer after the second pass. Slash accumulations on the trails appeared to reduce vehicle effects on soil strength near the surface (25–100 mm) on one of the units (harvester-forwarder), whereas no clear relationship was seen with variations in trail slope. Dry season operations, limited passes, slash in trails, and low ground-pressure vehicles with enhanced stability and traction features helped control soil disturbance and probably kept it within agency guidelines.

Keywords: mechanized harvesting, soil compaction, soil penetrability, skid trails

The Pacific Northwest has a long history of interest in and concern about the physical effects of ground-based timber harvest on forest soils, which is reflected in the number of published research studies and the array of notable policies and practices to limit or mitigate impacts to soils and related resources (Cafferata 1992, Adams 2005). The evolution of more diverse logging vehicles and ground-based harvest systems (Kellogg et al. 1993) and a wider scope of environmental concerns have raised important questions about the applicability of earlier research findings (Adams 2005), although attention remains focused on soil compaction and other ground disturbance. Soil compaction is defined generally as an increase in soil bulk density (weight per unit volume) as a result of applied pressure or vibration and is a common result of logging vehicle traffic on undisturbed forest soils that are relatively weak and porous (Froehlich and McNabb 1984).

When soil is compacted significantly, its strength is increased, and soil porosity shifts from larger to smaller voids, with diverse effects that include increased vehicle traction, soil volumetric water content, and field capacity and decreased soil aeration, infiltration, and root penetration (Greacen and Sands 1980). Gomez et al. (2002) reflect the complexity of such effects, with observed tree growth responses to compaction that ranged from negative to positive, depending on soil type and the related differences in porosity, strength, and moisture availability. The variable effects of soil compaction on tree growth are now more widely recognized in forest management, and techniques such as designated skid trails have been shown to be effective in avoiding negative impacts (Miller et al. 2007). However, concerns persist about potential runoff and erosion from soil compaction and exposure from ground-based harvest operations on steeper slopes. These concerns are reflected in state

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; millimeters (mm): 1 mm = 0.039 in.; hectares (ha): 1 ha = 2.47 ac; kilograms (kg): 1 kg = 2.2 lb; grams (g) 1 g = 0.035 oz.

and federal guidelines such as slope and disturbed soil area restrictions for ground-based timber harvest (e.g., Oregon Administrative Rule 629-630-0150, US Department of Agriculture [USDA] 1998).

Interest in ground-based harvesting on steeper slopes also continues because of the relatively high cost of cable harvest systems (Murphy and Adams 2005) and the availability of vehicle designs and modifications (e.g., flexible tracks fitted over multiple rubber tires) that provide greater capability in steep terrain. These advantages, combined with suitable timber stands and a relatively reliable dry season for reduced ground disturbance, have prompted some private landowners in western Oregon to use harvester-forwarder or harvester-cable systems on steeper slopes (e.g., greater than 50%). However, such operations remain relatively unusual in the region, particularly on public lands where managers consistently avoid ground-based operations on such slopes. Thus, our objective was to clarify the degree and pattern of soil exposure and strength effects for a pair of such operations and also to assess some of the data for conformance with some existing soil protection guidelines.

Methods

Study Sites and Harvest Operations

The study sites were established on private forestland owned and managed by Starker Forests, Inc., about 15 miles west of the city of Corvallis in the Coast Range of western Oregon (44°38′56″ N and 123°32′12″ W), USA. The treated forest was a 28-year-old Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) plantation; within the study sites the average tree diameter (dbh) was 20 cm, and the average tree height was 22 m. General ground slope on the sites ranged from 0 to 70%, whereas the average slope of the primary harvester trails where soil measurements were taken ranged from 30 to 60%. The Digger-Remote-Umpcoos very gravelly loam soil complex dominates the harvest areas (USDA 2010), which includes loamy-skeletal, isotic, mesic Dystric/Typic/Lithic Eutrudepts (USDA 2009). Particle-size analyses (ASTM D6913-04) of composite samples from the harvest trails show a well-graded sand soil with clay (SW-SC) under the Unified Classification System. The soil types in the complex have similar surface (0–400 mm) layers, varying primarily in the depth to bedrock, and our onsite observations (e.g., aspect and geomorphology) and soil sampling confirmed that the soils were relatively uniform within and between the harvest units. The mean annual precipitation is about 1,760 mm and the mean annual maximum and minimum air temperatures are about 16.1 and 4.8° C, respectively (estimates using PRISM Data Explorer, based on 1971–2000 records). Local elevation ranges from about 270 to 330 m.

The study focused on two harvest units, 3.3 and 1.7 ha in size, specifically selected as the steepest of a five-unit thinning operation. Both units were thinned with the same harvester, but the first unit (harvester-forwarder) used a harvester-forwarder system, whereas on the second unit (harvester-cable), a skyline cable system was used for log yarding with the harvester trails serving as cable corridors. The units were both cut-to-length operations using a Ponsse Ergo 8w (8 wheels) harvester, with a manufacturer-specified machine weight of 21,000 kg. On harvester-forwarder, a Ponsse Buffalo forwarder, with a specified weight of 20,000 kg and maximum load of 14,000 kg, was used for log yarding. On both the harvester and forwarder vehicles, wheel pairs on the tandem axles on the tractor and trailer chassis were fitted with band tracks to enhance traction. From an initial stand density of about 690 trees/ha, the thinnings removed about 285 trees/ha on each unit. All thinning and log yarding operations took place between late July and early August 2011, a 2-week period when no significant precipitation occurred.

Five steep, adjacent vehicle trails provided primary access for thinning each unit, and these were used for detailed study (Figure 1); the trails ranged from 81 to 125 m in length and were about 3 m wide, and ran parallel to (i.e., straight up and down) the general slope. The thinning trails on harvester-forwarder had two downhill vehicle passes, more specifically a single pass by the harvester followed by a single pass by the forwarder. Harvester-cable had only a single, downhill pass by the harvester, followed by uphill cable yarding. After the harvesting was completed, global positioning systems (GPS) data were collected with a Visiontac device to create postharvest trail maps using ArcGIS (version 10). These data also were used to estimate the percent area of the thinned stands that was accessed by the steep trails. (Note that any mention of trade names is for information only and does not imply endorsement.)

Soil Measurements and Statistical Analyses

To estimate the degree of exposed mineral soil, sample transects 15 m apart (slope distance) were located perpendicular to each of the five main trails (Figure 1) on each of the two study units. Thus, there were five soil exposure transects per trail on harvester-forwarder and five per trail on harvester-cable. At 30-cm intervals on each transect across the trail (Figure 2), mineral soil exposure was recorded as positive or negative depending on whether exposed soil extended over a continuous length (uphill or downhill) along the trail for a slope distance greater than 2 m. This distance is consistent with that for other procedures for evaluating forest soil exposure and disturbance (e.g., Page-Dumroese et al. 2009), as it reflects conditions more likely to contribute to surface runoff or other site impacts. In total, we evaluated 300 and 349 sample points on harvester-forwarder and the harvester-cable units, respectively. The percentage of exposed soil sample points was calculated as

$$(Ex/(Ex + Ne)) \times 100,$$

where *Ex* is the number of sample points with exposed mineral soil and *Ne* is the number of sample points with no exposed mineral soil. These records were complemented by field notes using visual indicators of soil disturbance, based on the forest soil disturbance protocol developed by the USDA Forest Service (Page-Dumroese et al. 2009). The soil exposure and disturbance assessments were made within 2 weeks after harvest operations were completed on each unit, a period of continued dry weather.

Soil penetrability measurements have long been used in agriculture to assess soil compaction and have been correlated with observed root growth, crop yields, and other soil physical properties (Lowery and Morrison 2002). Although they have some limitations such as sensitivity to varying moisture levels, these measurements can be conducted more efficiently than other methods of evaluating forest soil compaction (Miller et al. 2001), a desirable feature in this situation where many measurements were needed within a short period. Soil penetrability was measured in transects perpendicular to each trail located every 10 m, with penetrability point samples taken in each vehicle track (2 disturbed samples) and the adjacent area just off the trail (2 undisturbed samples) on each transect (Figure 2). A total of 408 soil penetrability point samples were taken in both harvest units, reflecting four points in each transect in the 10 sample trails. There were 34 soil penetrability transects on harvester-cable;

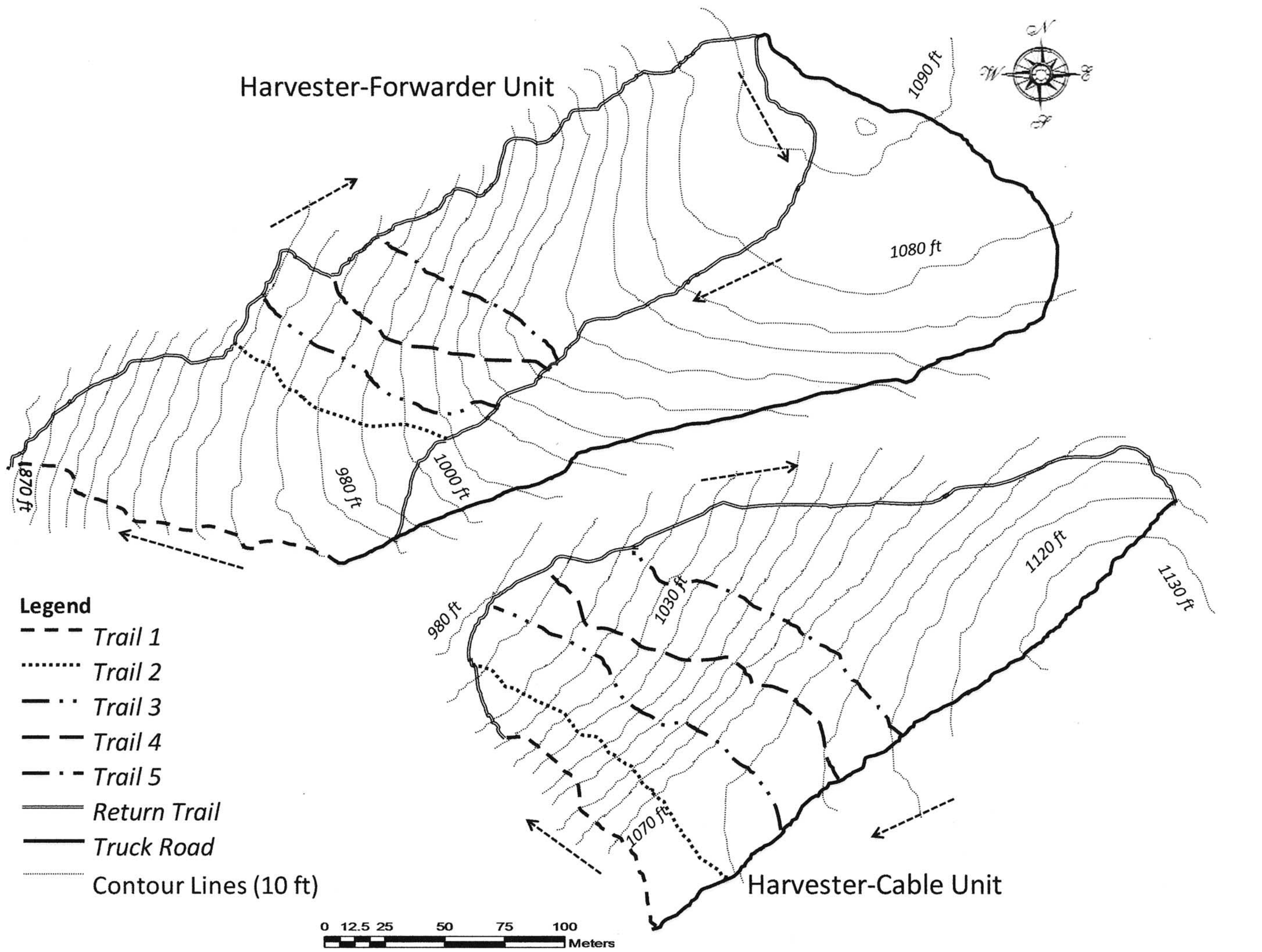

Figure 1. Map of harvest vehicle trails and topography on the study units harvester-forwarder and harvester-cable. The direction of vehicle travel is shown by the arrows; travel on the steep, thinning trails was downhill toward the top of each map, where the main return trails are shown.

on harvester-forwarder there were 38 transects after the harvester pass and another 30 transects after the harvester plus forwarder pass.

A Rimik CP20 cone penetrometer (Kees 2005 describes a very similar model) was fitted with a small cone (12.83-mm diameter and 130-mm^2 area) and used to generate cone index readings in kPa. For ease of subsequent discussion, we refer to these readings as strength measurements. At each sample point, strength measurements were recorded every 25 mm vertically down from the soil surface to a target depth of 400 mm, yielding 16 discrete readings (thus, a total of 6,080 readings for the entire study). A single individual took all measurements to minimize operator-based variability and followed the manufacturer's recommended procedures, which are generally consistent with American Society for Agricultural Engineers (ASAE) standards. To facilitate sampling, slash and surface duff were removed by hand or chainsaw to create a small, level area to position the instrument. Although surface vehicle tracks were evident from compressed slash and used to identify disturbed versus undisturbed sample points, soil compression or displacement appeared minimal, and thus no adjustment was made for the depths of the strength measurements. To evaluate potential effects on soil strength differences, slash depths were recorded where soil strength measurements were taken on harvester-forwarder. Similarly, the local trail slope was recorded at each soil strength transect on both harvest units.

Because soil moisture levels can affect soil strength, five bulk soil samples (~200 g each) were taken (~0–300 mm depth) on each of the sampled trails to assess gravimetric moisture content at the time of the soil strength sampling. These samples were collected every 20 m along each trail, placed and sealed in plastic bags, and then weighed and placed in a drying oven the same day they were collected. Soil moisture content was estimated according to ASTM standard D2216-10. Onsite differences and changes in soil moisture were expected to be minor because all logging activities and strength measurements were completed within a period of 2 weeks of dry weather and because of the proximity of disturbed and undisturbed sample points. Soil strength was measured immediately after one harvester pass on each harvest unit and also immediately after the forwarder pass on harvester-forwarder. Soil strength was not measured after cable yarding on harvester-cable because little or no additional compaction was expected, based on favorable log suspension on this steep unit as well as the results of previous studies of the soil effects of skyline cable thinning in similar young-growth stands in western Oregon (Allen et al. 1999).

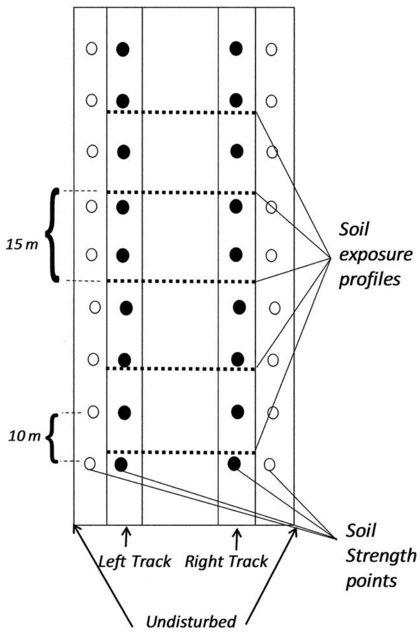

Figure 2. General illustration of transects and sample points for soil strength and soil exposure assessments on the steep harvest trails (not to exact scale).

Statistical analyses were performed using the Statistical Package for Social Sciences (version 15.0). For soil strength data, normality was evaluated using the Shapiro-Wilks W test; with departures from normality observed, differences in soil strength were evaluated using nonparametric tests. Differences between disturbed and undisturbed sites in both units were assessed with Wilcoxon Mann-Whitney tests. These tests were performed with strength data compiled by four depth classes: 25–100, 125–200, 225–300, and 325–400 mm. A one-sample z-test for a binomial proportion was used to compare the observed percent soil exposure with the Oregon Forest Practice Rule limit (10%) for disturbed soils. To interpret and discuss the data sets, comparisons with values of $P \leq 0.05$ were considered statistically significant, except for a Dunn-Sidak correction that yielded an adjusted level (0.0169) for post hoc multiple comparisons.

Results and Discussion

Slope and Area of Steep Trails

Slopes of the individual thinning trails (Figure 1) on harvester-forwarder ranged from 56 to 63%, averaging 58% overall; those on harvester-cable ranged from 61 to 70%, averaging 65%. Spacing of the 10 thinning trails ranged from 18 to 24 m on both units, and GPS data showed that the steep trails (full width, not just tracks) represented 10% of the thinned area on harvester-forwarder and 15% of harvester-cable. The percent area of steep trails is noteworthy because Oregon's Forest Practice Rules specifically state that "Operators shall limit the amount of ground with disturbed soils on steep (60% or greater) or erosion-prone (40% or greater) slopes…to no more than 10% of [these] slopes within the operation area" (Oregon Administrative Rule 629-630-0150). These Rules also require that "Skid trails shall not be located straight up and down steep or erosion prone slopes for a distance exceeding 100 ft [30.5 m] unless effective drainage and sediment filtration can be achieved."

Exposed Mineral Soil

On harvester-forwarder, 7% of the sample points in the transects on the steep, thinned area had exposed mineral soil after harvest. This exposed soil appeared to be related to surface soil displacement from the traffic of the harvester and/or forwarder, and slope. Surface track depressions were present along the trails especially where local slopes exceeded 60%, and some ruts were evident where the local trail slope exceeded 70%. However, the transect data and related field notes show that a high percentage of the trail surfaces remained covered with duff and slash after harvest, a reflection that they probably reduced soil displacement by helping distribute vehicle pressure, keeping the A horizon in place or locally mixed with surface debris or subsoil.

Sample transects on the steep trails on harvester-cable showed that 3% of the sample points had exposed mineral soil after harvest. With manual felling on less steep slopes (25%), Allen et al. (1999) reported low soil disturbance (<2% disturbed soil area) after skyline cable thinning in young Douglas-fir, which showed the benefits of partial to full log suspension. On harvester-cable, the low level of soil exposure likewise appeared to be a direct result of a cable system and site layout that provided good log lift above the ground surface, leaving duff and slash largely intact on all five trails. With only a single vehicle pass by the harvester, surface track depressions were less evident, although some soil displacement (typically, downhill or lateral soil movement of <2 m) was observed where local slopes exceeded 60%.

Guidance for implementing Oregon's Forest Practice Rules (Oregon Department of Forestry 2009) does not specify a method for quantifying disturbed soil. However, if our exposed soil data are assumed to be acceptable, statistical analyses generally confirmed that each harvest unit remained below the aforementioned 10% limit for disturbed soils under the Oregon Forest Practice Rules ($P = 0.046$ and $P < 0.001$ for harvester-forwarder and harvester-cable units, respectively, using a one-sample z-test for proportions). On both units, exposed soil did not extend very far within a trail and more commonly was interspersed with much larger areas of relatively intact duff, slash, and topsoil. Even if some local surface runoff occurred, these conditions would be expected to promote infiltration before the runoff could gain significant volume and erosive power. Oregon's Forest Practice Rules require "cross ditches" (i.e., water bars) to divert drainage water from skid trails on such steep slopes, but on an "as needed" basis to keep surface runoff from carrying sediment into nearby streams (Oregon Department of Forestry 2009). With the limited soil exposure and other disturbance on the study units after harvest, it is likely that cross ditch construction would unnecessarily disturb and expose soils on and near the steep trails, especially given that a heavy, bladed machine (e.g., crawler tractor) would be needed for such construction.

The total area (10 and 15%) and orientation of the steep trails on each harvest unit were at or exceeded the Oregon Forest Practice Rules limit of 10% "disturbed soils" limit and did not conform to the directive to avoid a "straight up and down" orientation. However, the guidance manual for implementation of these rules (Oregon Department of Forestry 2009) defines "disturbed soils" as areas of excavation, soil puddling, and/or soil ruts that exceed 1 ft (30 cm) in depth. Because the soil exposure transects were located only on the steep trails where soil disturbance was most obvious, there is no question that the total exposed soil on each harvest unit was well under the 10% limit for entire harvest units and that other negligible, in-unit soil disturbance would not significantly increase the

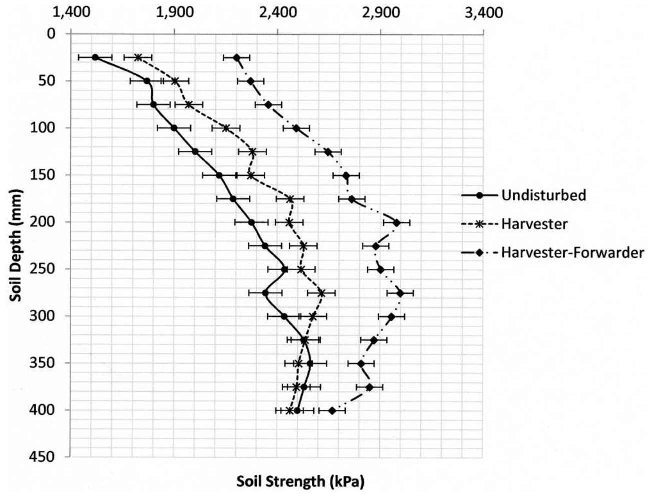

Figure 3. Soil strength (kPa) by depth on and adjacent to the steep trails after harvest vehicle traffic was completed (two passes total) on harvester-forwarder. Horizontal bars represent 1 SE.

total. Similarly, the retention of most duff and slash on the steep trails would be expected to provide for "effective drainage and sediment filtration."

Soil Strength

Figure 3 shows the average soil strength profiles with depth for the steep trails on harvester-forwarder, including those for undisturbed, one harvester pass, and one harvester plus one forwarder pass conditions. For all three sample point strata, the data show the common pattern of increasing strength with depth, with particularly large increases in the initial successive measurements below the soil surface. With the data aggregated into four depth classes (Table 1), soil strength was 19–34% higher than that of undisturbed soil in the upper depth classes (25–200 mm) after a single harvester pass on harvester-cable. With use of an adjusted significance level for multiple comparisons between undisturbed, one harvester pass, and one harvester plus one forwarder pass conditions ($\alpha^* = 0.0169$), no significant difference in soil strength was apparent after the initial harvester pass on harvester-forwarder. However, an additional vehicle (forwarder) pass on harvester-forwarder resulted in soil strength levels that were 33–40% higher than those of undisturbed soil in the upper depth classes (25–200 mm) and 21% higher in-depth class III (225–300 mm). Statistical evidence for a soil strength difference in depth class IV was suggestive but inconclusive with this test.

The moisture content of the soil (dry weight basis) in the steep trails on both units was relatively high, ranging from 30 to 39% among the trails on harvester-cable and from 30 to 36% on harvester-forwarder. Although forest soils often have lower strength when relatively moist and are more prone to general disturbance, the specific relationships between soil moisture and compaction from logging vehicles are complex and may not conform to the common expectation of greater compaction with higher moisture levels (Froehlich and McNabb 1984). Han et al. (2006), for example, found that high soil moisture (near field capacity) during harvest resulted in widely different levels of compaction on two units after a cut-to-length harvest in northern Idaho.

Field notes for local slash levels and slope from the soil strength transects on both units were used to evaluate relationships between soil strength and slash and soil strength and slope. With the thinning of the stands, the harvester operations resulted in about 30% of the steep trails covered in slash accumulations that averaged 23–35 cm in depth. Because the harvester worked downhill on the units, it can be assumed that it traveled over most of these slash mats and that they were substantial enough to disperse the vehicle weight over a larger area and limit the resulting compaction. With the soil strength data stratified into no-slash and with-slash categories, a suggestive difference ($P < 0.055$) was observed only for the upper depth class (25–100 mm) on harvester-forwarder. However, for this depth there appeared to be a notable effect of the slash, with the no-slash sample points showing 39% higher soil strength than the undisturbed soil versus 25% for the with-slash points. Other studies in the region have shown how slash mats created during mechanized, ground-based harvest operations can help limit the degree of soil compaction from logging vehicle traffic, but they also observed some variable results that included little or no benefit from slash on vehicle trails in some locations (Allen 1998, Han et al. 2006, 2009).

Earlier research showed that logging vehicles operating on slopes can have significantly higher dynamic ground pressures than the static values reported by manufacturers (Lysne and Burditt 1983), and we had expected to see some relationship between slope and the observed soil strength levels on the harvest units. However, regression analyses of these data revealed no apparent pattern ($R^2 = 0.0121$ for the harvester-forwarder unit and $R^2 = 0.0006$ for the

Table 1. Median soil strength by depth class in undisturbed areas, after harvester-only (one vehicle pass) and harvester plus forwarder traffic (two vehicle passes) on harvester-forwarder and after harvester-only traffic (one vehicle pass) on harvester-cable.

	Median soil strength (kPa)				Median soil strength:		
Depth class	Undisturbed	Harvester only	P value	Difference (%)	harvester + forwarder (kPa)	P value	Difference (%)
Harvester-forwarder							
I: 25–100 mm	1,671 (606)	1,934 (644)	0.208		2,336 (368)	<0.001	39.8
II: 125–200 mm	2,120 (656)	2,326 (608)	0.226		2,810 (438)	0.001	32.6
III: 225–300 mm	2,478 (656)	2,589 (621)	0.360		3,003 (299)	0.001	21.2
IV: 325–400 mm	2,478 (633)	2,634 (533)	0.757		2,931 (409)	0.039	
Harvester-cable							
I: 25–100 mm	1,489 (549)	1,989 (498)	0.001	33.6			
II: 125–200 mm	1,856 (606)	2,204 (425)	0.051	18.7			
III: 225–300 mm	2,370 (690)	2,423 (578)	0.101				
IV: 325–400 mm	2,667 (479)	2,679 (478)	0.665				

Percent differences between undisturbed and postvehicle pass strength values are shown for differences that were statistically significant (Mann-Whitney tests, using the 0.05 level for harvester-cable and using the 0.0169 level from the Dunn-Sidak correction for harvester-forwarder). Parenthetical values represent the median absolute deviation, a measure of data variability relative to the median value shown (Pham-Gia and Hung 2001).

harvester-cable unit, using simple linear regression procedures) and thus merit no further discussion.

Because soil strength can affect tree and plant root penetration and growth, the observed differences in strength are of interest in their potential effects on forest site productivity. Over the full sample depth (25–400 mm), soil strength on the steep trails on harvester-forwarder after harvest (two vehicle passes) averaged about 2,770 kPa or about 26% higher than that for the adjacent undisturbed soil. For the upper sample depth classes that showed significant differences (25–200 mm) on harvester-cable (one vehicle pass), soil strength averaged about 2,096 kPa, or about 25% higher. Other studies suggest not only that soil strength levels about 2,500 kPa or higher can be growth limiting on a variety of soils (Page-Dumroese et al. 2006), but also that the growth benefits of higher moisture availability in compacted coarser-textured soils may equal or exceed the negative effects of higher soil strength (Gomez et al. 2002).

Although significant differences in soil strength were observed on the steep trails in both study units, the total trail area on both units did not exceed 15% and the in-trail soil strength sampling was purposefully biased toward the location (right and left tracks) where the greatest compaction would be expected. Penetrometer and other compaction measurements in transects across mechanized harvesting trails have shown this pattern in other studies, although some variability also was evident (Allen 1998, Craigg and Howes 2007). Thus, the areal extent where significant soil strength differences occurred is likely to be less than 15% on both units; this area is potentially higher than the aforementioned Forest Practice Rule standard (10%) for soil disturbance steep trails, but it is important to note that the observed soil strength changes and visual characteristics do not represent soil disturbance as defined by excavation, puddling, or rutting. It is also noteworthy that, had the same results occurred on local National Forestlands, they would have been well within the Region 6 standard for soil disturbance (USDA 1998). In addition, other studies of Douglas-fir thinnings with ground-based equipment in the Oregon Coast Range (Miller et al. 2007) suggest that the growth of residual trees near the harvest trails would be unlikely to be negatively affected due to the systematic location and limited extent of the trails.

Conclusions

The harvest operations on the study units differed from more common practices and guidelines for steep slopes in that they used ground-based vehicles and relatively long skid trails located directly up and down the slopes. Although some strength changes and exposed soil were observed, they were relatively limited in degree and areal extent and thereby appeared to be in compliance with regulatory standards and guidelines for both private and national forestlands in Oregon. These positive outcomes appeared to result from several key factors, including dry season operations, no more than two vehicle passes, and a cut-to-length harvest system and operations that added slash to the trails and generally limited ground disturbance. Another important factor, which was not formally evaluated but soon became apparent to the authors during multiple, extended visits to the study sites, was the exceptional skill of the operators of both the harvester and the forwarder. The degree to which this key human factor may influence the results of similar ground-based harvests on steep slopes awaits further study. In addition, extended monitoring of these and similar harvest units would help clarify expectations about potential runoff and erosion from such steep skid trails when relatively large, infrequent storms occur after harvest. Finally, given the limited harvest scale and geographic scope of this study and the current lack of similar research on steep slope harvests with ground-based vehicles, the observed results should not be extrapolated to other harvest operations.

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