SOIL COMPACTION AND DISTURBANCE FROM SKYLINE AND MECHANIZED PARTIAL CUTTINGS FOR MULTIPLE RESOURCE OBJECTIVES IN WESTERN AND NORTHEASTERN OREGON, U.S.A

Marganne M. Allen, Mark Taratoot, Paul W. Adams

ABSTRACT

Soil disturbance and bulk densities were evaluated in several dense conifer stands that were partially cut with mechanized and skyline logging systems on National Forests in western and northeastern Oregon. Some soil disturbance or compaction was observed on all harvest units, but varied widely within and among the units. Local stand and site conditions and harvest planning and implementation probably are important contributors to the observed variation, and highlight the need for careful and intensive sampling schemes to help clarify key differences and trends. Some contrasts between the harvest systems were apparent, however, with the harvester plus forwarder system generally producing more compacted soil area than skyline yarding, although the latter system was generally more costly to plan and operate. The specific effects and environmental and economic significance of the observed disturbance and compaction requires further research, including the evaluation of trade-offs between potential impacts from active versus passive management strategies to accomplish diverse objectives.

KEY WORDS

timber harvest, cable logging, thinning, single-grip harvester, forwarder, environmental impacts, site productivity

INTRODUCTION

Management objectives for federal forest lands in the U.S.A. have changed considerably in recent years (Fedkiw 1997), particularly in the Pacific Northwest region. Major reviews to help direct federal forest policies, such as the Forest Ecosystem Management Assessment Team report (FEMAT) and the Interior Columbia Basin Ecosystem Management Plan (ICBEMP) clearly exhibit these changes, with their focus on such issues as maintaining and improving fish and wildlife habitat and addressing forest health concerns. While timber production remains a consideration on federal lands, its priority has been substantially reduced and timber harvest has been more often viewed largely as a tool for achieving other resource objectives.

Concurrent with these changes in management emphasis has been ongoing development and expanded use of highly mechanized logging systems, including both skyline cable and ground-based systems. Interest in prescribing these systems on federal lands has increased not only because of their growing availability, but also because of perceptions that they are effective in reducing site disturbance and in achieving other multiple resource objectives. Verification of these positive attributes remains somewhat limited, however, and thus detailed analyses of operational results provide valuable data for forest managers and decision makers.

This report offers such findings for some recent partial cuttings conducted with mechanized and cable systems on federal forest lands in Oregon. Although these studies were not specifically designed for a regional comparison, the contrasting sites in northeastern and western Oregon provide an interesting view of the range of conditions and management objectives that can be encountered in the Pacific Northwest U.S.A. The studies focus on an evaluation of soil compaction and disturbance from the harvest operations, which are of concern due to legal mandates for federal lands to maintain site productivity and to protect threatened and endangered aquatic species. Although soil compaction from timber harvest has been studied extensively in the region (Cafferata 1992, Froehlich and McNabb 1984), there has been only limited research on the soil effects of partial cuttings with mechanized and cable systems for multiple resource objectives.

STUDY SITES AND METHODS

Western Oregon

The western Oregon soils research is part of a much larger integrated study, the "Young Stand Thinning and Diversity Project" conducted on the Willamette National Forest of the Oregon Cascade Range (Kellogg et al. 1998). The objective of this parent project is to better understand the environmental and economic effects of thinning young conifer stands for the purpose of increasing stand structural and biological diversity and accelerating the development of late-successional forest habitat. The soils investigation focused on operations conducted in dense, second-growth forest stands comprised primarily of Douglas-fir (Pseudotsuga menziesii), located on the Oakridge Ranger District approximately 20 km northeast of the town of Westfir (Allen 1997).

The skyline harvest units were located in an area of moderately deep, generally well-drained, loamy soils with slopes averaging 25 percent (maximum 60 percent). The conifer stands averaged about 500 stems per ha with a mean diameter at breast height (dbh) of 26 cm. Cutting prescriptions for the stands were: (a) 0.20 ha clearcuts spaced 100 m apart with the rest of the area thinned to 250-270 stems per ha, and (b) heavy thinning to 125-135 stems per ha. The skyline system included a small, trailer-mounted 3-drum yarder and a mechanical slackpulling carriage. Skyline corridors were identified and marked prior to felling, and were spaced 30-45 m apart in both parallel and fan-shaped patterns. Manually felled and processed trees were primarily yarded uphill, using tail trees and a few intermediate supports to provide at least partial log suspension. Yarding occurred from November through August, over dry to wet soils and over a light snowpack in some cases.

The mechanized harvest units were located about 1 km from the cable units in an area of deep, well-drained, loamy to silt loam soils with an average slope of 5 percent. The stands averaged 685 stems per ha with dbh's ranging from 33-58 cm. Because wet weather resulted in high soil moisture conditions that led to the suspension of logging, only one unit was available for post-harvest sampling during the study period. The cutting prescription for this unit was the same as (a) above, i.e., 0.20 ha clearcuts spaced 100 m apart with the rest of the area thinned to 250-270 stems per ha. Felling, processing, and yarding was conducted with a cut-to-length (CTL) system that used a single harvester-forwarder combination. The harvester was a tracked carrier with a boom and hydraulic harvesting head, with a total static ground pressure of 54 kpa. The forwarder was an eight-wheel drive vehicle with "bogie tracks" on the rear tires; front and rear ground pressures were estimated to be 48 and 26 kpa unloaded, and 56 and 72 kpa loaded. During this study the average load and diameter were 82 pieces and 33 cm. Both machines traveled on designated skid trails that were flagged by the operator and spaced about 18 m apart. Delimbing and bucking took place on the skid trail in front of the harvester such that both it and the forwarder traveled over many tops and limbs.

Because the CTL units had been previously logged, very likely with heavy tractors, it was important to characterize soil compaction and disturbance levels prior to the new cuttings on these units. The skyline units also had been logged, but this was done using cable or other methods that left no apparent disturbance or compaction. Soil compaction was evaluated with a dual-probe, nuclear densimeter that allowed direct field measurement of soil bulk densities at 10 and 20 cm depths. Soil disturbance levels and areal extent were assessed concurrently with the density sampling, using categories that included undisturbed, compacted, mixed, exposed, scalped and rutted. In addition, sample points on skid roads were identified as either rut, berm, or center.

On the skyline units, soils were assessed in flagged cable corridors prior to felling. Within 45 m of the landing, bulk density sample plots were spaced 15 m apart along the corridor to more intensively examine the zone where the greatest changes were expected from logging; beyond 45 m the plots were spaced 60 m apart. Each plot consisted of 3 bulk density samples, the first taken at plot center, the second 3 m from the center (this also was the edge of the corridor clearing), and the third halfway to the next cable corridor or a maximum of 30 m. The second and third sample points were on an azimuth perpendicular to the corridor, with the direction of these azimuths alternating to opposite sides down the corridor.

Two soil sampling schemes were used on the CTL units. The first located plot centers by randomly selecting points on a full grid covering each unit, then using a random azimuth and distance offset from the selected grid points; three sets of soil measurements were taken on equally spaced azimuths (120 degrees apart) radiating 6 m out from each plot center. The second sample scheme consisted of a subsample of old skid trails for measurement, which were identified as the nearest trail section encountered beyond the 6 m radius of the first type of sample plot. After testing for significant differences using standard statistical methods, compaction and disturbance data for both the skyline and CTL units were converted to areal estimates.

Northeastern Oregon

Like the western Oregon research, this investigation is part of a larger study of a series of partial cuttings on the Wallowa-Whitman National Forest in the Blue Mountains of Oregon (McIver 1998). The objective of the larger project is to evaluate the economics and environmental effects of harvest treatments designed primarily to reduce fire hazards in overstocked stands containing large amounts of dead, dying, and down trees. The study was conducted on Limber Jim ridge, on the La Grande Ranger District about 15 km southwest of the city of La Grande. Prior to harvest, the stands contained diverse species typical of the higher elevation, mixed conifer forests of the region, including lodgepole pine (Pinus contorta), subalpine fir (Abies lasicarpa) and western larch (Larix occidentalis).

Six harvest units (2.6-9.7 ha) were studied, with soils generally moderately deep, well drained silt loams developed in a surface mantle of volcanic ash, with a few patches of cobbly loams that are shallow to basalt bedrock. Slopes ranged from nearly flat to about 20 percent. Stand densities ranged from 240 to 410 stems per hectare, with average diameters from 24 to 29 cm dbh. Fuel loadings in these stands were among the highest observed in this general area, with and average loading of 125 tonnes per hectare and a maximum of 180 tonnes per hectare. Although specific prescriptions varied somewhat with individual stand conditions, the general objective was to substantially reduce the standing and down material over 2.4 m in length and between 10 and 40 cm, large-end diameter. Green trees with over 30 percent crown were left (except where they directly interfered with harvesting), as well as standing and down dead wood over 40 cm in diameter.

Three harvest units were skyline yarded using a swing yarder with a 13 m tower and a motorized, slackpulling carriage (Doyal 1997). Skyline corridors were identified and marked prior to felling and were oriented in both parallel and fan-shaped patterns depending on terrain and landing location. Uphill, downhill, and relatively flat span yarding occurred, using tail trees and some intermediate supports to to provide at least partial log suspension. Yarding began after snowmelt allowed road access to this area above 1500 m elevation, and extended from June to October, with soil moisture levels declining significantly over this general dry season.

All felling and bucking was conducted with a tracked hydraulic excavator equipped with a 9m boom and single grip harvesting head. The harvester made single, parallel passes about 45 m apart throughout each harvest unit, cutting, processing, and bunching the stems for subsequent yarding along identified corridors. Tops and limbs generated by the processing were oriented in the direction of machine travel to help protect the soil from disturbance and compaction. Forwarder yarding followed on the harvester trails, whereas the wider spacing of skyline corridors (about 90 m apart) usually resulted in a harvester-only trail between corridors. Ground-based yarding was conducted on three harvest units directly adjacent to the skyline units, using an 11 tonne, six-wheel forwarder.

Due to an equipment problem, soil bulk densities were not measured prior to harvest. This was considered not a serious limitation because the study area generally had not been affected by historical logging. Post-harvest soil effects were estimated with a stratified sampling design that considered: a) yarding corridors or trails, b) areas between corridors or trails and c) areas that appeared undisturbed. Sample plots for corridors and trails were located every 38 m, and in forwarder trails separate measurements were taken in trail ruts and centers. Areas between trails were located in a random direction from each trail plot. At each sample plot a visual assessment of soil displacement was made, using the USDA Forest Service Region 6 standard: 9.3 square meters of displaced soil at least 1.5 meters wide, observed within 1.5 meters of the plot. Soil compaction was determined by soil bulk density measurements with a nuclear densimeter, using samples from areas between trails that had no apparent disturbance to establish a baseline density.

RESULTS AND DISCUSSION

It is important to preface the discussion of observed soil effects by noting that soil disturbance alone does not necessarily result in reduced site productivity or other environmental impacts. In fact, certain types of disturbance (e.g., soil mixing) can sometimes have a positive effect on forest regeneration, at least in the near term. Thus, detailed classification of soil disturbance is very important, and should include more specific distinction between altered soil characteristics and documented damage to forest productivity or other resource attributes (Abeels 1995). In our studies, the collection of both soil disturbance and bulk density data was intended to provide such distinction, particularly given the documented relationship between soil density and seedling and tree growth in the Pacific Northwest U.S.A (Cafferata 1992, Froehlich and McNabb 1984).

Western Oregon

The mechanized harvest units showed significant areas of visible soil disturbance (13-27 percent) from historical logging, and a notable proportion of this area (6-10 percent) had significantly higher bulk densities ($p<0.10$) than locations judged to be undisturbed (Table 1). The disturbed areas were primarily old skid trails, which were evident from visible ruts and berms as well as local changes in the productivity and type of ground vegetation. Soil bulk densities in the old skid trails were generally at least 10 percent higher than in undisturbed areas, although the densities varied considerably among trail ruts, center, and berms. The observed area, degree, and persistence of compacted soil conditions support general concerns about potential site productivity impacts, particularly when there are multiple harvest entries that may add to the extent or degree of compaction.

Although the operators used designated trails and were instructed to locate these trails on old trails wherever possible, the area of both disturbed and compacted soil substantially increased after the harvester and forwarder operations (Table 1). It is likely that few of the old, randomly oriented trails were suitable for use with the systematic, mechanized harvest. In addition, the 60-foot trail spacing needed to accommodate the reach of the harvester would be expected to lead to at least 12-13 percent of the harvest area covered in machine trails. The forwarder traffic probably was the most important contributor to the observed soil disturbance and compaction, because the harvester typically made only 1-2 passes over a given trail and the duff generally remained intact. In addition, some selected soil measurements (Allen 1997) revealed only small and statistically insignificant differences in bulk density between harvester-only trails and either undisturbed areas or old skid trails.

After both harvester and forwarder traffic, soil bulk density in the machine trails was about 12 percent higher than in the undisturbed areas. Soil densities did vary across the skid trails, generally being highest in the ruts and trail centers. Interestingly, the recent mechanized harvest traffic apparently did not significantly increase the density of old trails that were reused, although there was only limited sampling of this specific situation. In addition to the notable persistence of soil strength associated with the increased bulk densities from the historical logging, this may reflect differences in vehicle passes, ground pressure and disturbance between the heavy vehicles and large log sizes in the old logging and the newer equipment and smaller timber.

As mentioned, historical logging on the skyline units left no apparent legacy of soil disturbance and compaction. After the recent skyline logging, soil disturbance and compaction also was very limited, with disturbance not exceeding 2 percent of the harvest unit areas and no statistically significant differences ($p<0.10$) in bulk density observed between disturbed and undisturbed areas (Table 1). The latter was true even for samples from the center of the cable corridor, where slightly higher densities were generally observed.

Soil disturbance clearly was concentrated in the cable corridors; no disturbance was observed on any sample transects between corridors. Positive relationships were observed between total soil disturbance and both cable road length and wood volume yarded, likely due to more variable log suspension and generally increased opportunities for disturbance with more log turns. The most common disturbance was mixing of mineral and organic soil horizons, which likely has little or no negative impact. Areas of exposed and rutted soil were small, discontinuous and usually occurred within 150 feet of the landing, which similarly alleviates concerns about potential erosion and sedimentation problems.

The soil disturbance and compaction observed after the mechanized logging raises some important questions about potential effects on site productivity. Although relatively extensive in area, soil disturbance appears to be a lesser issue on these generally level sites where significant soil displacement or runoff and erosion are unlikely. Impacts of compaction on the productivity of residual trees in thinned stands have been documented in the region (Cafferata 1992, Froehlich and McNabb 1984), but such evaluations are complicated by the confounding effects of stem release by the thinnings and the specific area and proximity of compaction relative to individual residual trees. The observed degree of compaction (12 percent increase in bulk density) on these sites also is at the low end of the range of levels that can produce discernible effects on tree growth. Thus, a very carefully designed monitoring effort that includes several years of post-harvest soils and tree growth data are needed to provide a clearer picture of the specific effects of compaction, particularly at the stand level.

Northeastern Oregon

Both the harvester plus forwarder and the harvester plus skyline logging systems produced significant areas of soil disturbance (in this case defined primarily as displacement) on the harvest units, although these levels varied from 5 to 43 percent (Table 2). Some disturbance on all the units was expected because all experienced traffic from the harvester operations, although most disturbance was concentrated in the skyline corridors and forwarder trails. The relatively high disturbance seen on two of the skyline units (23-43 percent) was somewhat surprising, but on Unit 16 with the highest disturbance it may be partly explained by the fact that this unit was yarded in a distinct fan pattern, which often leads to greater soil disturbance near the landing.

On this specific unit there also was some concern that the limited sampling intensity may have biased the average unit disturbance towards a high value.

Unit 11, which was relatively flat, showed the least areal disturbance with both the forwarder and skyline systems (Table 2); the latter result may be due to the relatively low corridor density on this site, as well as the extensive use of intermediate supports. Although small in area, disturbance on this skyline unit was often in the form of relatively deep ruts along the cable corridors. On the forwarder units, the heavy slash generated by the harvester probably helped limit soil disturbance from the forwarder traffic by providing some additional physical protection. This unit had the highest wood volumes, which probably contributed to both heavy slash and much natural woody debris and duff on the soil surface.

Neither the harvester plus forwarder nor the harvester plus skyline logging systems produced statistically significant differences ($p<0.10$) in soil bulk density among the three sample strata (i.e., yarding corridor, between corridor, undisturbed) on any of the harvest units (Table 2). This is not to say that soil compaction did not occur; in fact, the large variability in bulk density values observed in both disturbed and undisturbed soil sample populations very likely helped mask the appearance of significant differences using standard methods for statistical comparison. More intensive soil sampling of each strata or re-measurement of the same sample points before and after harvest probably would have improved our ability to distinguish some actual differences, but also would have added significant time and expense due to the size and number of harvest units.

The occurrence of some compaction, at least on the forwarder units, is suggested by regression analysis of soil bulk density values with distance from the landing. Such analysis shows the expected association, i.e., higher densities in trails closest to the landing (Figure 1) where more vehicle passes would likely result in greater compaction than farther out on the logging unit. Another estimate of compacted area on the harvest units, using the USDA Forest Service Region 6 standard, is shown in Table 2 (parenthetical values). Although the statistical validity of these values is questionable, they do follow the expected pattern, i.e., there appears to be little or no compaction on the skyline units whereas the forwarder units show some higher compaction levels.

Although soil compaction appeared to be relatively limited on most of the study units and thus not a major concern, the observed degree of soil disturbance raises some significant questions about potential effects on- and off-site. Some of the answers may be provided by additional studies now underway to assess the effects of the harvests on soil biota, as well as on the growth of the residual forest stands (McIver 1998). Because some concerns were raised about possible erosion from the harvest units, a series of photo points was used to identify visual evidence of sediment transport beyond the lower boundaries of each harvest unit. This evaluation showed that a small amount of sediment was produced during the year after harvest, but it remained within the units and was highly localized, except in skyline corridors and along roads, where some very limited off-unit movement was seen. In no case did any sediment reach a defined stream channel.

The experience on these sites revealed both environmental and economic trade-offs between the two harvest systems that were studied. In general, the harvester plus forwarder system produced more soil compaction, whereas the harvester plus skyline system produced more soil disturbance. The high operating cost of the skyline system also contributed to an average net revenue loss of US$1183 per hectare versus a net income of US$2748 with the forwarder system (Drews et al. 1998). Both harvest systems were successful in achieving reduced fire hazards by removing at least 50 percent of the pre-harvest fuels (McIver 1998). Thus, it is important to also consider the environmental and economic trade-offs between the harvest treatments and the potential impacts of tree mortality and wildfire, including both the lost value of wood products as well as the potentially serious erosion and sedimentation that may occur in mountainous terrain. The latter is an especially important consideration where water resources are a major concern, as some of the highest rates of erosion and sedimentation ever recorded in the Pacific Northwest have been observed following wildfire (Helvey 1980).

CONCLUSIONS

Both mechanized and skyline harvest systems were capable of producing significant soil disturbance or compaction when used for partial cut prescriptions in dense conifer stands for multiple resource objectives in western and northeastern Oregon. Not surprisingly, the harvester and forwarder systems generally produced greater compaction than skyline yarding. However, both compaction and disturbance varied considerably among harvest units, which suggests the important influence of local site conditions as well as of the harvest planning, layout, and implementation. High variability among the compaction and disturbance measurements also shows the importance of sampling design and intensity for monitoring and research programs to clearly evaluate harvest effects. Moreover, additional research is needed to more carefully identify the specific effects of harvesting-related soil changes on other important forest resources, particularly soil disturbance that encompasses many types of changes that are capable of producing positive, negative, neutral or complex effects.

Clearly, modern mechanized and skyline harvest systems are not a panacea for avoiding soil disturbance and compaction, but they do show promise in reducing the area and degree of these changes, particularly when carefully planned and implemented. Where soil compaction remains significant after historical or current harvest, soil tillage with equipment suitable for challenging forest conditions has been shown to be a viable option for ameliorating the compacted condition (Andrus and Froehlich 1983) in major trails and landings that will not be soon used again. In addition, some limited site impact may be a reasonable trade-off in efficiently achieving other benefits of forest management, which can include non-economic values and reducing the risk of events (e.g., wildfire, insect and disease outbreaks) that can result in substantially greater environmental and economic impacts.

REFERENCES CITED

Abeels, P.F.J. 1995. General implications of mechanization in soil environmental conditions. p. 196-208 in: Proc. Council on Forest Engineering, 18th Annual Meeting, June 5-8, Cashiers, North Carolina. College of Forest Resources, North Carolina State Univ., Raleigh.

Allen, M.M. 1997. Soil compaction and disturbance following a thinning of second-growth Douglas-fir with a cut-to-length and a skyline system in the Oregon Cascades. Master of Forestry paper. Forest Engineering Dept., Oregon State Univ., Corvallis. 105p.

Andrus, C.W. and H.A. Froehlich. 1983. An evaluation of four implements used to till compacted forest soils in the Pacific Northwest. Research Bulletin 45. Forest Research Laboratory, Oregon State Univ., Corvallis. 12p.

Cafferata, P. 1992. Soil compaction research. p. 8-22 in A.E. Skaugset, ed., Forest soils and riparian zone management: The contributions of Dr. Henry A. Froehlich to forestry. Forest Engineering Dept., Oregon State Univ., Corvallis.

Doyal, J.A. 1997. The Limber Jim case study. Master of Forestry paper. Forest Engineering Dept., Oregon State Univ., Corvallis. 112p.

Drews, E., B. Hartsough, J.A. Doyal and L.D. Kellogg. 1998. Comparison of a forwarder CTL and skyline yarder CTL system in a natural, eastern Oregon forest. In: Proc. Council on Forest Engineering, 21st Annual Meeting, Vancouver, British Columbia. Council on Forest Engineering, Corvallis, OR.

Fedkiw, J. 1997. The Forest Service's pathway toward ecosystem management. J. Forestry 95(4):30-34.

Froehlich, H.A. and D.H. McNabb. 1984. Minimizing soil compaction in Pacific Northwest forests. p. 159-192 in: E.L. Stone, ed., Forest soils and treatment impacts. Proc. 6th N. Am. Forest Soils Conf. Univ. Tennessee Conferences, Knoxville.

Helvey, J.D. 1980. Effects of a north central Washington wildfire on runoff and sediment production. Water Resources Bulletin 16(4):627-634.

Kellogg, L.D., G.V. Milota and B. Stringham. 1998. Logging planning and layout costs for thinning: Experience from the Willamette Young Stand Project. Research Contribution 20. Forest Research Laboratory, Oregon State Univ., Corvallis. 20p.

McIver, J. 1998. Economics and environmental effects of fuel reduction at Limber Jim. BMNRI-TN-10. Blue Mountains Natural Resources Institute, La Grande, Oregon. 12p.

Table 1. Soil disturbance and compaction before and after mechanized and skyline harvesting, Willamette National Forest, Oregon, U.S.A.

Harvest Unit	Treatment	% Area Disturbed[a]	% Area Compacted[b]
81	Pre-New Harvesting	27	6
82	Pre-New Harvesting	13	10
82	Post-Harvester & Forwarder	38	31
86	Post-Skyline Yarding	0.9	0
88	Post-Skyline Yarding	1.8	0
89	Post-Skyline Yarding	0.4	0

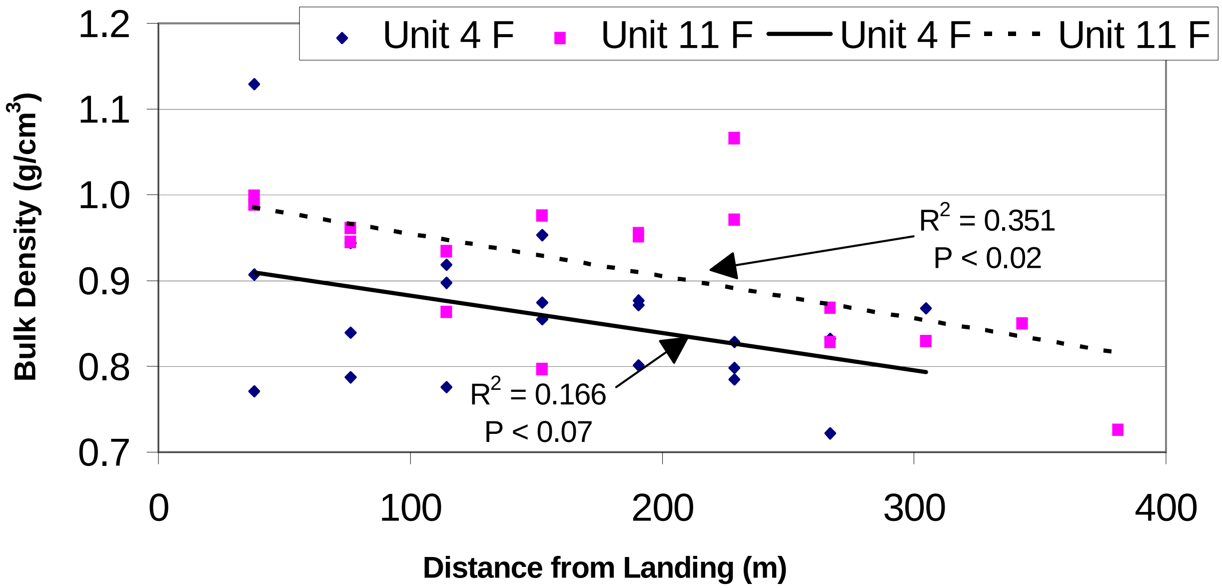
[a]old or new harvest-related disturbance
[b]significantly different ($p<0.10$) bulk densities between disturbed and undisturbed areas

Table 2. Soil disturbance and compaction before and after mechanized and skyline harvesting, Wallowa-Whitman National Forest, Oregon, U.S.A.

Harvest Unit	Treatment	% Area Disturbed[a]	% Area Compacted[b]
4-F	Post-Harvester & Forwarder	8	0 (7)
11-F	Post-Harvester & Forwarder	5	0 (32)
16-F	Post-Harvester & Forwarder	18	0 (3)
4-S	Post-Harvester & Skyline Yarding	23	0 (1)
11-S	Post-Harvester & Skyline Yarding	5	0 (0)
16-S	Post-Harvester & Skyline Yarding	43	0 (0)

[a]USDA Forest Service Region 6 standard for soil displacement (see text)
[b]significantly different ($p<0.10$) bulk densities between disturbed and undisturbed areas; amounts in parentheses are non-statistical estimates based on observed individual density measurements that exceeded the USDA Forest Service Region 6 standard for ash-derived soils (i.e., a 20 percent difference in bulk density compared with undisturbed soils)

Figure 1. Relationships between soil bulk density and distance from landing on two partial cut units logged with a harvester and forwarder, Wallowa-Whitman National Forest, Oregon, U.S.A.



THE AUTHORS

Marganne Allen is a Monitoring Specialist, Forest Practice Program, Oregon Dept. of Forestry, Salem; Mark Taratoot is a Research Assistant and Paul Adams is a Professor and Extension Specialist, Forest Engineering Dept., Oregon State Univ., Corvallis.

REFERENCE CITATION:

Allen, M.M., M. Taratoot and P.W. Adams. 1999. Soil compaction and disturbance from skyline and mechanized partial cuttings for multiple resource objectives in western and northeastern Oregon, U.S.A. p. 107-117 in: J. Sessions and W. Chung (eds.), Proceedings of the International Mountain Logging and 10th Pacific Northwest Skyline Symposium, 28 March-1 April 1999, Corvallis, Oregon. Forest Engineering Dept., Oregon State University, Corvallis.