AN ABSTRACT OF THE PAPER OF

DAVID ARMLOVICH

for the degree of Master of Forestry in Forest Engineering presented on February 23, 1995.

Title: Soil Compaction Study on a Cut-To-Length Mechanized Harvesting System

Abstract approved: Loren D. Kellogg

Loren D. Kellogg

This study looked at the soil compaction effects resulting from a cut-to-length harvest system on an area in the western Cascade Range of Oregon. The cut-to-length harvest system is a mechanized system in which trees are fell, delimbed, and bucked into short log lengths by a mechanical harvester. Logs are then picked up and carried to a landing area by a forwarder. The trails created by the harvester are typically also used by the forwarder.

On this area, the locations of the equipment trails were laid out in advance of logging operations by the logging contractor. Equipment use of the trails was monitored and mapped. Trails were then divided into stratums based on the number of equipment passes. Stratum categories used were 1-4, 5-6, 7-8, 9-12, 13-20, 21-29, and 30+ equipment passes. Soil bulk density was determined by pass stratum using a single probe nuclear densiometer. Density measurements were taken at depths of 0-4, 0-8, and 0-12 inches. At each measurement

point additional measurements made were: slope, O horizon depth, post harvest slash depth, slash quantity, and average slash size. Slash quantity and average slash size were ocular estimates categorized using index values.

To estimate the change in soil bulk density, background density was estimated from a grid of measurement points placed on undisturbed areas over the entire unit.

Compaction was found to increase significantly in areas with four or fewer passes, then remain relatively constant in areas up to at least twenty passes. After thirty or more passes, an increase in compaction was again noted. Density increases over undisturbed were greatest in the upper 4 inches of the soil surface, increasing 20 percent after four or fewer passes and 28.6 percent after thirty or more passes.

The values for slash parameters were greatest for the 1-4 stratum and least for the 30+ stratum. Mean values for the slash parameters for the 5-6, 7-8, and 9-20 pass stratums are not statistically different but in general, there was a trend of decreasing mean values for slash parameters with increasing number of equipment passes. Regression analysis showed no association with slope, O horizon depth or any of the slash parameter values. Only a root value of number of equipment passes was significant though r-squared values were low.

Total percentage of area covered by equipment trails was 23.2 percent.

Soil Compaction Study

on a Cut-To-Length

Mechanized Harvesting System

by

David Armlovich

A Paper submitted to
Department of Forest Engineering
College of Forestry
Oregon State University

In partial fulfillment of the
requirements for the degree of
Master of Forestry

February 23, 1995

APPROVED:

Loren D. Kellogg

Dr. Loren D. Kellogg, Major Professor
Forest Engineering

William A. Atkinson

Dr. William A. Atkinson, Department Head
Forest Engineering

Paper presented to graduate committee February 23, 1995.

Acknowledgments

I would like to acknowledge the assistance I received from Pete Bettinger and Earl Eckley. This project could not have been accomplished without their assistance. I would further like to thank Professor Loren Kellogg for his patience in awaiting for completion of this paper. Lastly, I would like to thank the U. S. Forest Service for giving me the opportunity to attend Oregon State University.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. Introduction

As the supply of old growth timber decreases, especially in the Pacific Northwest, there is an increasing shift toward younger, second growth forests (Sessions et al. 1990). The small diameter and uniform size of these second growth stands are well suited to mechanized harvesting (Kellogg and Brink 1992). According to Bettinger et al. (1993), approximately 60 percent of the commercial timberland in western Oregon is suitable for various types of in-woods mechanized equipment.

Mechanized harvesting operations as defined by Kellogg et. al. (1992) are:

> "Operations with at least one single or multi-function machine for manufacturing (felling, delimbing, bucking or chipping), or operations where trees or logs are placed in bunches prior to primary transport, or operations where primary transportation is able to handle multiple stems."

There are several advantages that mechanized harvesting can offer over conventional ground-based harvesting systems including more consistent and higher quality end products, smaller crew sizes and a safer work environment (Jarmer and Kellogg 1991). These advantages when combined with potentially higher production rates may result in more economical operations when compared to conventional harvesting despite higher capital outlays for equipment. There are mechanized harvest systems that can also address environmental concerns relating to maintaining site productivity through leaving tree limbs and tops in the woods as a nutrient base, reducing truck road density and minimizing landing size.

Most mechanized harvest systems fall into one of three categories: whole-tree, tree-length or cut-to-length systems (Kellogg et al. 1993). With a whole-tree system, trees are typically felled with a swing-boom or tree-to-tree feller-buncher. The whole tree is then skidded to a landing with limbs and top attached, usually with a grapple or clam-bunk skidder. At the landing they are mechanically delimbed and may be cut into log lengths. Tree-length systems are similar to whole-tree except that the tree is delimbed and the top removed in the woods with a machine that has a processing head. With the cut-to-length system, trees are felled, delimbed and cut into short log lengths in the woods, usually with a swing-boom machine. The logs are then gathered and carried to roadside decking areas with a forwarder.

Most mechanized harvest systems use equipment that is larger and heavier than that used in traditional skidding operations. The increased size of equipment used with mechanical harvesting systems may result in different degrees of site impacts when compared to traditional skidding operations. Study and evaluation of the impacts resulting from mechanized harvesting systems is needed. Impacts of particular concern are the residual stand damage in partial cuts, the effects on soils (compaction, displacement, puddling and surface erosion - U.S. Forest Service 1990), the areal extent of the soil impact and the effects of compaction on tree growth.

1.1. Objectives

This study evaluated some physical soil effects from a cut-to-length harvest system used in a commercial thinning. Specific goals of this study were:

1. Measure soil compaction resulting from a cut-to-length harvesting system related to the following variables: ground slope; post-harvest depth of litter and organic layer (O horizon); post-harvest depth, quantity and size of slash in the equipment trails; and number of machine passes.
2. Compare soil compaction that occurs after logging to background (undisturbed) levels.
3. Determine the percent of area impacted by harvester and forwarder trails in relationship to the number of equipment passes and degree of compaction.

1.2. Scope

This is an observational field study that examines the soil effects on one site with logging machines, equipment trail locations, and other operational factors controlled by the logger. Field measurements were made approximately one month after logging was completed. Results reported in this paper are limited only to this area in Western Oregon.

2. Literature Review

Soil compaction has long been recognized as a problem in agricultural and forest environments. Soil compaction can be defined as the densification of soils by the application of vibration and pressure to produce packing of soil particles and aggregates (peds and clods). As reported by Adams and Froehlich (1981) many studies have shown that compaction is unfavorable to plant growth. Root penetration is impeded in soils of high density due to the high strength soils offering physical resistance to penetration. In addition, decreased porosity of compacted soils may decrease the supply of water, air, and nutrients to plants. Decreased ability for water to infiltrate the soil may also lead to increased surface runoff and consequent soil erosion.

The primary factors influencing the degree of compaction are the amount and type of compactive energy applied (static and dynamic), soil texture and structure, the depth and nature of the surface litter, and the soil moisture content (Adams and Froehlich 1981). Forest soils in the Pacific Northwest due to high organic-matter content and other inherent properties are particularly susceptible to compaction (Froehlich and McNabb 1984). It can be concluded through review of literature on soil compaction that the interaction of the primary factors cause a wide range of results both within and between studies. Most of the studies completed have dealt with the effects of rubber-tired skidders, crawler tractors, and to some extent, low ground pressure torsion-suspension skidders. Few studies have been done on the effects of equipment used in "mechanized" harvesting. This literature review focuses on those studies that included equipment used for "mechanized" harvesting. Also reviewed was literature that evaluated compaction as influenced by multiple equipment passes, driving on slash, compaction across the trail profile, comparisons between different types of equipment with different degrees of ground pressure, the areal extent of soil effects, and the effects compaction on tree growth.

2.1. Mechanized Harvesting Studies

McNeel and Ballard (1992) analyzed stand and soil impacts resulting from use of a cut-to-length harvest system. Their study took place in a commercially thinned Douglas-fir stand in northwestern Washington. Logging equipment included a harvester with a boom-mounted, single-grip harvesting head and a forwarder. Soils were classified as sandy loam.

Trail spacing averaged approximately 85 feet (26 m) but was highly variable. Trails were stratified as either main "heavily traveled" or short "lightly traveled" for purposes of measuring soil compaction. Control measurements were taken

9.8 feet (3 m) to the side of the track. Compaction as determined by soil bulk density measurements were taken at depths of 3.0 to 4.9 inches (7.5 to 12.5 cm), 6.9 to 8.9 inches (17.5 to 22.5 cm), and 10.8 to 12.8 inches (27.5 to 32.5 cm) using the soil core method. A summary and comparison of soil compaction measurements is shown in Table 2-1.

TABLE 2-1. (after McNeel and Ballard 1992) Summary and comparison of soil compaction measurements by trail type on a coarse fragment-free basis and percent change over control (background).

SOIL LAYER (inches)	AVERAGE BULK DENSITY (g/cc)	% CHANGE OVER CONTROL
LIGHTLY TRAVELED CONTROL		
3.0 to 4.9	0.751 (0.150)	
6.9 to 8.9	0.825 (0.215)	
10.8 to 12.8	0.947 (0.221)	
LIGHTLY TRAVELED		
3.0 to 4.9	0.940 (0.215)	+25.2% **
6.9 to 8.9	0.996 (0.293)	+20.7% *
10.8 to 12.8	1.071 (0.227)	+13.1% ns
HEAVILY TRAVELED CONTROL		
3.0 to 4.9	0.714 (0.178)	
6.9 to 8.9	0.818 (0.216)	
10.8 to 12.8	0.865 (0.257)	
HEAVILY TRAVELED		
3.0 to 4.9	0.854 (0.212)	+19.6% *
6.9 to 8.9	0.920 (0.170)	+12.5% ns
10.8 to 12.8	0.987 (0.171)	+14.1% ns

Standard deviation in parenthesis
** Significantly different at .05 confidence level
* Significantly different at .10 confidence level
ns No significant difference at the .10 confidence level

Their results show that increases in density over background are highest at the 3.0 to 4.9 in. level for both the lightly and heavily traveled. Increases over background ranged from a high of 25.2 percent in the lightly traveled stratum at 3.0 to 4.9 in. level to a low of 12.5 percent at 6.9 to 8.9 in. level in the heavily traveled stratum.

McNeel and Ballard, based on transects of the study area, reported that 13.02 percent of the area was in lightly traveled trails and 6.67 percent of the area was in heavily traveled trails for a total of 19.69 percent (std. dev. = 7.63 percent). No estimate was given for the percent of area in roads and landings.

Zaborske (1989) studied a mechanized harvest operation on volcanic ash soils in eastern Oregon. The change in density and percent of area impacted by two feller-bunchers and two grapple skidders were measured. Density measurements were made after 1 to 5 and 6 to 10 passes by the feller-buncher and; 1 to 4, 5 to 8, and 50+ passes by the skidder. Depths of density measurements were 0 to 4, 0 to 8, and 0 to 12 inches (0 to 10.1, 20.3, and 30.5 cm). Slash depth at each sample point was also measured. Soil moisture at the time of logging was low. Results of Zaborske's sampling are shown in Table 2-2.

Zaborske found a significant difference in density between before logging and after 1 to 5 and 6 to 10 passes by the feller-buncher. There was no significant difference between the 1 to 5 and 6 to 10 passes thus he combined them into one stratum. The lack of a significant difference between the two stratums would indicate that the majority of compaction created by the feller-buncher occurred within the first few passes.

No significant difference was found between 1 to 10 passes by the feller-buncher and 1 to 4 passes by the skidder however there were significant differences between 1 to 4, 5 to 10, and 50+ passes by the skidder.

TABLE 2-2. (after Zaborske 1989) Mean bulk density by pass stratum by measurement depth and percent change over background.

SOIL LAYER (inches)	AVERAGE BULK DENSITY (g/cc)	% CHANGE OVER BACKGROUND
BEFORE LOGGING		
0-4	0.699 (0.065)	
0-8	0.690 (0.055)	
0-12	0.651 (0.063)	
AFTER FELLER-BUNCHER		
0-4	0.717 (0.064)	+2.56%*
0-8	0.750 (0.057)	+8.73%
0-12	0.708 (0.062)	+8.81%
AFTER SKIDDER, 1-4 PASSES		
0-4	0.694 (0.074)	-0.69%**
0-8	0.735 (0.075)	+6.60%
0-12	0.712 (0.078)	+9.34%
AFTER SKIDDER, 5-8 PASSES		
0-4	0.796 (0.064)	+13.95%
0-8	0.799 (0.057)	+15.84%
0-12	0.780 (0.081)	+19.83%
AFTER SKIDDER, 50+ PASSES		
0-4	0.874 (0.058)	+25.00%
0-8	0.854 (0.039)	+23.81%
0-12	0.887 (0.108)	+36.30%

Standard deviation in parenthesis
Significance level of difference <.01 except as noted below
* significance = .11
** significance = .40

Percent of area in each stratum is shown in Table 2-3. Approximately 54.5 percent of the area was in skid trails as determined using line transects. This is quite high when compared to other studies.

TABLE 2-3. (after Zaborske 1989) Percent of area in each category of disturbance area.

STRATUM	**PERCENT OF AREA IMPACTED**
NO DISTURBANCE	45.5% (18.8)
AFTER FELLER-BUNCHER ONLY	6.7% (8.8)
AFTER SKIDDING 1-4 PASSES	23.0% (11.8)
AFTER SKIDDING 5-8 PASSES	12.4% (6.4)
AFTER SKIDDING 50+ PASSES	12.4% (14.8)

Standard deviation in parenthesis

In looking at the affect of slash on density, Zaborske found that based on regression analysis, slash depth was a significant variable. As slash depth increased, predicted density decreased within the same category of machine passes.

Wronski (1984) compared the impacts of a Volvo 971 forwarder with a "bogie" axle and up to a 15 ton load, with a John Deere 540 skidder. The comparison was based on soil compaction and disturbance in a winter thinning operation in western Australia. Soils ranged from gravely clay loam to gravely loam. His conclusions were that both machines caused the same degree and areal extent of compaction (within the trail). The skidder required approximately six times more passes to remove the same volume of logs. He also found based on measurements of penetrometer resistance that soil compaction extended up to 0.75 m laterally from the wheel tracks.

Omberg (1969) looked at the formation of tracks made by forwarders on forest soils in Sweden. His conclusions were that the depth of the tracks were dependent on ground conditions (soil type, moisture content, and reinforcement), type of vehicle (weight, track or wheel), total transported weight, and the amount of slash. The two factors of primary importance were stated to be ground conditions and the amount of transported weight. He states that the amount of slash is also of great importance. His results show a significant decrease in the degree of sinkage when driving over a "normal" amount of slash (2 to 11.8 in., 5 to 30 cm) but, total transported weight when driving on "normal" slash was less than when driving on no slash in two out of three cases.

In regard to slash on the skid trail Omberg also reported on two unpublished experiments. One by the Swedish Forest Service showed a linear decrease in track depth with increasing thickness of slash. There was a sinkage of 2 inches (5 cm) with no slash after 3 forwarder passes (45 tons) decreasing to 0 inches with 7.1 inches (18 cm) of slash. The second experiment showed that average sinkage was reduced 0.86 inches (2.2 cm) with a 9.8 inch (25 cm) bed of slash after 7 passes with a forwarder (75 tons transported weight).

Shetron et. al. (1988) looked at the impact of mechanized harvesting in a hardwood stand in Wisconsin. Equipment used included a Timberjack Timbco Feller-Buncher, John Deere 640 grapple skidder and a Model 4501F Gafner Iron Mule forwarder. Skid trails were stratified into high use and low use. High use trails had one pass with the feller-buncher and eight with the skidder. Low use trails had one pass with the feller-buncher and four with the skidder. In a controlled loading test with the forwarder three different weight loads were used with soil density measured after four and twelve passes. Density measurements were made at 0 to 2, 2 to 3.1, and 3.1 to 4.7 inches (0-5, 5-8, and 8-12 cm) but density of undisturbed soil was made only from 0 to 2 inches. Soils moisture was at or near field capacity. The typical soil profile had a 2.0 to 3.0 inches (5-7.5 cm) of fresh to well-decomposed duff layer over the A horizon.

Results from the feller-buncher and skidder trails showed that intensity of use was not significant. Densities increased 90 percent on the high use trails and 83 percent on the low use trails. They concluded that "as much compaction occurs with few passes as with numerous passes."

In the controlled loading test there was a significant difference between undisturbed and each treatment, however there were no significant differences in the mean densities due to loading or number of passes.

Huyssteen (1989) compared soil impacts resulting from three different four wheeled forwarders in Kwambonambi, Zululand. Soils were classified as medium sand within 80 percent of field water capacity. A handheld recording penetrometer was used to measure soil strength as an indicator of different compaction levels. The maximum penetrometer soil strength values (PSS) and depth of occurrence are shown below.

TABLE 2-4. (after Huyssteen 1989) Maximum penetrometer soil strength values (PSS) and depth for three forwarders.

FORWARDER	CUMULATIVE LOAD OVER SITE (TONS)	MAX. PSS (KPA)	DEPTH (mm)
Thor	146.8	1731	350-400
Massey Ferguson	174.6	2372	350
Massey Ferguson under brush	174.6	2029	350
Bell T12	198.1	2750	500
Bell T12 under brush	198.1	2138	500

Under one forwarder (Thor), PSS was measured after every pass, up to ten passes and at approximately 30 passes. The increased rate of "compactness" was reported as almost linear. Measurements taken between the tracks for one of the forwarders showed a "slight" increase in PSS.

Huyssteen also reported on differences in the effect of driving on brush compared to bare ground by two of the forwarders (as shown in Table 2-4). He found that maximum PSS was reduced by 14.5 percent in one case and 22.3 percent in the other. Maximum PSS occurred at a depth of 19.7 and 13.8 inches (50 and 35 cm) whether driving on brush or not. He also reported that all three machines compacted the soil down to a depth of 31.5 inches (80 cm).

Soil bulk density was determined using the core method from samples obtained from six profile pits. The percent increase in density over uncompacted is shown in Table 2-5. Differences in effects between machines was ascribed to different tire sizes and their varying loads per axle.

TABLE 2-5. (after Huyssteen 1989) Percent change in bulk density for three forwarders.

FORWARDER	WEIGHT LOADED (pounds)	DEPTH (cm)	% INCREASE IN BULK DENSITY OVER UNCOMPACTED
Bell T12 (8 loaded passes)	54,590	0-20	24.2
		20-40	12.1
		40-60	8.4
		60-80	4.6
Thor (10 loaded passes)	32,360	0-20	16.9
		20-40	10.5
		40-60	6.3
		60-80	0.4
Massey Ferguson (8 loaded passes)	48,100	0-20	9.7
		20-40	3.6
		40-60	2.2
		60-80	0

Jakobsen and Greacen (1985) looked at soil compaction created by repeated trips of a loaded forwarder (Volvo TC860 - estimated loaded weight 57,200 lbs - 26,000 kg) on two different soils in South Australia under wet conditions. As determined by measuring the depth of the tracks after repeated passes they concluded that compaction increased linearly with the log of the number of passes up to 27 passes. Bulk densities measured after 3 passes showed increases of 25.6 and 26.6 percent over undisturbed for the two soils at the 2.0 to 3.9 inch (5-10 cm) depth and 31.2 and 34.4 percent after 27 passes. The major portion of the change in density occurred after only three passes. At the 7.9 to 9.8 inch (20-25 cm) depth, only the change after 27 passes was reported, which was 22.6 and 27.5 percent for each soil. They also reported that impacts occurred down to a depth of 31.5 inches (80 cm) based on penetrometer readings.

King (1979) reported on bulk density changes after the felling stage only, by five different mechanized felling machines as shown in Table 2-6 (each operated in one of six study sites in south Alabama and southeast Tennessee). Bulk density measurements were taken at 2.0 and 3.9 inches (5 and 10 cm). He reported that compaction occurred at only two sites, one thinned by the RW-30 and the other by the Franklin. This was attributed to the fact that these two sites had the highest soil moisture content. Increases in density were 11.6 and 20.3 percent at the 2.0 inch (5 cm) depth and 7.8 and 16.7 percent at the 3.9 inch (10 cm) depth (the 16.7 percent increase was not significant at 99 percent confidence level).

TABLE 2-6. (after King 1979) Harvester type, weight and estimated ground pressure.

HARVESTER TYPE	WEIGHT (lbs)	(kg)	ESTIMATED GROUND PRESSURE (psi)	(kg/cm²)
Clark Melroe Bobcat with 16 in. cm Morbark shear	15232	6908	5.76	.405
TH-105 Thinner Harvester	21047	9545	17.52*	1.232
Franklin 170 XLN with 20 in. Morbark shear	26370	11959	17.52*	1.232
RW-30 Harvester (without delimbing attachment)	22850	10363	17.52*	1.232
TJ-30 Harvester	30003	13607	17.52*	1.232

*As published

Kairiukstis and Sakunas (1989) reported that in the former USSR using "organized" technology with multifunctional machines (feller-buncher and grapple skidding) in clearcuts, 16.4 feet (5 m) wide skid trails every 46 to 49 feet (14-15 m) covered one-third of the logging area. They reported that numerous studies showed that impacts were greatest on moist soils with heavy compaction (>15 percent) comprising 45 percent of the logging area whereas on dryer soils heavy compaction does not exceed 25 percent of the area.

Kairiukstis and Sakunas also state that several studies in eastern Europe have shown that soil compaction is reduced by skidding on a layer of slash. One study indicated that with only a few passes by a crawler tractor on slash covered trails there is significantly less compaction but after 15 passes compaction sharply increased. Another study indicated that on branch-covered skid trails with wet soil, density increased only 8 percent and no tracks were formed (no information was given on the number of passes) whereas with no branches, track depths ranged from 15.7 to 19.7 inches (40-50 cm).

2.2. Effect of Multiple Passes

Most literature reviewed shows that the greatest percentage of total compaction occurs with the first few passes by a piece of equipment, changing little with additional passes. In addition to those studies reviewed in Section 2.1 that included multiple pass effects in mechanized harvest operations (Jakobsen and Greacen 1985, Huyssteen 1989, Shetron et al. 1988, and Zaborske 1989) the following studies looked at multiple pass effects with conventional harvesting equipment.

Froehlich (1978) studied the impact of an FMC skidder with relatively low ground pressure on soil compaction at three different sites in Oregon. On one site he found the density at the two inch depth increased 58 percent after only one trip and increased gradually through twenty trips. At six inches the density reached a maximum (16.1 percent over undisturbed) after six trips and remained essentially unchanged through twenty trips. At the ten inch depth, density increased 10 percent with one pass but decreased with several more trips. Froehlich attributed this to a sampling problem due to high variability resulting from very stony soils at this site. At a second site he found very little change with increasing number of passes up to twenty. This was attributed to a high initial density, thick litter layer, and low soil moisture. Samples taken on a trail with 90-100 passes though did show a substantial increase in density (approximately 25 percent for 2, 4, and 6 inch depths and 15 percent for 10 inch depth). At the third site he found that density increased after the first few trips and changed little with increasing number of trips. These changes occurred primarily at the two and four inch depth. At the six and ten inch depth there was very little change from the undisturbed condition.

Steinbrenner (1955) examined soil infiltration rates, macroscopic pore space and bulk density changes in the upper three inches after using a HD 20 crawler tractor in western Washington. He looked at two different soils; one under wet and the other under dry conditions. Samples were taken after every trip up to 6 trips and then after the eighth and tenth trip for the wet soil and after every second trip up to ten trips for the dry soil. Under wet conditions the density peaked at six trips (approximately 30 percent over undisturbed) then decreased to near original density. This apparent anomaly was explained by an abnormal amount of organic matter in samples taken after the eighth and tenth trips. With the dry soil the greatest change in density occurred after the sixth trip (approximately 22 percent).

Sidle and Drlica (1981) studied soil compaction resulting from a partial cut in the Oregon Coast Range using a low ground pressure FMC skidder. Their objectives were to look at the relationship between compaction and the number of turns, and to determine if compaction differs by slope gradient or direction of skidding (uphill or downhill). Soil bulk density measurements were made at four soil depths, 3.0, 5.9, 8.9, and 11.8 inches (7.5, 15.0, 22.5, and 30 cm). Increases in density values down to 11.8 inches were noted in their data. Using regression analysis they found that the most important variable relating to soil compaction under wet conditions was the log of the number of turns. They also determined that at the 3.0 and 5.9 inch depth, skidding uphill caused greater compaction than downhill. Slope gradient was not a significant variable at any depth, but they noted that a greater variety of slope gradients may have been needed to adequately test this parameter.

Guo and Karr (1989) simulated a log skidding operation in north-central Mississippi to study the effects of trafficking and soil moisture on bulk density and porosity. They measured density after 1, 3, 6, and 12 passes at depths of 0 to 3.1, 3.1 to 5.9, and 5.9 to 9.4 inches (0-8, 8-15, and 15-24 cm) with three soil moisture levels (dry, medium and wet). No significant difference was found in density between medium and wet soils presumably because the difference between medium and wet soil moisture content was only 2.2 percent.

Reported results indicated that soil moisture and number of equipment passes had a significant effect on the degree of compaction. Under dry conditions, most of the effects of travel were limited to the upper 3.1 inches. In the moist soils, changes were noted throughout the 9.4 inch depth studied. Under dry conditions, one pass with the skidder increased density 16 percent (67 percent of the total). Under wet conditions, generally more than 50 percent of the total compaction occurred after one pass and 90 percent or more after three passes.

Greene and Stuart (1985), in the southern Appalachians of northwest Georgia, reported on the effect of tire and skidder size by traffic level of 1, 3, and 10 passes for dry and wet soils at 0, 4, and 8 inches (0, 10.1, and 20.3 cm). They stated that in moist soil, the rate of change in bulk density was greatest in the first three passes, with little increase after the third pass. In dry soil, one pass caused little soil compaction. Three and ten pass results in dry soil were highly variable, reflecting variation in soil properties across the soil type.

Burger et al. (1985), in southern Virginia, evaluated changes in bulk density at two depths, 0 to 2.4 and 5.9 to 8.3 inches (0-6 and 15-21 cm), two soil moisture contents, and 1, 3, and 9 passes with two machine types (rubber-tired skidder and crawler tractor). No effect on soil density was found at the 5.9 to 8.3 inch depth with either machine at either moisture level. Moisture level had a significant effect on the degree to which the soil in the top 2.4 inches was compacted with no interaction between machine type or number of passes. Density increased sharply with the first three passes, after which density increased at a much lower rate with additional passes. The change in density was proportional to the square root of the number of passes.

Froehlich et al. (1980), on the Tahoe National Forest in northern California, studied compaction effects as influenced by the following variables: four soil types, three distinct moisture regimes, and three different logging vehicles. With repeated trips they found that soil density increased rapidly during the first few trips, with the rate of change decreasing for successive trips. For all machines, about 60 percent of the change in density occurred by the sixth trip.

In developing a prediction equation they found that the number of machine passes and a cone index measure of initial soil strength were the most important variables, explaining 54 percent of the variability in change in bulk density. Machine derived dynamic pressure (MDP) accounted for only a small portion of the variation, though incorporating vibration and lateral pressure may have improved the ability of MDP to explain variability. They also found that the greatest change in density occurs near the soil surface and progressively decreases with increasing depth. Increase in density below 12 inches (30.5 cm) was found to be negligible.

Koger et al. (1985) looked at the effects of tire size, dynamic load, inflation pressure, and multiple passes on soil compaction. Using soil bins they tested two different tires each at two different inflation pressures and two different dynamic loads. Soil bulk density was measured after 1, 2, 3, and 4 passes for each combination of variables. The test was repeated for three different soil types. Their results varied significantly with soil type. In regard to number of passes, they found that only one soil showed significant increases in density after each pass. For the other two soils there was no significant increase between the second and third passes and in only 50 percent of the cases did density values increase significantly between the first and fourth pass.

2.3. Slash Protection

Several previously reviewed studies (section 2.1) looked at the effect of slash debris in reducing the amount of compaction that can occur compared to operating on bare ground (Zaborske 1989, Omberg 1969, Huyssteen 1989, Kairiukstis and Sakunas 1989). In all cases some reduction in the amount of compaction was reported.

Fries (1974), in Sweden, reported the average frequency of soil breakage (humus layer torn off from surrounding untouched humus and pressed or crumpled under wheels or tracks) was reduced by up to 80 percent when slash from a thinning covered the skid trail. However, Jakobsen and Moore (1981), in South Australia, found that for a FMC 220 CA skidder and D-7 Caterpillar, slash offered some soil protection, but was only effective for the first few cycles.

2.4. Effects Across Trail Profile

It is has been assumed in most studies that the zone of greatest compaction will occur directly beneath the tire or track tread, as most studies have measured compaction in the center of the tread. Raghavan et al. (1976) determined the location of compaction isobars under various sized tires with ground pressures ranging from 6 to 23 psi (0.42 to 1.62 kg/cm^2). Their results show that compaction effects radiate outward as much as one and a half tire widths or more.

Huyssteen (1989), in Zululand, found that measurements taken between the tracks of a forwarder showed a "slight" increase in penetrometer soil strength. Wronski (1984) in his forwarder/skidder study found evidence of increased soil compaction up to 2.5 feet (.75 m) laterally from the wheel track. Allbrook (1986) found that in a skidder trail in central Oregon, there was no significant difference between the bulk density between the center of the trail and undisturbed areas. There was a significant difference, however, between the center of the track, edge of the track, and undisturbed areas.

2.5. Areal Extent

McNeel and Ballard (1992) in a commercial thinning in northwestern Washington, using a cut-to-length harvest system, determined that 19.7 percent of the total area was in equipment trails (see page 7). Zaborske (1989) in a partial cut in eastern Oregon, removing approximately three quarters of the stand volume using feller-bunchers and grapple skidders, found that 54 percent of the total area received some impact by the feller-bunchers, skidders or both (see page 9). Kairiukstis and Sakunas (1989) reported that in the former USSR using "organized" technology with multifunctional machines (feller-buncher and grapple skidding) covered one-third of the logging area (see page 15).

Murphy (1982) examined soil damage associated with thinning Douglas-fir in western Oregon using five different skidding machines. Total area impacted by skid trails ranged from 11 to 30 percent. The largest percent of area occurred when skid trails were not prelocated. In areas with the lowest percentage in skid trails, trees were prebunched with a radio controlled skid-mounted winch. In other areas without prebunching, area impacted was 14-21 percent.

Dyrness (1965), in a tractor logged clearcut in western Oregon, reported 28 percent of the area in skid trails. Froehlich et al. (1981) found in their western Oregon thinning study, that skid trails covered 20 percent of the ground in a unit that was conventionally logged with logger selection of trails as the thinning progressed. With predesignation of trails, they found that 11 percent of the area was impacted when the trails were 100 feet apart, 7 percent when the trails were 150 feet apart, and 4 percent when trails were 250 feet apart.

2.6. Equipment Comparisons on Soil Impacts

Some studies involving a comparison different types of logging equipment used in conventional logging operations found little difference in machine type vs. compaction despite differences in static ground pressure (SGP). Most studies reporting this fact though involve a high number of machine passes.

Froehlich et al. (1980), found no significant difference for increase in soil density between a rubber-tired skidder with 12.43 psi (0.876 kg/cm^2) SGP on the front axle and a low ground pressure skidder with 5.68 psi (0.400 kg/cm^2) after 20 trips. There was a statistically significant difference between the a crawler tractor (SGP equaled 8.87 psi - 0.625 kg/cm^2) and the skidders for increase in soil density (tractor being higher), however the crawler tractor was used on a trail that had a lower initial soil density. Less dense soils given a uniform load will tend to show a greater change in density than a soil of higher density. In addition, the crawler tractor skidded about twice as much volume as the rubber-tired skidder.

Burger et al. (1985), found that there was no statistical difference in soil compaction created between a crawler tractor and rubber-tired skidder despite a more than three fold increase in mean ground pressure (8.71 vs. 33.37 psi - 0.612 vs. 2.34 kg/cm^2). Burger did not indicate at what pass category (1, 3, or 9) this result was based on.

Greene and Stuart (1985) found in their study that under dry soil conditions increasing ground pressure between various rubber-tired skidders with various size tires (SGP ranged from 4.80 to 9.20 psi on the front axle - 0.340 to 0.647 kg/cm^2) did not increase the frequency or magnitude of soil compaction. However, under moist soil conditions which approached the plastic limit, the frequency and magnitude of compaction increased with increasing ground pressure.

Jakobsen and Moore (1981), in an Australian study, found no significant difference in the effects on soil properties between a FMC 220 CA skidder weighing 27940 lbs. (12700 kg) and D-7 Caterpillar weighing 46200 lbs (21000 kg). Both machines carried a 17600 lb (8000 kg) log. Compaction measurements were made up to 15 cycles. It was not reported at what cycle the difference in effects between the two pieces of equipment were not significant.

In studies involving mechanized harvesting equipment, Shetron et al. (1988) in their forwarder, controlled-loading test, found no significant difference in soil compaction created between different size forwarder loads whose ground pressures ranged from 9.0 to 16.25 psi (0.62 kg to 1.12 kg/cm^2)

Wronski (1984) in comparing the impacts of a Volvo 971 forwarder with bogie axle (ground pressure estimated at 29.02 psi - 2.04 kg/cm^2) and John Deere 540 (ground pressure estimated at 11.61 psi - 0.82 kg/cm^2) skidder, found that they both caused the same degree of compaction. The skidder, though, required approximately six times as many passes to remove the same amount of volume.

In Zaborske's study (1989), the soil compaction after 1 to 10 passes by a feller-buncher (ground pressure of approximately 7 psi - .49 kg/cm^2) and 1 to 4 passes a grapple skidder, were the same.

Similarity of compaction results comparing equipment of different size and weight is not surprising considering that the static ground pressures produced by large equipment such as harvesters and forwarders is often not that much greater than and sometimes less than that produced by most conventional logging equipment due to the larger footprint of their tires or tracks as shown in Table 2-7. Even where large differences in ground pressure do exist between types of equipment, repeated trips that are often necessary by smaller equipment appear to result in comparable compaction.

TABLE 2-7. Harvesting equipment weight, tire/track print area, and static ground pressure.

EQUIPMENT TYPE	WEIGHT* (lbs)	(kg)	STATIC GROUND PRESSURE* (PSI)	(kg/cm^2)	TIRE/TRACK PRINT AREA (in^2)	(cm^2)
CRAWLER TRACTOR						
D6D Caterpillar[1/] w/20 inch tracks	39337	17840	8.87	0.625	4240	27355
RUBBER TIRE SKIDDER						
John Deere 640[1/] w/23.1 x 26 tires	20021	9080	12.46-f 5.86-r	0.876 0.412	2096	13523
John Deere 440D[2/] w/68/34 x 26 tires	17104	7757	4.84-f	0.340	4768	30761
Same as above w/16.9 x 30 tires	15411	6989	9.20-f	0.647	2260	14581
LOW GROUND PRESS. SKID.						
FMC 210CA[1/]	9503	3380	5.69	0.400	4972	32077
HARVESTER						
Timberjack 2518[3/] w/23.6 in. wide tracks & 3000 lb processing head	53800	24399	≈ 8.3	≈ 0.58	≈ 6513	≈ 42019
Same as above w/30.0 in. tracks	≈ 54330	≈ 24639	≈ 6.6	≈ 0.464	≈ 8279	≈ 53412
FORWARDER						
Timberjack 1010[4/] w/600 x 34 16 PR tires-f 600 x 26.5 16 PR tires-r (loaded w/24250 lbs)	50639	22966	9.7-f 11.7-r	0.682 0.822	1800-f 2828-r	11613 18245
Same as above with bogie tracks	52623	23865	9.7-f 10.4-r	0.682 0.731	1800-f 3376-r	11613 21781
Same as above with bogie tracks and 700 mm tires	53569	24294	8.5-f 9.1-r	0.598 0.640	2086-f 3938-r	13458 25406

* Unloaded unless otherwise noted.
f = front tires
r = rear tires
[1/] Source: Froehlich et al. (1980)
[2/] Source: Greene and Stuart (1985)
[3/] Source: FMG Timberjack technical bulletin. Data with "≈" were calculated and not published data.
[4/] Source: FMG Timberjack Cut-To-Length Reference Manual (2/93).

2.7. Effects of Compaction on Tree Growth

Of concern to land managers is the potential for reduced soil productivity on compacted areas. Many studies have shown that the characteristics of compacted soils are less favorable for tree growth. Root penetration and growth are often decreased due to the high strength of compacted soils offering physical resistance. Also, supplies of air, water, and nutrients are decreased due to decreased porosity.

Studies on the effect of compaction on tree root growth have predominantly been greenhouse studies, growing seedlings in containers compacted to some known bulk density. Zisa (1980) found substantial reduction in root growth with increasing soil density for Austrian pine, pitch pine, and Norway spruce. Minore et al. (1969) grew seven different tree species in pots compacted to three different bulk densities. He found that the roots of lodgepole pine, Douglas-fir, red alder, and Pacific silver fir were able to penetrate soil columns that the roots of Sitka spruce, western hemlock, and western red cedar could not. Heilman (1981) studied root penetration of Douglas-fir seedlings and found that root penetration decreased with increasing soil bulk density. He also reported that when the downward growth was restricted by high bulk density most roots grew laterally in the uncompacted surface soil to a greater total length than they grew vertically in the lowest bulk density containers. This indicated perhaps an adaptation of the roots to the restricting of downward movement.

The results of six studies that looked at the relationship between increases in bulk density and the decrease in seedling height growth were reported by Froehlich and McNabb (1984). They found that the relationship was strongly proportional when expressed as a percentage of change from control bulk density and height.

Effects on site productivity on a stand level were examined by Helms and Hipkin (1986) and Wert and Thomas (1981). Helms and Hipkin stratified a portion of a 16 year old ponderosa pine plantation in northern California based on five levels of soil compaction with one being the highest and five the lowest level of compaction. Their results are shown in Table 2-8. Their findings are summarized below:

- No trend was found for mean tree diameter.
- Mean tree height generally decreased with increasing bulk density.
- Stocking and survival in strata one, two and three were substantially lower than in strata four and five.
- Volume per tree for stratum one and two versus three, four, and five are significantly different.
- Volume per unit area reflects the combined effects of reduction in mean tree volume and mortality per unit area.

Overall reduction in productivity for the entire area was not reported, perhaps because the study area did not encompass the entire plantation. But they stated that, assuming full stocking, reduction in productivity by age 40 in the most heavily compacted areas is equivalent to about one site class.

TABLE 2-8. (after Helms and Hipkin 1986) Characteristics of each of the five bulk density strata.

		Bulk Density Stratum				
		1	2	3	4	5
Sample Size		28	50	75	216	50
Bulk Density (g/cm³)		1.19	1.08	0.98	0.90	0.83
Standard Error		±0.008	±0.006	±0.004	±0.003	±0.004
% of stratum 5		143	130	118	108	100
Mean Diameter	**(cm)**	17.8	17.0	19.2	19.0	18.7
	(in.)	7.0	6.7	7.6	7.5	7.4
Standard Error	**(cm)**	±0.84	±0.65	±0.40	±0.27	±0.50
Mean Height	**(m)**	7.29	7.38	8.36	8.48	8.45
	(ft.)	23.9	24.2	27.4	27.8	27.7
Standard Error	**(m)**	±0.26	±0.22	±0.12	±0.10	±0.19
% of stratum 5		86	87	99	100	100
Trees/ha		418	658	872	1125	1041
Trees/acre		169	266	353	455	421
Survival % (relative to stratum 5)		40	63	84	108	100
Vol./tree	**(m³)**	0.056	0.051	0.075	0.075	0.072
	(ft.³)	1.98	1.80	2.65	2.65	2.54
% of stratum 5		78	71	104	104	100
Vol./ha	**(m³)**	23.41	33.56	65.40	84.38	74.95
Vol./acre	**(ft.³)**	334.5	479.6	934.5	1205.8	1071.0
% of stratum 5		31	45	87	113	100

Wert and Thomas (1981) studied the effects of compaction in and adjacent to skid trails on the growth of Douglas-fir. This study took place in the Oregon Coast Range on a 10.70 acre (4.33 ha) plot within a clearcut harvested in 1947. They categorized the area into three zones: skid trails, transition (9.8 feet - 3 m, on both sides of skid trail), and undisturbed areas. Volume of every tree over 5 cm (1.97 inches) was estimated and forty randomly selected trees in each category were measured for their age/growth relationship. Soil bulk density was taken at random grid points within each category. The results of their study are shown below:

TABLE 2-9. (after Wert and Thomas 1981) Characteristics of three bulk density strata.

	Total Area (acres)	**Trees/acre**	**Volume/acre (ft^3)**
Skid Trails	1.09	280	487
Transition Zone	1.88	394	1389
Undisturbed	7.73	477	1842

Wert and Thomas attributed the reduced volume on skid trails to inadequate seedling survival and delay in reaching breast height which they said was 4.1 years longer than those growing in the undisturbed areas. Their measurement of older trees showed that they grew at the same rate regardless of the strata. This suggests that seedling growth was retarded until a certain age/height combination was reached, at which time surviving individuals grew at a normal rate. They estimated the overall volume loss from the entire stand to be 11.8 percent.

Greacen and Sands (1980) reported that compaction effects on root growth may be a complex interaction between soil strength, water and nutrient availability, and aeration. For example, under some circumstances as a result of compaction, plant water supply can be improved because of greater water retention and hydraulic conductivity. Greacen and Sands report that results from experiments designed to exam the effects of compaction on growth appear to be inconsistent, probably due to the complex interactions and great spatial variability in the field.

3. Study Design

3.1. Study Area Description

3.1.1. Site Selection

This area was selected for several reasons:

1. The logging contractor was experienced in mechanized harvesting operations and was willing to cooperate in the study.
2. The landowner was willing to allow access to the property and was interested in having a study of this type done.
3. A production study was also planned in which equipment trails were to be mapped and equipment passes recorded over each trail (Kellogg and Bettinger 1993).

3.1.2. Location

The area studied is located on the west side of the Cascade Mountains, approximately 7 miles south of Lyons, Oregon, R. 2 E., T. 10 S., Section 29. It is part of the Avery land holdings managed by Mason, Bruce and Girard.

3.1.3. Site Description

3.1.3.1. Vegetation

Douglas-fir (*Pseudotsuga menziesii*) is the primary tree species with minor amounts of western hemlock (*Tsuga* *heterophylla*). The stand was approximately 40 years old in 1993. Diameter at breast height was approximately 8 inches prior to thinning. A detailed presentation of average stand conditions before and after thinning is shown in Table 3-1 (Kellogg and Bettinger 1993). Hardwood species were present but are a minor component. Very little ground vegetation was present due to the dense canopy.

TABLE 3-1. (after Kellogg and Bettinger 1993) Average site conditions before and after thinning. Note: Per hectare units are shown in parenthesis

Before Thinning		
Total Trees per Acre	537	(1,327)
DBH	8.2 in. 20.9 cm	
Volume per Acre	7430 ft^3 210.4 m^3	(18,360) (520)
Basal Area per Acre	240.1 ft^2 22.3 m^2	(97.2) (55.1)
After Thinning		
Total Trees per Acre	173	(427)
DBH	11.8 in. 29.9 cm	
Volume per Acre	4921 ft^3 139.4 m^3	(12,160) (344)
Basal Area per Acre	144.1 ft^2 13.4 m^2	(356.1) (33.1)

3.1.3.2. Soils

Soils are classified in the USDA Soil Conservation Service Survey (1987) as Flane-Moe gravely loam and Moe gravely loam. These are described as very cobbly silty clay loam and very cobbly silty clay. One soil sample was taken within the unit for classification using the Unified Soil Classification System. The resultant USC soil classification was silty sand, SM, based on determination of the Atterberg limits and grain size distribution. Grain size distribution curves are shown in Appendix A.

3.1.3.3. Topography

The elevation of the study site ranges from approximately 2700 to 2900 feet (823 to 884 m). Slopes range from 0 to 42 percent, averaging approximately 25 percent. There are two benches that transect the site which divide it approximately into thirds. The aspect of the site is generally north.

3.1.3.4. Size

The entire area thinned covered approximately 100 acres (40.5 ha). The portion of this area identified for the study covers approximately 12 acres (4.6 ha).

3.1.3.5. Climate

Precipitation in this area averages approximately 75 to 85 inches per year. Most of the precipitation falls from October through June. The elevation places the study in the transient snow zone of the Cascade Range, therefore most of the precipitation falls in the form of rain or quickly melting snow. During the period that logging occurred, July 1 through July 23, 1992, there were frequent rain showers. The period when soil compaction data was gathered was generally dry (August 17 through September 15, 1992).

3.1.4. Site History

The study area was originally clearcut in 1947 using ground-based harvesting equipment. The site was naturally regenerated. Very little visible evidence of skid trails from the first entry was apparent. Approximately 20 years ago the area was precommercially thinned with a herbicide application.

3.2. Equipment Used In Logging

3.2.1. Harvester

The harvester used was a Timberjack 2518 carrier with a Koehring Waterous 762 single-grip harvesting head. This is a tracked machine with a swing-boom capable of reaching approximately 25 feet (7.6 m). The machine (with the harvesting head attached) weighed 53,800 pounds (24399 kg). Machine width was 110.5 inches (280.7 cm). Track width was 23.6 inches (60 cm). The harvesting head is capable of cutting trees up to 20 inches (50.8 cm). Static ground pressure (SGP) on level ground with harvesting head unloaded is approximately 8.3 pounds per square inch (0.58 kg/cm^2) assuming uniform pressure distribution. Actual pressure distribution would be highly variable based on boom and processing head position and tree weight.

3.2.2. Forwarder

The forwarder used was a Timberjack FMG 910. This was a medium size 6-wheel drive forwarder, weighing 10 tons (9070 kg). Tire sizes were 600 x 34 on the front and 600 x 26.5 on the rear. Rear tires had "bogie tracks" mounted. Payload capacity was rated at 11 tons (9977 kg). Machine width was 104 inches (265 cm). SGP could not be found, but the FMG 1010 (successor to the 910) weighing 25773 pounds (11688 kg) with a payload rated at 24250 pounds (10998 kg) produces an unloaded SGP of 7.9 psi (0.555 kg/cm^2) on the front tires and 4.2 psi (0.295 kg/cm^2) on the rear tires with bogie tracks. Loaded, SGP is approximately 9.7 psi (0.683 kg/cm^2) on the front and 11.7 psi (0.822 kg/cm^2) on the rear. It can be expected that SGP for the 910 model may be approximately 16 percent less since the total loaded weight of the 910 is approximately 16 percent less than the 1010, and tire sizes are the same.

3.2.3. Logging Operation Description

Harvester trails for the operation were laid out prior to logging by the logging contractor. Trails were approximately 50 feet (15.2 m) apart. Most arterial trails were located perpendicular to the slope. Collector trails were generally located on the benches transecting the unit. Except for a small part of the stand that was leave-tree marked (1-2 acres), the harvester operator selected the trees to be cut. Two products (sawlogs and pulpwood) were forwarded to the landing. The operator sorted most of the material in the woods, forwarding one product to the landing at a time. For approximately 32 percent of the loads, the operator forwarded both products and sorted the material at the landing (Bettinger and Kellogg 1993). Most forwarder loads were loaded directly onto truck trailers.

Where possible, the harvester operator would purposefully delimb trees over the trail in front of the machine in the direction of travel. This would create a bed of slash to drive on. Although there was no estimate made of the percentage of the trail system covered by slash, the majority of arterial trails had some slash on them.

3.3. Equipment Used in Data Collection

3.3.1. Nuclear Densiometer

A single probe Campbell Pacific nuclear densiometer was used for measuring soil compaction. The single probe nuclear densiometer measures average soil density between the tip of the probe and the soil surface. Maximum probe depth with this gauge is 12 inches (30.5 cm). Using this gauge provides a method for quickly measuring soil density with minimal disturbance to the soil profile. It works under the principle that radiation absorbed by the soil is proportional to its mass. A radiation source in the tip of the probe emits gamma radiation. A radiation detector located in the body of the machine at the soil surface measures the amount of radiation transmitted through the soil. The radiation count can then be converted to wet bulk density using calibration curves.

Since the radiation emitted from the probe is absorbed by all material, it is important to properly prepare the sample point by removing all litter and organic material that can affect results. Other factors that will affect results are moisture, buried roots, organic material, and rocks.

An initial attempt was made to use a double probe nuclear densiometer that will measure soil density between two probes at a specific depth but, because of the high stoniness of the soil, it proved too difficult and time consuming to put both probes into the soil without excessive soil disturbance.

3.3.2. Densiometer Calibration

Calibration of the densiometer for measurement of bulk density at the depths desired in this study was accomplished by packing material to a known density into a large aluminum box. Mediums used were: soil from the study site, sawdust, soil sawdust mix, concrete block, and a wood block. The machine was calibrated at 12 and 8 inches probe depth using all mediums except the wood block. At 4 inches probe depth, all mediums were used.

The first step for instrument calibration is to take a standard count. The standard count is a radiation count taken with the probe sitting on a standard plastic block. This count is made once daily and used to adjust that day's radiation counts (known as field counts) taken through the soil or calibration medium, for background radiation and nuclear decay of the gauge radiation source.

In the calibration box, for each medium, twenty field counts were made at each depth and the ratios of the average of the field counts to the daily standard count were plotted against the known densities. Using multiple linear regression, the known densities were regressed against the ratio and the natural log of the ratio to develop the calibration equations and curves for each depth (Appendix B). The regression equations developed for each depth were then used to determine wet soil bulk densities from the field count/standard count ratio.

3.4. Data Collection

3.4.1. Background Soil Density

To evaluate the soil compaction resulting from the harvest operations it was necessary to determine the average soil bulk density in undisturbed areas and compare the results to soil bulk density in trails. A grid was developed to equally space 33 measurement points throughout the study area. Initially, soil density at every other point was measured. The instrument counts at each depth were used to estimate variability and determine sample size for 95 percent confidence in the mean with 10 percent error (Appendix C).

If point locations fell on an unusable area such as an existing or old skid trail, down log or stump, the point was moved in 5 foot increments at 90 degree intervals from north to the east until a usable point was located. Methods and depths used for taking density measurements are described in Section 3.4.3.2.

3.4.2. Trail Soil Density

Soil density in the machine trails was measured as well as: 1) percent slope; 2) slash depth; 3) slash density; 4) slash size; 5) O horizon depth; and 6) number of machine passes. To determine the difference in soil compaction as a result of machine passes it was necessary to stratify the trails into machine pass groupings and measure soil density in each stratum. In this study, a machine pass was defined as one pass of either machine up or down a trail, loaded or unloaded. Methods and depths used for taking density measurements are described in Section 3.4.4.2.

3.4.2.1. Equipment Trail Mapping

Equipment trails were surveyed as flagged on the ground by the logging contractor prior to the start of logging. The survey was accomplished using a hand compass, clinometer and cloth tape. Using the survey information, a map of the equipment trails was drafted (Figure 3-1). During logging, deviations from the flagged trails were changed on the map by hand. It is estimated that 90 percent of the trails were used as flagged.

3.4.2.2. Determination of Machine Passes

The harvester operator delineated movement of the harvester on a map of the surveyed trails each day. The movement of the harvester was slow and deliberate, thus it was easy to delineate on maps. Forwarder travel was faster thus it was recorded by the production study researcher. A separate map was made for each turn of the forwarder showing the vehicle route and distance traveled along each trail. An example of the forwarder turn map is shown in Appendix D. When logging was completed the maps of harvester and forwarder travel were compiled onto one map showing number of passes on each trail or portion thereof.

3.4.2.3. Machine Pass Stratification

Because most literature reports the greatest percent change in soil compaction occurs after the first few machine passes, it was desirable to stratify low pass trails as much as possible while clumping the high pass trails. It was also important that there was enough area in each stratum to obtain a sufficiently large sample size. Logical stratum groupings as shown below were apparent on examination of the compiled machine pass map.

TABLE 3-2. Stratum Groupings

STRATUM GROUPINGS		
1 - 4	machine	passes
5 - 6	"	"
7 - 8	"	"
9 - 12	"	"
13 - 20	"	"
21 - 29	"	"
30+	"	"

Most of the trails had 6 passes, 2 with the harvester and 4 with the forwarder. Because the forwarder was often using the trails shortly after the harvester created them, it was not logistically possible to measure compaction that occurred after the harvester alone. Also, it was determined not critical to isolate compaction resulting from each machine alone since for the vast majority of trails are traveled on by both pieces of equipment.

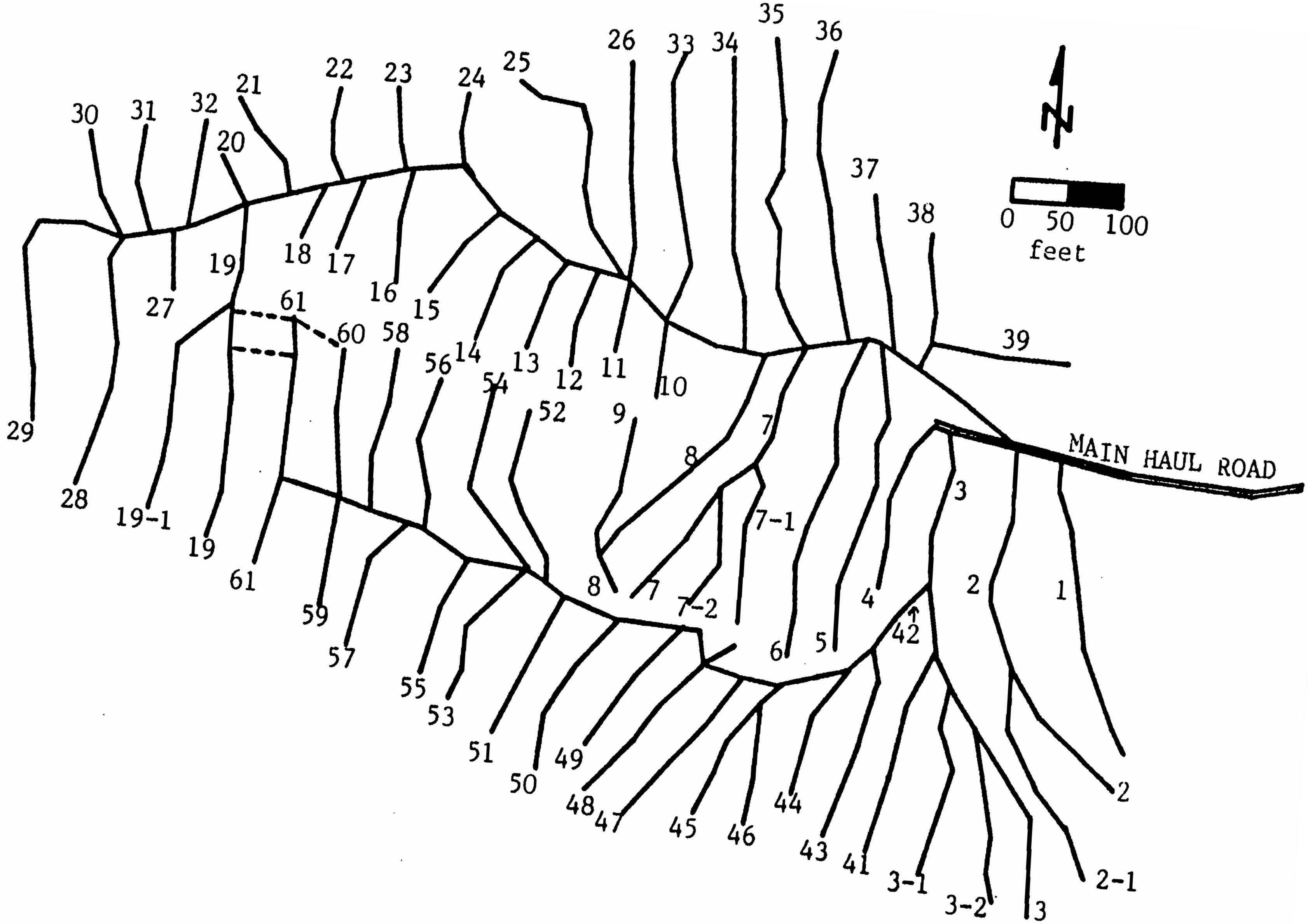


FIGURE 3-1. Avery study site equipment trail layout map.

3.4.2.4. Trail Measurement Point Selection

Prior to beginning compaction measurements in trails it was determined that if measurement points were spaced 50 feet apart there would be 166 possible measurement points with all stratums combined. In the field, all stratum locations were identified, examined and marked on the ground. If there was any question as to whether or not the division between stratums could be accurately located, trails or portions of them were not included for compaction measurement. Other areas not included for compaction measurement were, portions of trails within 20 feet of the trail end, because the entire machine would not have passed over the entire distance and, areas within 10 feet on both sides of a stratum division located midway on a trail, which provided a buffer for possible error in location of the stratum division.

The first measurement point on a trail was determined by generating a random number from 1 to 10 and going that distance in feet from the trail beginning. Successive measurement points were spaced 50 feet apart. If the trail or stratum segment was shorter than 50 feet the measurement point was placed in the center of the segment. Measurements were taken in the center of the tread track. If the point location fell on an unusable location due, for example, to a large submerged decomposed log or too much rock to use the nuclear gauge, the point was moved in five foot increments until a suitable point was found.

3.4.3. Point Measurements

3.4.3.1. Post-harvest Slash Measurement

At trail measurement points the first step was to take post-harvest slash measurements. Slash measurements included measurement of slash depth, slash density, and average slash size. Slash depth was determined by pushing a dowel graduated in inches through the slash until it came in contact with the ground. A 12 by 9 inch (30.5 by 22.9 cm) board with a hole in the middle of it was then placed over the dowel and brought into contact with the slash. The slash depth was then read directly from the dowel rod at the point where the board laid on the slash. Slash quantity was a subjective estimate made by the same person on all measurement points. Index values of 0 through 3 were given for no slash, low, medium and high quantity. Slash size was an ocular estimate of the average diameter of slash over the measurement point. Index values for slash size were determined as shown in Table 3-3.

TABLE 3-3. Slash size index values.

Average Slash Diameter		
(inches)	(cm)	Size Index
< 1/4	< .64	1
1/4 to 1/2	.64 to 1.27	2
1/2 to 1	1.27 to 2.54	3
1 to 2	2.54 to 5.08	4
2 to 4	2.08 to 10.16	5
> 4	> 10.16	6

3.4.3.2. Soil Density Measurement

After all slash measurements were made on a trail measurement point, all slash was removed. On both background and trail measurement points the O horizon depth was recorded then removed to the mineral surface. The surface of the mineral layer was examined to determine if the densiometer could be placed flat with minimal air gaps. If surface imperfections were slight they were filled with soil (approximately 1/4 inch or less). If imperfections were too great a new measurement point was located. The next step was to drive a metal pin the size of densiometer's probe 12 inches into the ground, using a guide plate to allow placement of the hole at 90 degrees to the soil surface.

Bulk density measurements were take with the single probe at 12, 8 and 4 inches (30.5, 20.3 and 10.1 cm). The 0 to 4 inch depth represented compaction in the surface layer. The density of the 0 to 8 and 0 to 12 inch layers indicated of the pattern of change in the surface 12 inches.

3.4.3.3. Other Measurements

Soil moisture at each measurement point was determined by taking a representative soil sample from the soil profile from 0 to 12 inches. Each sample was weighed, oven dried overnight, and weighed again for moisture content determination. Soil moisture was used to convert wet bulk density, as determined from the calibration curves, to dry bulk density.

Other measurements at each point included slope percent, an ocular estimate of rock content and size, and whether or not any visible soil compaction from current operations was evident.

4. Results

Mean dry bulk density for pass stratums and background and their statistical significance were determined using one-way ANOVA analysis. The influence on dry bulk density of the measured variables: number of equipment passes, post harvest slash (depth, size, and quantity), O horizon depth, and slope, were examined using multiple linear regression.

4.1. Number of Sample Points Taken

A total of 174 sample points were taken. Part way through the gathering of field data the nuclear densiometer malfunctioned. After repairing the gauge it was found that the standard counts were on average 260 points lower than prior to the gauge malfunction. It was assumed that field counts would also be affected. The number of sample points pre- and post-gauge malfunction by pass stratum are shown below:

TABLE 4-1. Number of sample points pre- and post-machine malfunction.

	EQUIPMENT PASS STRATUM								
	0	1-4	5-6	7-8	9-12	13-20	21-29	30+	Total
PRE	18	11	18	7	1	7	6	0	67
POST	16	20	31	17	8	5	0	10	107

No method was found to combine pre- and post-malfunction data. Comparing means of the stratum field counts for pre- and post- sample points showed no pattern (i.e., means were not consistently lower or higher for all post-malfunction stratums when compared to pre-malfunction stratums). Because of the inconsistent pattern of means and the fact that calibration curves had not been developed prior to starting field measurements, pre-gauge malfunction sample points were not included in the analysis.

4.2. Normality of Distribution and Outliers

The first step in analysis, was to examine the data for outliers and normality. Examination for outliers indicated extreme values at four sample points (three were low and one was high). These outliers were removed from analysis because their values did not appear reasonable when compared to all other values. Figure 4-1 shows box-and-whisker plots with and without outliers. The number of measurement points and outliers removed from each stratum are shown below:

TABLE 4-2. Number of sample points used in analysis.

	EQUIPMENT PASS STRATUM							
	0	**1-4**	**5-6**	**7-8**	**9-12**	**13-20**	**21-29**	**30+**
POST	16	20	31	17	8	5	0	10
4 OUTLIERS REMOVED		2	2					
TOTAL ANALYZED	16	18	29	17	8	5	0	10

The 9-12 and 13-20 stratums were combined because of the low number of sample points in each and because the means were not significantly different (95 percent confidence level). No sample points were available for the 21 -29 pass stratum in the post-gauge malfunction data. Examination of the distribution shape shown by the box-and-whisker plots with outliers removed (Figure 4-1) shows that the normality of the distributions of point data was adequate to use ANOVA analysis.

<u>Box and Whisker Key</u>

Q_U = upper quartile, Q_L = lower quartile, interquartile range = Q_U - Q_L

Whisker is extended to the smallest and largest data point within 1.5 interquartile ranges of the upper and lower quartile respectively.

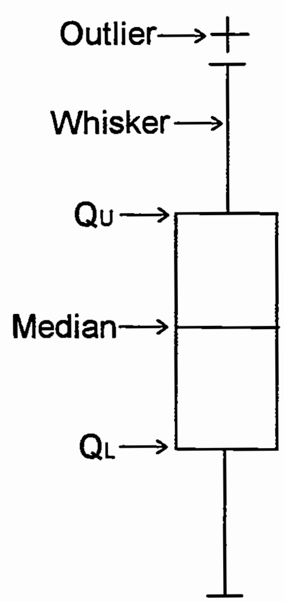
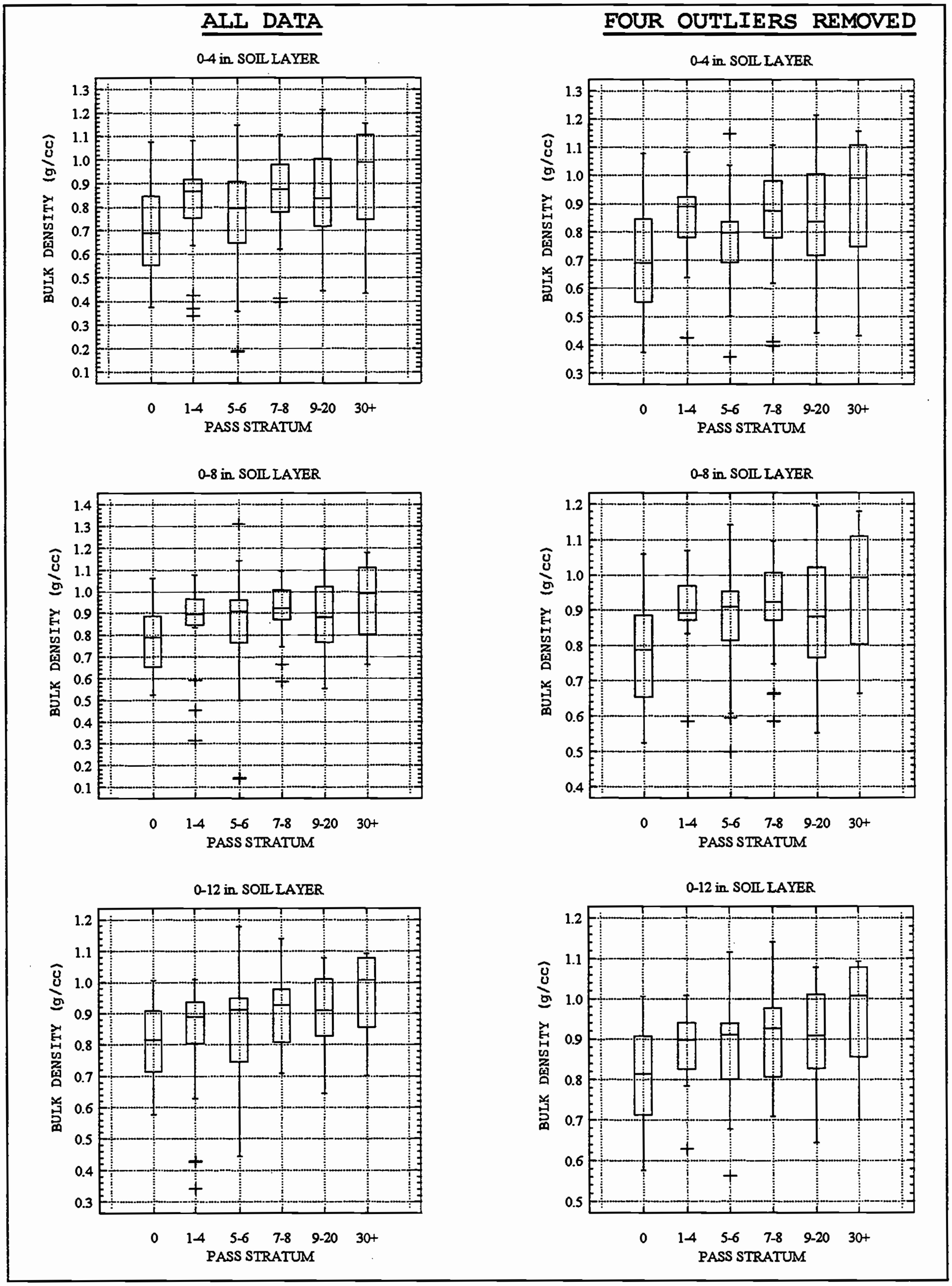


FIGURE 4-1. Box-and-whisker plots of soil bulk density data.



4.3. Bulk Density Measurement Results

Table 4-3 displays the mean soil bulk density for the background (no equipment passage) and equipment pass stratums by soil layer. Pooled *t* tests were used to determine if differences in means were significant. Trends in bulk density changes by stratum and soil layer will be examined in following sections.

TABLE 4-3. Bulk density (BD) results by equipment pass stratum and soil layer.

		SOIL LAYER					
PASS		0-4 in.		0-8 in.		0-12 in.	
STRATUM	n	BD	SE	BD	SE	BD	SE
0	16	.709 a	.048	.785 a	.038	.812 a	.031
1-4	18	.851 bc	.046	.898 bc	.036	.884 b	.029
5-6	29	.776 ab	.036	.861 ab	.028	.873 ab	.023
7-8	17	.827 bc	.047	.907 bc	.037	.904 bc	.030
9-20	13	.836 bc	.054	.879 abc	.042	.894 bc	.034
30+	10	.912 c	.061	.963 bc	.048	.971 c	.039

n = sample size; BD = dry bulk density (g/cm^2); SE = pooled standard error; Means in columns followed by the same letter are not significantly different at the 90 percent confidence level.

4.4. Bulk Density Changes With Increasing Number of Passes

Table 4-4 quantitatively shows the change in bulk density between each successive equipment pass stratum by soil layer. The greatest percent change in bulk density occurs from background to the 1-4 pass stratum in all soil layers. Except for an unexplainable drop in mean density for the 5-6 pass stratum, density changes little with increasing traffic before increasing in the 30+ stratum. Figure 4-2 graphically shows bulk density by stratum for each soil layer. Figure 4-3 gives a scaled perspective to change in bulk density with increasing number of equipment passes.

TABLE 4-4. Additive change in bulk density between stratums for each soil layer (i.e. Stratum 1-4 minus stratum 0).

	SOIL LAYER					
	0-4 in.		0-8 in.		0-12 in.	
EQUIPMENT PASS STRATUM	ADDITIVE BULK DENSITY CHANGE (g/cm²)	PERCENT CHANGE	ADDITIVE BULK DENSITY CHANGE (g/cm²)	PERCENT CHANGE	ADDITIVE BULK DENSITY CHANGE (g/cm²)	PERCENT CHANGE
0	-	-	-	-	-	-
1-4	0.142*	20.03%	0.115*	14.39%	0.072**	8.87%
5-6	-0.075	-8.81%	-0.039	-4.33%	-0.011	-1.24%
7-8	0.051	6.57%	0.046	5.34%	0.031	3.55%
9-20	0.009	1.09%	-0.028	-3.09%	-0.010	-1.11%
30+	0.076	9.09%	0.084	9.56%	0.077	8.61%

* Change significant at 95% confidence level
** Change significant at 90% confidence level

FIGURE 4-2. Mean bulk density by stratum for each soil layer.

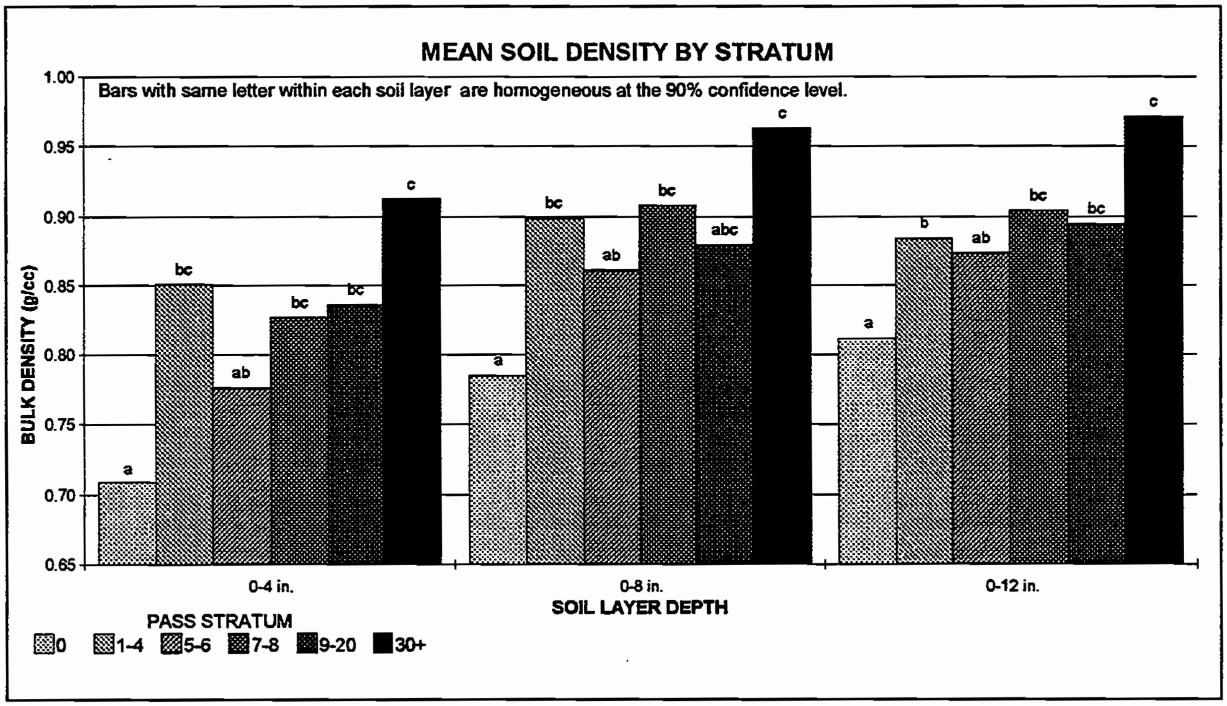
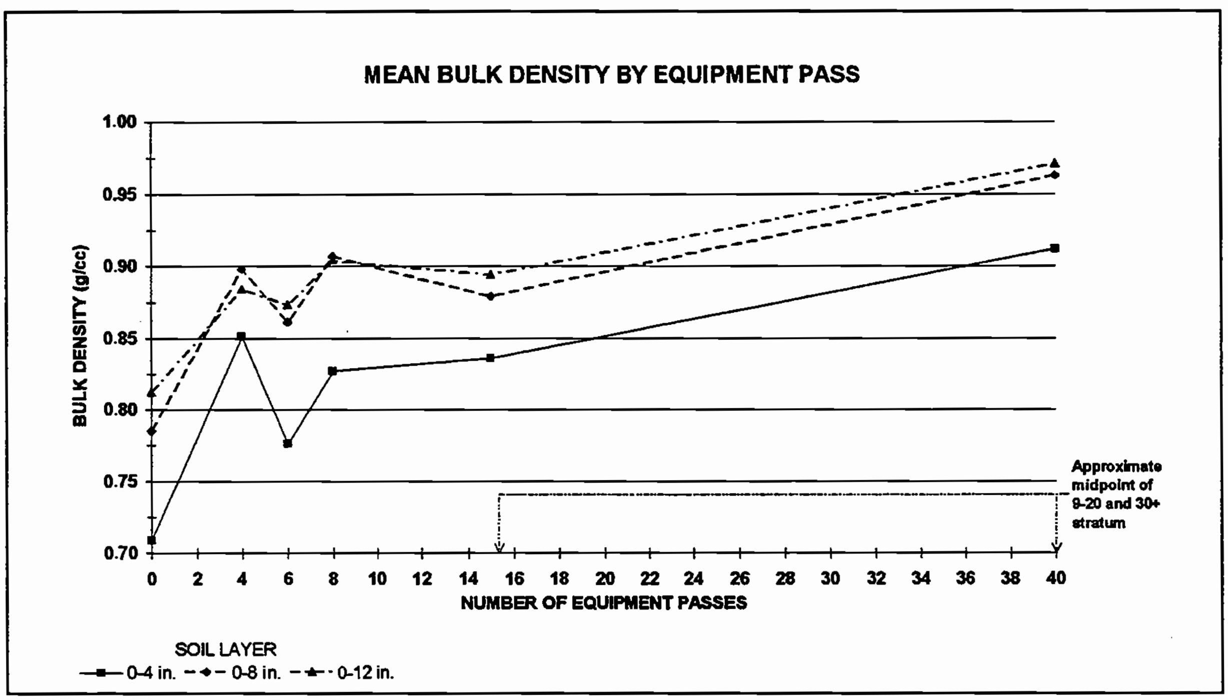


FIGURE 4-3. Change in bulk density by equipment pass.



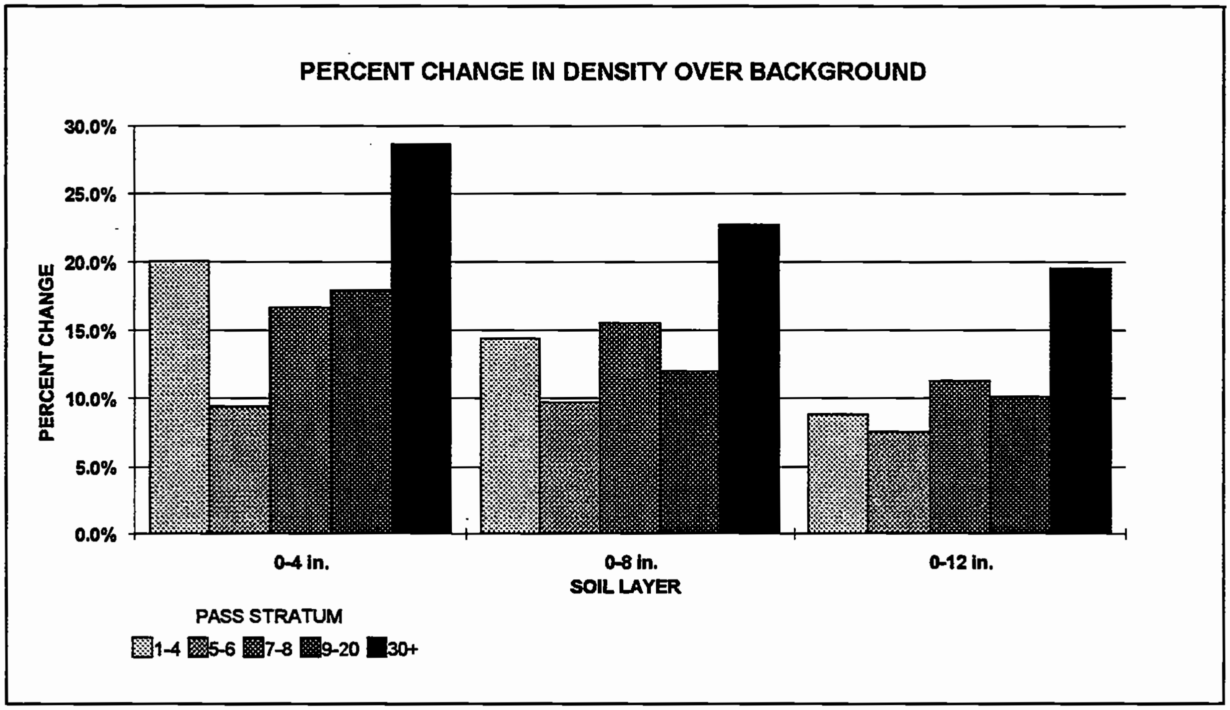
4.5. Bulk Density Increase Over Background

Change in bulk density over background is shown in Table 4-5. Most stratums and soil layers show a statistically significant increase over background for all strata in each soil layer. Comparing strata (Figure 4-4), the greatest percent change in bulk density over background occurs in the 30+ pass stratum for all three soil layers. Within each stratum (except 5-6) the greatest percent change in density occurs in the 0-4 inch soil layer decreasing with increasing depth of the soil layer. This indicates that the immediate impact of compaction is greatest in the upper soil layers.

Table 4-5. Soil density comparisons of pass stratums with background density.

EQUIPMENT PASS STRATUM AND SOIL DEPTH (in.)	NET CHANGE FROM BEFORE LOGGING (g/cc)	PERCENT CHANGE FROM BACKGROUND	SIGNIFICANCE LEVEL OF CHANGE FROM BACKGROUND	
			90%	95%
1-4 PASSES				
0-4	+0.142	20.03%		X
0-8	+0.115	14.65%		X
0-12	+0.072	8.87%		X
5-6 PASSES				
0-4	+0.067	9.45%		
0-8	+0.076	9.68%		
0-12	+0.061	7.51%		
7-8 PASSES				
0-4	+0.118	16.64%	X	
0-8	+0.122	15.54%		X
0-12	+0.092	11.33%		X
9-20 PASSES				
0-4	+0.127	17.91%	X	
0-8	+0.094	11.97%		
0-12	+0.082	10.10%		X
30+ PASSES				
0-4	+0.203	28.63%		X
0-8	+0.178	22.68%		X
0-12	+0.159	19.58%		X

FIGURE 4-4. Percent change in bulk density over background.



4.6. Bulk Density Changes With Increasing Soil Depth

Table 4-6 shows additive changes in bulk density between the three soil layers for each equipment pass stratum. There is a significant difference between the 0-4 and 0-12 inch soil layers for the zero pass stratum indicating that soil density is increasing with depth, which is typical for undisturbed soil. In four of the five equipment pass stratums the densities of the three soil layers are statistically homogeneous. This may indicate that the effect of equipment travel may be to create a more uniform level of soil strength as reflected by the more uniform density throughout the entire 12 inch soil layer.

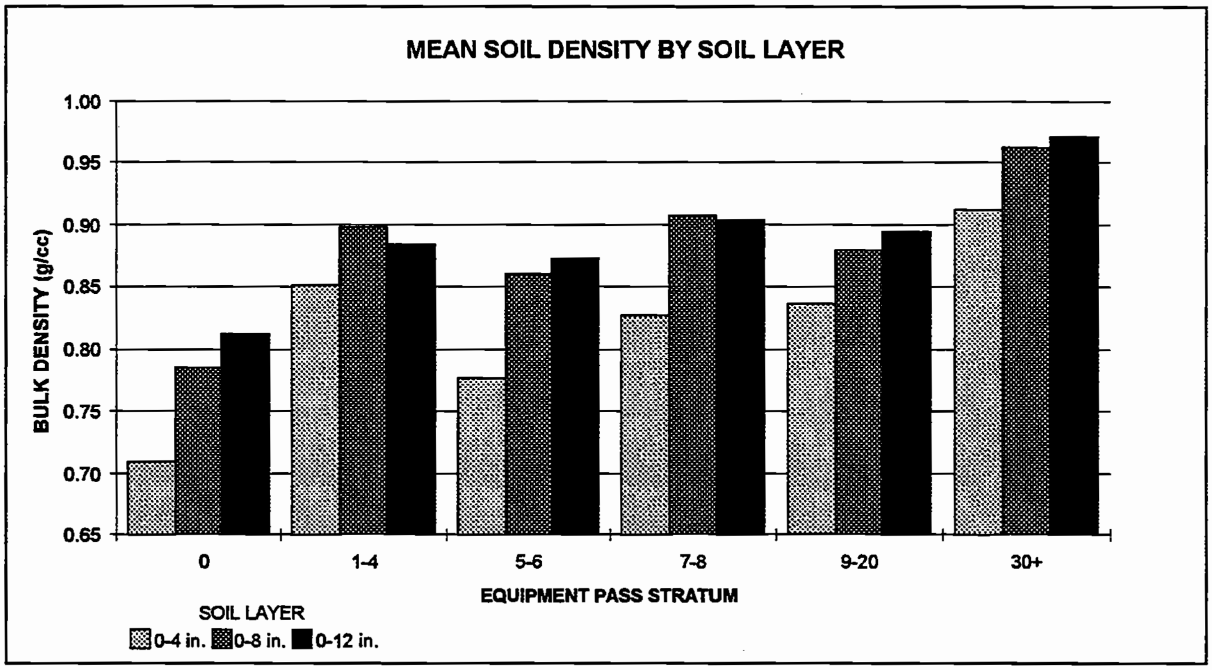
As observed in Figure 4-5, with equipment passage, though density tends to become more homogeneous, the upper 0-4 inch layer continues to have a lower (though not necessarily statistically significant) density than the density of deeper layers. This may be explained in part by the fact that the 0-4 inch layer had the lowest initial density. Other possible reasons may be that it has a higher organic content which is less compatible or on points not protected by a layer of slash there may have been some churning action by the equipment tires that reduced the level of potential compaction.

TABLE 4-6. Additive change in bulk density between soil layers (i.e. 0-8 in. minus 0-4 in. density).

PASS STRATUM AND SOIL LAYER (INCHES)	ADDITIVE DENSITY CHANGE IN SOIL LAYERS (g/cm^2)	PERCENT CHANGE	HOMOGENEOUS GROUPS AT A 90% CONFIDENCE LEVEL*
0 PASSES			
0-4	-	-	a
0-8	+0.076	+10.72%	ab
0-12	+0.027	+3.44%	b
1-4 PASSES			
0-4	-		a
0-8	+0.049	+5.76%	a
0-12	-0.016	-1.78%	a
5-6 PASSES			
0-4	-		
0-8	+0.085	+10.95%	a
0-12	+0.012	+1.39%	a
7-8 PASSES			
0-4	-		a
0-8	+0.080	+9.67%	a
0-12	-0.003	-0.33%	a
9-20 PASSES			
0-4	-		a
0-8	+0.043	+5.14%	a
0-12	+0.015	+1.71%	a
30+ PASSES			
0-4	-		a
0-8	+0.051	+5.59%	a
0-12	+0.008	+0.83%	a

* Groups with the same letter are not statistically different.

FIGURE 4-5. Mean soil bulk density by soil layer.



4.7. Slash Parameters and O Horizon Depth

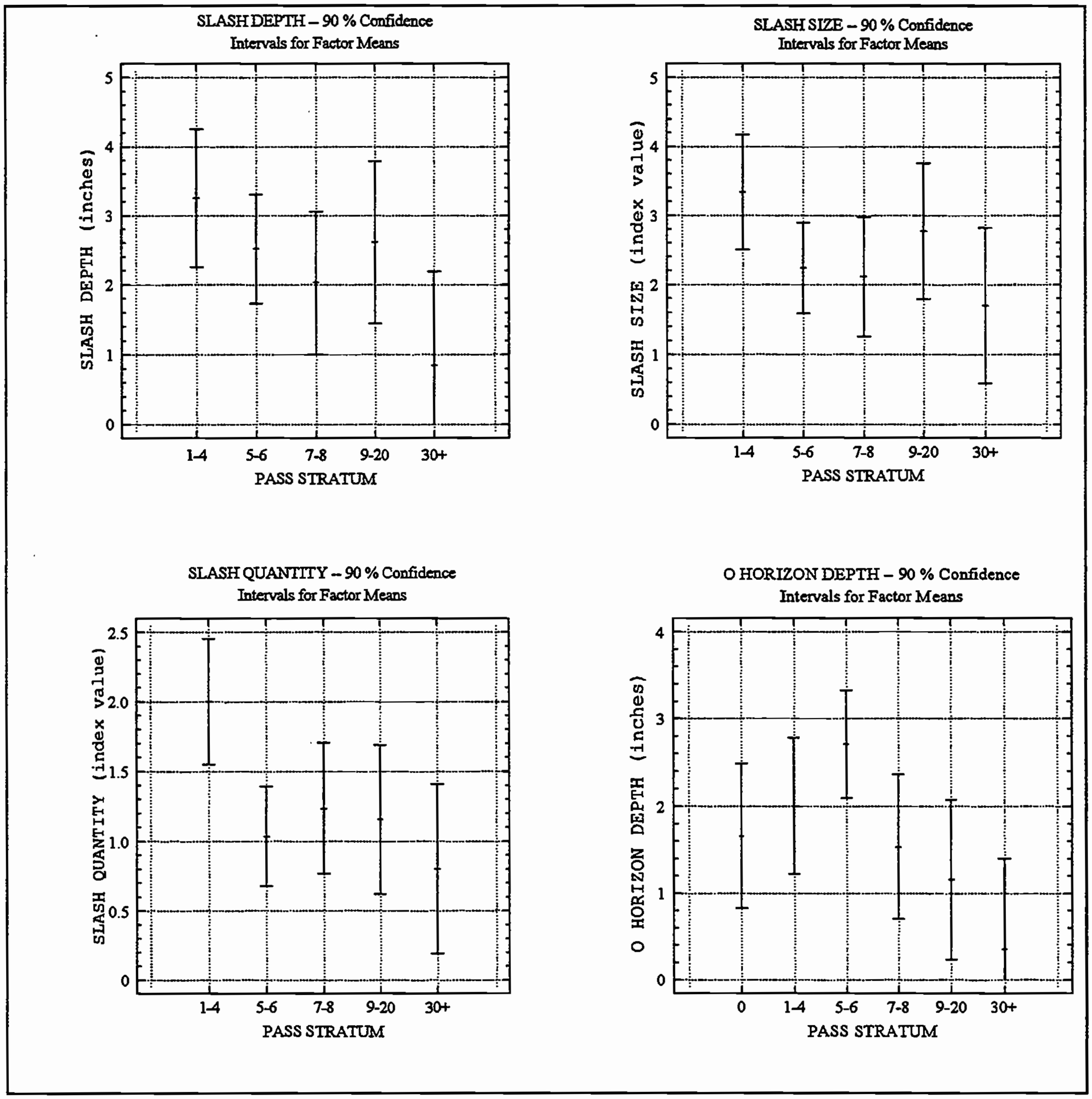
Mean values for slash parameters (size, quantity, and depth) and O horizon depth are shown in Table 4-7 and graphically displayed in Figure 4-6. The values for slash parameters are greatest for the 1-4 stratum and least for the 30+ stratum. Mean values for the slash parameters for the 5-6, 7-8, and 9-20 pass stratums are not statistically different but in general, there is a trend of decreasing mean values for slash parameters with increasing number of equipment passes. There is no evidence of any correlation between O horizon depth with equipment passes.

TABLE 4-7. Mean values for slash parameters and O horizon.

PASS STRATUM	MEAN SLASH SIZE (index value)	MEAN SLASH QUANTITY (index value)	MEAN SLASH DEPTH (inches)	MEAN O HORIZON DEPTH (inches)
0	0	0	0	1.65 (.50)ab
1-4	3.33 (.50) b	2.00 (.27)	3.25 (.60) b	2.00 (.45) bc
5-6	2.24 (.39)a	1.03 (.21)a	2.52 (.47) b	2.71 (.37) c
7-8	2.11 (.51)a	1.24 (.28)a	2.02 (.62)ab	1.53 (.48)ab
9-20	2.77 (.59)ab	1.15 (.32)a	2.61 (.70)ab	1.15 (.55)ab
30+	1.70 (.67)a	0.80 (.37)a	0.85 (.80)a	0.35 (.63)a

Number in parenthesis equals pooled standard error; Means in columns followed by the same letter are not significantly different at the 90 percent confidence level.

FIGURE 4-6. Mean values of slash parameters and O horizon depth with 90 percent confidence intervals.



4.8. Regression Analysis

Stepwise regression analysis was used to determine if the variables describing slash conditions at the sample points (depth, size, and quantity), slope, O horizon depth and number of equipment passes were associated with soil compaction. For the slash size and quantity index values, indicator variables of 0 or 1 were used. The results of the regression indicated that only a root value of the number of equipment passes was significant, with low r-squared values (< 20%).

Failure of the regression analysis to demonstrate an influence of slash size and quantity on soil density may stem from the use of index values. The index values were subjective estimates and may not correlate as well as actual values or actual determination of slash mass. Slash depth may not have shown any correlation due to the fact that depth was measured after equipment passage. The crushing of the slash by the equipment would tend to create a more uniform slash depth there by masking any potential correlation between depth and soil density.

Other non-measured variables such as rock content, soil moisture at the time of logging and potentially, a non-linear relationship with equipment passes, probably contributed to the low r-squared values.

4.9. Area Impacted

The amount of area in each stratum, its percent of the total trail system, and percentage of the total study area is shown in Table 4-8 and Figure 4-7. Area was determined using GIS software, ARC/INFO (ESRI 1992). The trail survey data were imported into ARC/INFO and trail arcs were buffered 9.8 feet wide (3.86 m) wide. The road through the unit was buffered 18 feet wide (5.49 m). Widths used for buffer distances were determined by taking random measurements of the equipment trails and road width throughout the unit.

Total area logged was determined by creating a boundary 25 feet (9.84 m) from the ends of all trails, the reach of the harvester from the trail. Figure 4-8 is the final map produced using ARC/INFO. Using tables functions in ARC/INFO, total area harvested and trail area within each stratum could be determined.

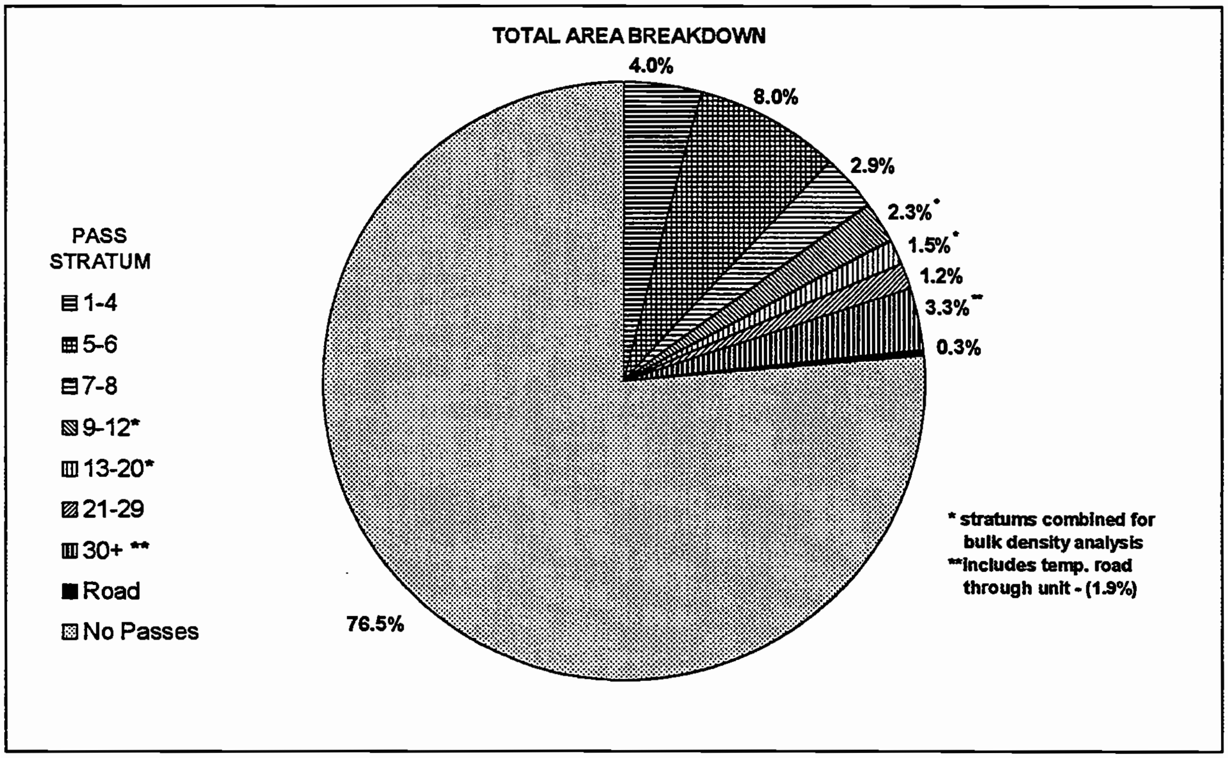
Disturbed area in equipment trails equals 23.2 percent of the total area. The road through the unit is included in this total because initially it was an equipment trail in the 30+ stratum then constructed as a road. Of the area in trails the largest percentage (8.0 percent) is in the 5-6 pass stratum. This category typically included a round trip with the harvester and two round trips with the forwarder, one for pulpwood and another for sawlogs.

TABLE 4-8. Area of logging unit by equipment pass strata.

PASS STRATUM	HECTARES	ACRES	% OF TOTAL AREA	% OF TOTAL TRAIL
1-4	0.202	0.50	4.0	17.4
5-6	0.399	0.99	8.0	34.4
7-8	0.146	0.36	2.9	12.6
9-12*	0.114	0.28	2.3	9.8
13-20*	0.077	0.19	1.5	6.6
21-29	0.059	0.15	1.2	5.1
30+**	0.164	0.41	3.3	14.1
Trail Subtotal	1.161	2.87	23.2	100.0
Background	3.830	9.46	76.5	
Main Road	0.015	0.04	0.3	
Total Area	5.006	12.37	100.0	

* Stratums combined for soil bulk density determination.
** Includes temporary road
- 0.097 hectares
- 0.24 acres
- 1.9% of total area
- 8.4% of total trail area

FIGURE 4-7. Percent of area in each pass stratum.



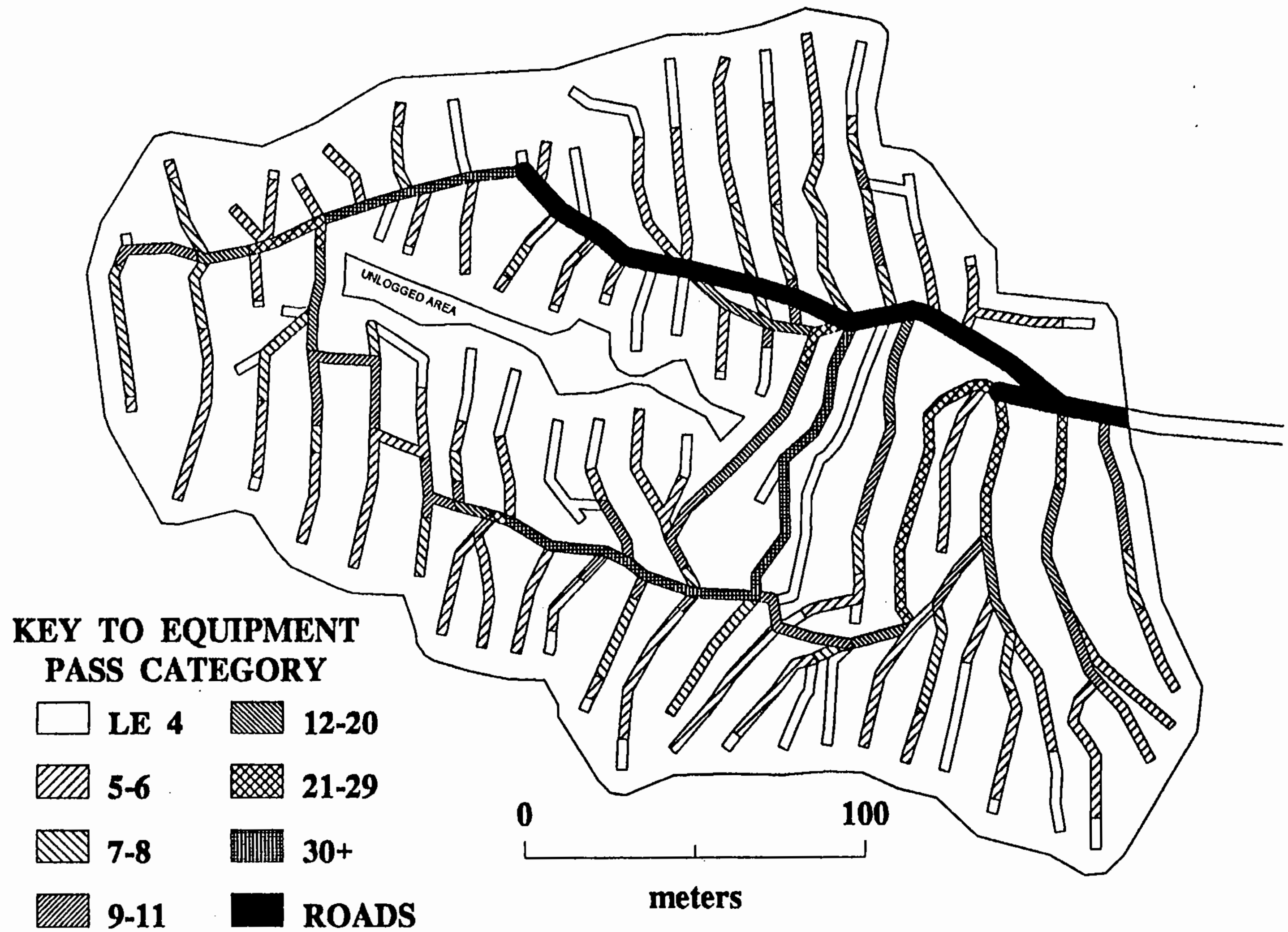


Figure 4-8. Buffered trail map.

5. Discussion

Direct comparison of the actual density values determined in this study with those of other soil-logging impact studies is not reasonable because of the tremendous variation in soils, machinery, logging conditions, and study methods. However, it is possible though to look at general trends between this study compared with others. Of particular interest is how the results of this study compare with others with regard to increasing soil density as a function of number of equipment passes and associated variables (slash, O horizon depth, and slope), depth of compaction, and areal extent of impact. Also of interest is the effect of the coarse rock fraction of the soil on soil compaction and potential impacts on site productivity.

5.1. Effects of Multiple Passes

In general the results of this study are similar to other studies reviewed that looked at the effect of multiple passes. Nearly all studies that measured change in density with increasing equipment passes reported the major portion of the total increase in density occurs within the first few passes changing little with additional passes (Froehlich 1978 and 1980; Steinbrenner 1955; Shetron et al. 1988; Guo and Karr 1989; Greene and Stuart 1985; and Burger 1985). The only exception to this found, was Huyssteen (1989) who reported an almost linear increase in the rate of "compactness" with increasing passes.

Results of this study show that the major portion of density increase occurred within the first four passes, but that density increased again sharply somewhere after 20 passes. (Note: This statement is based on the fact that the actual jump in density was observed in the 30+ pass stratum but since no data was available for passes between 20 and 30 it is possible that a 21-29 pass stratum may have shown an increase in density.)

Few studies looked at equipment passes beyond 20 but in one that did (Froehlich, 1978), change in density at one site was small through 20 passes but after 90 to 100 passes there was a substantial increase in density.

There are several possible explanations why there was a large increase in soil density in the 30+ pass stratum. If driving on slash does reduce ground pressure, the fact that the 30+ stratum had the lowest slash parameter values (see figure 4-6) indicates that these high use trails either never had or lost the benefits of slash protection as a result of high traffic. It is also possible that heavy travel may have removed the upper soil horizons exposing the lower horizons which had a higher initial density. Another possible explanation is along the lines of conclusions reached by Wingate-Hill and Jakobsen (1982). They state that "under certain soil conditions increasing soil strength with an increasing number of passes in the same track will cause a reduction of soil-tire contact area with consequent increased ground pressure. This leads to an even higher final soil density, which will be reached only after a large number of passes." It is probable that in this study the increase in density measured after 30+ pass was a combination of all the factors mentioned above.

5.2. Effects of Other Variables

5.2.1. Slash

An interesting trend for the measured slash parameters (size, quantity and depth) is that they mirror the changes in density with increasing passes. Although the difference in the slash parameter values are not all statistically significant (ref. Table 4-7) the general trend is that the 1-4 pass stratum has the highest slash values, the intermediate stratums tend to level off then decrease in the 30+ pass stratum. The low slash parameter values in the 30+ stratum may be due either to no or very little slash placed on the main equipment trails and/or after a large number of passes the slash and duff layer that was present was diminished through crushing and/or removal from the trail surface. Since the highest slash values are associated with the low density values in the 1-4 pass stratum and the lowest slash values are associated with the highest density values in the 30+ pass stratum this suggests that there may be a factor of protection offered by the slash layer. A relationship between slash and reduced soil compaction was found in other studies reviewed (see Section 2-3).

The potential reasons that regression analysis did not show any correlation between the slash parameter values and soil density were brought forth in Section 4-8.

5.2.2. Slope and O Horizon Depth

No correlation was found with either slope or O horizon depth and soil compaction levels (Section 4.8). Sidle and Drlica (1981) also found that slope gradient had no apparent effect on soil compaction although direction of travel (uphill or downhill) did.

The lack of correlation between O horizon depth and level of soil compaction may have resulted from a high variability of O horizon depth on the study area, and the fact that the slash covering may have prevented it from being crushed or removed.

5.2.3. Coarse Rock Fragments

The soils in the study area were very stony. Though no quantitative measure was made regarding the amount of rocks in the soil an ocular estimate of average size and relative quantity was made in regard to the rock content immediately below the measurement point. Approximately 75 percent of all measurement points had a moderate or high estimate of rock content. No research was found that discussed the impact of coarse fragments on soil compaction. Froehlich (pers. comm.) feels that a significant amount coarse fragments may lead to a soil being less susceptible to compaction due to bridging between large fragments and dispersion of the load, however little research has been done to support this theory. It is probable though, that even with a "bridging effect" there will be some increased soil density due to particle and aggregate consolidation due to vibration. Where there is no "bridging effect" though, the effect may be to make a bad situation worse if the soil density surrounding rock fragments is strong enough to prevent root penetration. It is not possible to specifically determine in this study whether or not the effect of coarse fragments on soil compaction is notably positive or negative.

5.3. Depth of Compaction

Because the method of measuring soil compaction in this study measured soil density from the soil surface down to the bottom of each soil layer and not at a specific depth, it is not possible to determine a what point, if any, compaction did not occur. The data in Table 4-5 shows that with increasing depth the percent change in density over background (0 passes) decreased with increasing depth. This infers that less compaction occurred with increasing soil depth.

It can be inferred from the data for the 0 pass stratum in Table 4-6 that the 8-12 inch soil layer is significantly more dense than the 0-4 inch layer. This indicates that the deeper soil has more strength and therefor less susceptible to compaction.

Other studies have reported a wide range of results in regard to depth of compaction. Huyssteen (1989) and Jakobsen and Greacen (1985) both reported compaction to 80 cm (31.5 in) while Burger (1985) reported no compaction below 15 cm (6 in). It must be kept in mind though that density effects are determined by many factors, thus one would expect a wide range of results.

Despite the increased homogeneity in density of the soil layers due to equipment passage (see section 4-6) the upper 0-4 inch layer continues to have a lower (though not necessarily statistically significant) density than the density of deeper layers. This may be explained in part by the fact that the 0-4 inch layer had the lowest initial density. Other possible reasons may be that it has a higher organic content which is less compatible or on points not protected by a layer of slash there may have been some churning action by the equipment tires that reduced the level of potential compaction.

5.4. Areal Extent

The area in each pass category and the increase in soil compaction is summarized in Table 5-1.

Comparing the areal extent of soil impact in this study with that of other studies finds that it is approximately midrange. Zaborske (1989) found that 54.5 percent of his study area was covered by skid trails. Froehlich and McNabb (1984) reported that during conventional ground based operations where machine operators select travel routes as needed, the amount of area in skid trails can range from 18 to 40 percent. Murphy (1982) found that preplanning skid trails in a commercial thinning in western Oregon led to trail areas as low as 11.7 percent.

The harvester used in this study had a reach of approximately 25 feet. With perfect layout of trails the area covered would be 20 percent, assuming a 10 foot wide trail. Area reported in equipment trails (Tables 4-9 and 5-1) does include the center portion between the tracks. Studies have shown that there is measurable compaction that can occur beyond the actual width of the track both through the forces exerted by the machine and carried load and those exerted by the dragging end of a log load (Raghavan et al. 1976; Huyssteen, 1989). Although the compaction level between the tracks may not impede root growth, a tree growing between the tracks may eventually have its growth adversely affected by confinement of root spread due to compaction directly below the tracks.

TABLE 5-1. Stratum area and summary of percent soil density increase over background.

PASS CATEGORY	HECTARES	ACRES	% AREA	% SOIL DENSITY INCREASE ----- SOIL LAYER ----- 0-4 in.	0-8 in.	0-12 in
1-4	0.202	0.50	4.0	20.0%	14.4%	8.9%
5-6	0.399	0.99	8.0	9.45%	9.7%	7.5%
7-8	0.146	0.36	2.9	16.6%	15.5%	11.3%
9-12*	0.114	0.28	2.3			
13-20*	0.077	0.19	1.5	17.9%	12.0%	10.1%
21-29	0.059	0.15	1.2	1/	1/	1/
30+**	0.164	0.41	3.3	28.6%	22.7%	19.6%
TRAIL SUBTOTAL	1.161	2.87	23.2			
Back-ground	3.830	9.46	76.5			
Main Road	0.015	0.04	0.3			
TOTAL AREA	5.006	12.37	100.0			

* Stratums combined for soil bulk density determination.
**Includes Temp. Road: 0.097 ha; 0.24 ac; 1.9% of area.
1/ No data available for soil density determination.

5.5. Site Productivity

The effects of compaction on tree growth involve complex interactions between soil strength, water and nutrient availability, aeration, and mycorrhizal populations (Grecian and Sands 1980). Relationships between tree growth and increases in soil density have been reported in many studies

(Froehlich and McNabb 1984). The majority of studies with a few exceptions show that compaction does reduce volume growth. However, according to Froehlich and McNabb (1984) following commercial thinning reduction of growth of individual trees appears to be a function of the percentage of root zone compacted. Froehlich (1979) reported that for Douglas-fir growing in moderately compacted soil (10 to 40 percent of the rooting area compacted) growth was reduced and average of 17 percent. Trees grown in heavily compacted soil (more than 40 percent of the rooting area compacted) growth was reduced 27 percent.

In examining stand damage on this study site, Kellogg and Bettinger (1993) found that within 35 randomly located, non-overlapping, tenth acre plots, 2.8 percent of all trees had visible damage to parts of the tree which were previously below ground. Based on this fact and the fact that trails were systematically laid out and used, it is likely that the percentage of the tree root zone impacted overall is quite low. The potential reduction in total stand growth as a result of compaction is consequently likely to be small. Further, it is probable that any loss in growth by individual trees is more than compensated for by increased growth in the stand as a whole as a result of thinning.

The importance of limiting the amount of root zone impacted emphasizes the need to limit future operations to those trails already impacted.

6. Conclusions

It can be concluded through review of literature on soil compaction that the interaction of many physical, biological, and mechanical factors cause a wide range of results both within and between studies. A common thread though most of the studies of soil compaction after multiple passes is that the major portion of soil bulk density increase occurs within the first few passes by a machine. The results of this study tend to support this finding. In addition, although it can not be definitively said from the results of this study that driving on a layer of slash mitigated compaction, the results indicate that some protection may be offered.

The question of whether or not operating large mechanized harvesting equipment versus that used conventional harvest systems can cause more compaction is not an easy question to answer. Cafferata (1992) in a synopsis of Froehlich's work on soil compaction, states that "When comparing logging machines, there is surprisingly little difference in compaction due to different types of vehicles." Ground pressure produced by equipment is dependent not only on the weight and motion of a machine but the total amount of tire or track area in contact with the ground surface. As shown in Table 2-7 , static ground pressures produced by large equipment are not that much greater than, and sometimes less than that produced by most conventional logging equipment due to the larger footprint of their tires or tracks. Soil type and conditions are also important variables to be considered when addressing compaction issues.

Another important consideration in comparing "mechanized" and conventional harvesting equipment is the amount of travel over a given trail. Forwarders may require only one pass over a trail to remove the same amount of volume that would require many trips with a skidder. But conversely, a mechanized harvesting system may cover more area than a conventional harvesting system which uses designated skid trails and pulling winch line.

To answer the question of which harvest system is best to use in any given situation, not only should consideration be given to soil compaction impacts, but also to residual stand damage, loss of nutrients (in the case of whole-tree harvesting), and economics. Economics should not only include the operational factors, but also the costs of potential loss in site productivity. Stuart et. al (1988) developed an economic model for soil compaction which looks at changes in present value per acre based on changes in site productivity as a result of soil compaction. In an example of a model operation, their results indicated that avoiding soil compaction increased present value per acre. The increase represents the justifiable increase in cost for a yarding system that would reduce the adverse effects of soil compaction or the amount that could be spent for amelioration through for example, soil tillage of the skid trails.

When considering just the potential degree of soil compaction that can occur in a logging area, control of impacts is possible mainly through regulating the period of logging and the operational aspects such as the type of equipment used, the areal extent of equipment travel, and the amount of equipment travel.

One method of regulating the degree of site impact adopted by the United States Forest Service - Region 6 (1990), is to set standards on the maximum areal extent of detrimental compaction that can occur. Their manual direction states that a minimum of 80 percent of the activity area shall be left in a condition of acceptable productivity for trees and other managed vegetation following land management activities. Detrimental compaction, defined by an increase in soil bulk density of 15 percent or more on soils that are not volcanic ash or pumice, is one of the criteria used by the Forest Service to determine maximum limits of unacceptable site impact. In this study area, in considering the 0-4 inch soil layer which showed the largest increase in soil density, 15.2 percent of the had more than a 15 percent increase in density area (when including all area in stratum 21-29 and 30+). If the temporary road used as a trail in the 30+ stratum is excluded, the total would drop to 13.3 percent of the area.

The total area with a greater than 15 percent increase in soil density drops to 4.5 percent of the area when considering the 0-12 inch soil layer (21-29 pass stratum included with the 30+ stratum). Based on the criteria established by the U.S. Forest Service - Region 6, the compaction incurred on this study area would be acceptable when considering soil density increase in any layer.

Difficulties and concerns in applying this policy, though, include defining what detrimental compaction is and measuring the areal extent of compaction. One possible pitfall in defining detrimental compaction is that different vegetation may react differently to the same degree of compaction as shown by Minore et al. (1969) (see Section 2.7). Basing the areal extent of detrimental soil compaction simply on the total area in skid trails may not be reasonable as indicated by this study but conversely, determining the areal extent by percentage increase category based on statistically sound sampling can be very time consuming.

7. Further Research

Additional research, to add to the body of knowledge in regard to the effect of mechanized harvesting equipment on soil compaction, is needed. With a larger pool of information on how soil compaction is influenced by site and machine factors and their interactions, better decisions can be made in regard to how, when, and where various harvesting methods should be used. Suggested additional studies include:

1. Further research on the influence of driving on slash to mitigate soil compaction. An experimental design in which the depth and mass of the slash mat is determined and its effect on reducing soil compaction is quantitatively determined as influenced by the number of machine passes is suggested.

2. Examination of specific compaction effects across the trail profile. For example, at the edge and center of the trail.

3. Study alternative methods of trail layout or equipment use that may reduce the amount of area in trails.

4. Develop predictive equations for increases in soil density caused by mechanized harvesting equipment that can be used by land managers for differing site conditions and equipment types.

5. Investigate use of a global positioning system to record equipment position and usage within logging units.

In addition to the direct effect of compaction on soil bulk density, studies looking at the long term effect on site productivity on a stand level needs to be considered. Many previous studies have shown that trees grow poorly in heavily compacted soil. It may be possible, however that the crowns of nearby trees in non-compacted soil may be able to utilize the additional space, and over time compensate for loss of volume from trees growing poorly in, or immediately adjacent to, skid trails.

Studies defining operational standards for various harvesting systems that will achieve acceptable levels of site impacts will also be of value to land managers.

Literature Cited

Adams, P.W., and H.A. Froehlich. 1981. Compaction of forest Soils. A Pacific Northwest Extension Publication, No. 217. 13 pp.

Allbrook, R.F. 1986. Effect of skid trail compaction on a volcanic soil in central Oregon. Soil Sci. Soc. Am. J. 50:1344-1346.

Bettinger, P., and L.D. Kellogg. 1993. Residual stand damage from cut-to-length thinning of second growth timber in the Cascade Range of western Oregon. Forest Prod. J. 43(11/12):59-64.

Bettinger, P., J. Sessions, and L. D. Kellogg. 1993. Potential timber availability for mechanized harvesting in Oregon. Western Journal of Applied Forestry. 8(1):1-5.

Burger, J.A., J.V. Perumpral, R.E. Kreh, J.L. Torbert, and S. Minaei. 1985. Impact of tracked and rubber-tired tractors on a forest soil. In: Transactions of the ASAE 28(2):369-373.

Cafferata P. 1992. Soil compaction research. Forest Soils & Riparian Zone Management: The Contributions of Dr. Henry A. Froehlich to Forestry. Oregon State University, Corvallis Oregon. p. 8-22.

Dyrness, C.T. 1965. Soil surface condition following tractor and high-lead logging in the Oregon Cascades. J. Forestry. 63(4):272-275.

Environmental Systems Research Institute, Inc. 1992. PC ARC/INFO Version 3.4D Plus. Environmental Systems Research Institute, Inc., Redlands, CA.

FMG Timberjack. 1983. Reference Manual: Cut-to-length harvesting products. FMG Timberjack Inc., Woodstock Ontario, Canada.

Fries, J. 1974. Views on the choice of silvicultural methods and logging techniques in thinning. (British) Forestry commission report No. 55, Aspects of thinning. p. 95-101.

Froehlich, H.A. 1978. Soil compaction from low ground-pressure, torsion-suspension logging vehicles on three forest soils. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. Research paper 36. 13 pp.

Froehlich, H.A. 1979. The effect of soil compaction by logging on forest productivity. Final report to the USDI Bureau of Land Management, Contract 53500-CT4-5(N). Oregon State University, Corvallis, Oregon. 19 pp.

Froehlich, H.A., D.E. Aulerich, R. Curtis. 1981. Designing skid trail systems to reduce soil impacts from tractive logging machines. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. Research paper 44. 15 pp.

Froehlich, H.A., J. Azevedo, P. Cafferata, and D. Lysne. 1980. Predicting soil compaction on forested land. Final Project Report to USDA For. Serv. Pac. NW For. Range Exp. Stn. and Missoula Equipment Development Center, under Coop. Agree. No 228. 120 pp.

Froehlich, H.A. and D.H. McNabb. 1984. Minimizing soil compaction in the Pacific Northwest forests. In: Earl L. stone (Ed.) Forest Soils and Treatment Impacts. Proc. of Sixth North American Forest Soils Conference. Univ. of Tenn. Conferences, Knoxville, Tenn. June 1983 p. 159-192.

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

Green, W.D. and W.B. Stuart. 1985. Skidder and tire size effects on soil compaction. Southern Journal of Applied Forestry. 9(3):154-157.

Guo., Y. and B.L. Karr. 1989. Influence of trafficking and soil moisture on bulk density and porosity on Smithdale sandy loam in north-central Mississippi. Proceedings of the fifth biennial Southern Silvicultural Research Conference: Memphis, Tennessee, Nov. 1-3. Southern Forest Experiment Station, 1989. p. 553-538.

Helms, J.A. and C. Hipkin. 1986. Effects of soil compaction on tree volume in a California ponderosa pine plantation. Western J. Appl. For. 1(4):121-124.

Huyssteen, Van L. 1989. Soil compaction under the wheels of different forwarders. Unpublished. Report on visit to Kwambonambi, Zululand, Dec. 4-7, 1989. Stellenbosch, South Africa. 42 pp.

Jakobsen, B.F., and E.L. Greacen. 1985. Compaction of sandy forest soils by forwarder operations. Soil Tillage Res. 5:5-70.

Jakobsen, B.F., and G.A. Moore. 1981. Effects of Skidders and of a slash cover on soil compaction by logging of mountain ash. Aust. For. Res. 11:247-255

Jarmer, C., and L.D. Kellogg. 1991 Delimber/skyline tower: a reasonable choice in Northwest. Forest Industries. 118(1):24-26.

Kairiukstis, L. and Z. Sakunas. 1989. Impact on soil of machinery used for cutting and reforestation. Seminar on the impact of mechanization of forest operations on the soil, Louvain-la-Neuve, Belgium. Economic Commission for Europe Food and Agriculture Organization and International Labour Organization. 13 pp.

Kellogg, L.D., and P. Bettinger. 1993. Thinning productivity and cost for a mechanized cut-to length system in the northwest Pacific Coast region of the USA. Journal of Forest Engineering

Kellogg, L.D., and M. Brink. 1992. Mechanized felling in the Pacific Northwest: existing and future technology. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. Special Publication 25. 7 pp.

Kellogg, L.D., P. Bettinger, S. Robe, and A. Steffert. 1992. Mechanized harvesting: a compendium of research. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. 401 pp.

Kellogg, L.D., P. Bettinger, and D. Studier. 1993. Terminology of ground-based mechanized logging in the Pacific Northwest. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. Research Contribution 1. 12 pp.

Koger, J.L., E.C. Burt and A.C. Trouse Jr. 1985. Multiple pass effects of skidder tires on soil compaction. Transactions of the ASAE. 28:11-16.

King, A.L. 1979. Measuring soil compaction in mechanically thinned plantations. ASAE. Paper No. 79-1600, presented at 1979 Winter Meeting, Dec. 11-14, 1979. 8 pp.

McNeel, J.F. and T.M. Ballard. 1992. Analysis of site stand impacts from thinning with a harvester-forwarder system. Journal of Forest Engineering. 4(1):23-29.

Minore, D., C.E. Smith, and R.F. Wollard. 1969. Effects of high soil density on seedling root growth of seven northwestern tree species. USDA For. Serv. Pac. Northwest Forest and Range Exp. Stn., Res. Note PNW-112, Portland Oregon. 6 pp.

Murphy, G. 1982. Soil damage associated with production thinning. New Zealand Journal of Forestry Science. 12(2):281-292.

Omberg, H. 1969. The formation of tracks made by forwarders on forest soil. Royal College of Forestry, Stockholm, Sweden. Paper presented at the Int. Union Forest Res. Organization Meeting. p. 144-150.

Raghavan, G.S.V., E. Mckyes, and M. Chasse, 1976. Soil compaction patterns caused by off-road vehicles in eastern Canadian agricultural soils. J. Terramechanics. 13(2):107-15.

Sessions, J., coord. Authors, western Oregon: K.N. Johnson, J. Beuter, B. Greber, G. Lettman, and J. Sessions. Authors, eastern Oregon: K.N. Johnson, J. Beuter, G. Lettman, and J. Sessions. Author, economic impacts: B. Gerber. 1990. Timber for Oregon's tomorrow. The 1989 Update. Forest Research Laboratory, College of Forestry, Oregon State University, Corvallis. 183 p.

Shetron, S.G., J.A. Sturos, E. Padley, and C. Trettin. 1988. Forest soil compaction: effect of multiple passes and loading on wheel track surface soil bulk density. North. J. Appl. For. 5:120-123.

Sidle, R.C., and D.M. Drlica. 1981. Soil compaction form logging with a low-ground pressure skidder in the Oregon Coast Ranges. Soil Sci. Soc. Am. J. 45:1219-1224.

Soil Conservation Service. 1987. Soil survey of Linn County Area. USDA, Soil Conservation Service; in cooperation with USDI, Bureau of Land Management, and Oregon Agricultural Experiment Station. 343 p.

Steinbrenner, E.C., 1955. The effect of repeated tractor trips on the physical properties of forest soils. Northwest Science. 29(4):155-159.

Stuart, R., H.A. Froehlich, E. Olsen. 1988. Soil compaction an economic model. Western J. Appl. For. 3(1):20-22.

U.S. Forest Service. 1990. FSM 2500, Chapter 2520 - Watershed protection and management. R-6 Supplement 2500-90-1. 24 pp.

Wingate-Hill, R. and B.F. Jakobsen. 1982. Increased mechanization and soil damage in forests -- a review. New Zealand Journal of Forestry Science 12(2):380-393.

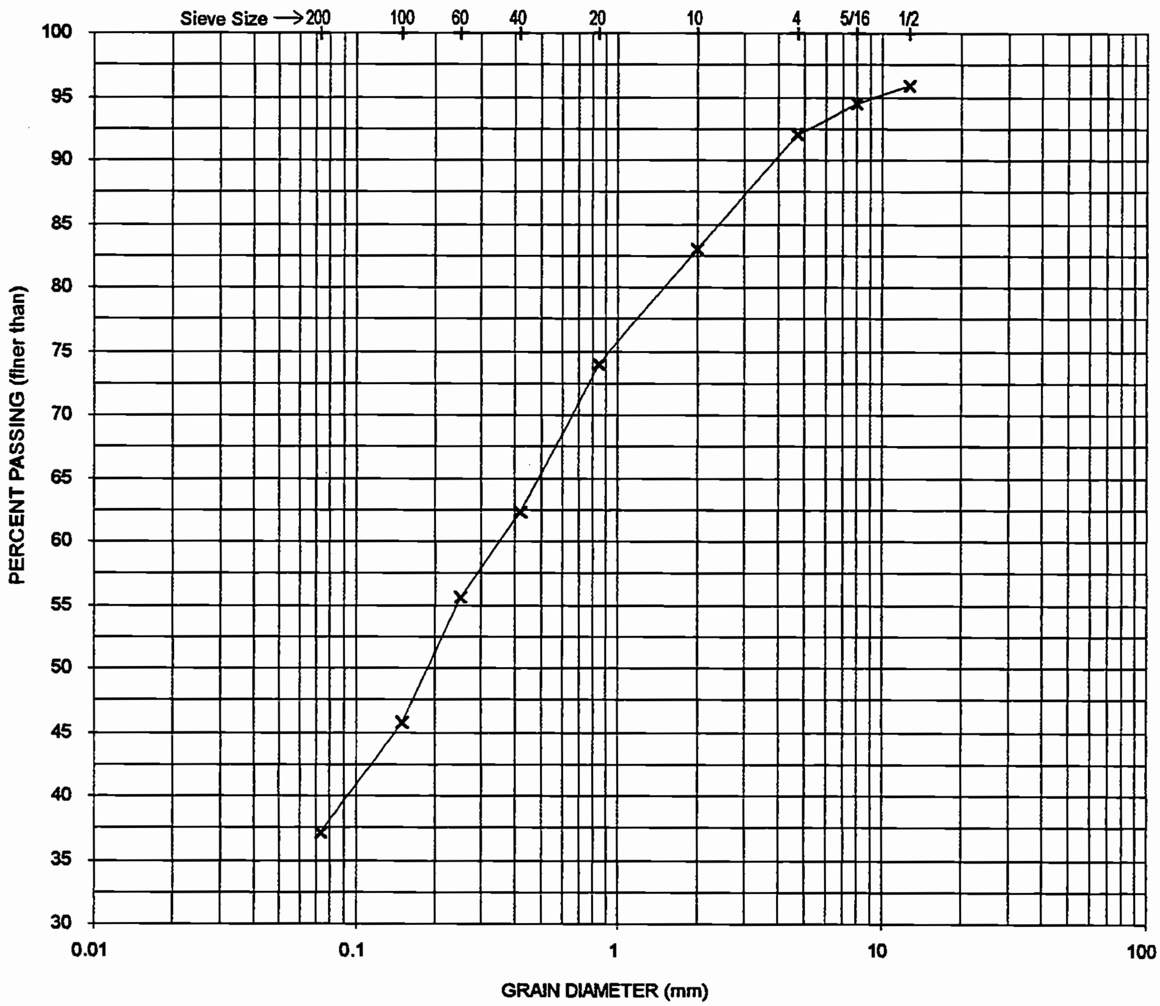
Wert, S. and B.R. Thomas. 1981. Effects of skid roads on diameter, height, and volume growth in Douglas-fir. Soil Sci. Soc. Am. J. 45:629-632.

Wronski, E.B. 1984. Impact of tractor thinning operations on soils and tree roots in a Karri forest, western Australia. Aust. For. Res. 14:319-332.

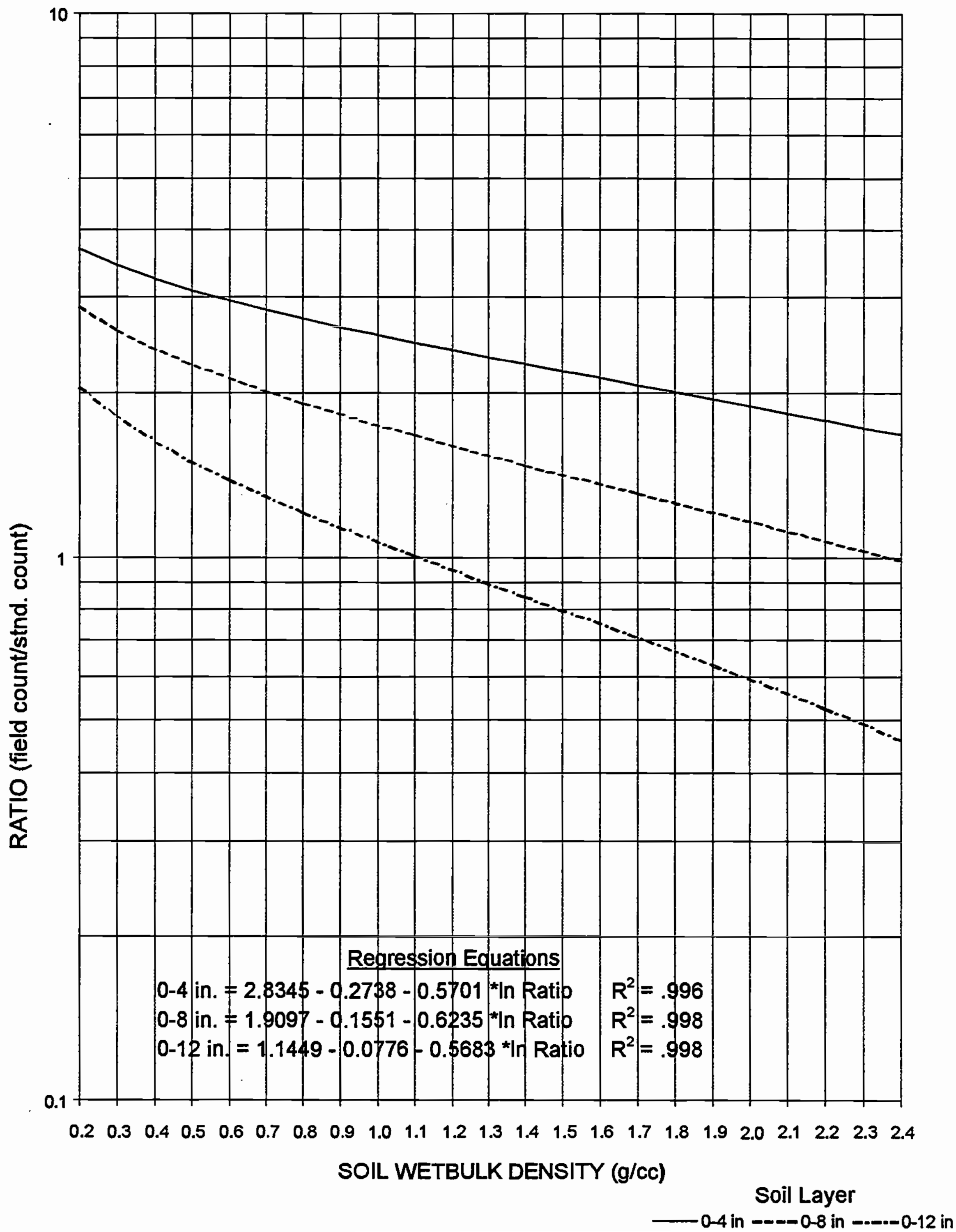
Zaborske, R. 1989. Soil compaction on a mechanized timber harvest operation in eastern Oregon. M.F. paper, Forest Engineering Department, Oregon State University. 89 pp.

Zisa, R.P., H.G. Halverson, and B.B. Stout. 1980. Establishment and early growth of conifers on compact soils in urban areas. USDA For. Serv. Northeastern Forest Exp. Stn., Res. Pap. NE-451, Broomall, PA. 8 pp.

Appendix A
Grain Distribution Curve



Appendix B
Soil Wet Bulk Density Calibration Curves



Appendix C
Sample Size Determination

The following formula was used for determining sample size (Zaborske 1989):

$$n = \frac{t^2 * s^2}{E^2}$$

n = sample size
t = student's t value for 90 percent confidence at infinite degrees of freedom (1.645)
s = computed standard deviation
E = allowable error (10% of the mean)

The result of the sample size analysis based on field count readings for the first 16 background measurement points are shown in the following table:

Depth of Measurement	Mean Field Count	Standard Deviation	Number of Samples*
0-4	17310.0	2406.0	6
0-8	9670.7	2393.6	17
0-12	4312.5	1424.6	30

*Number of samples based on 90% confidence within 10% of the mean

Appendix D
Forwarder Turn Map

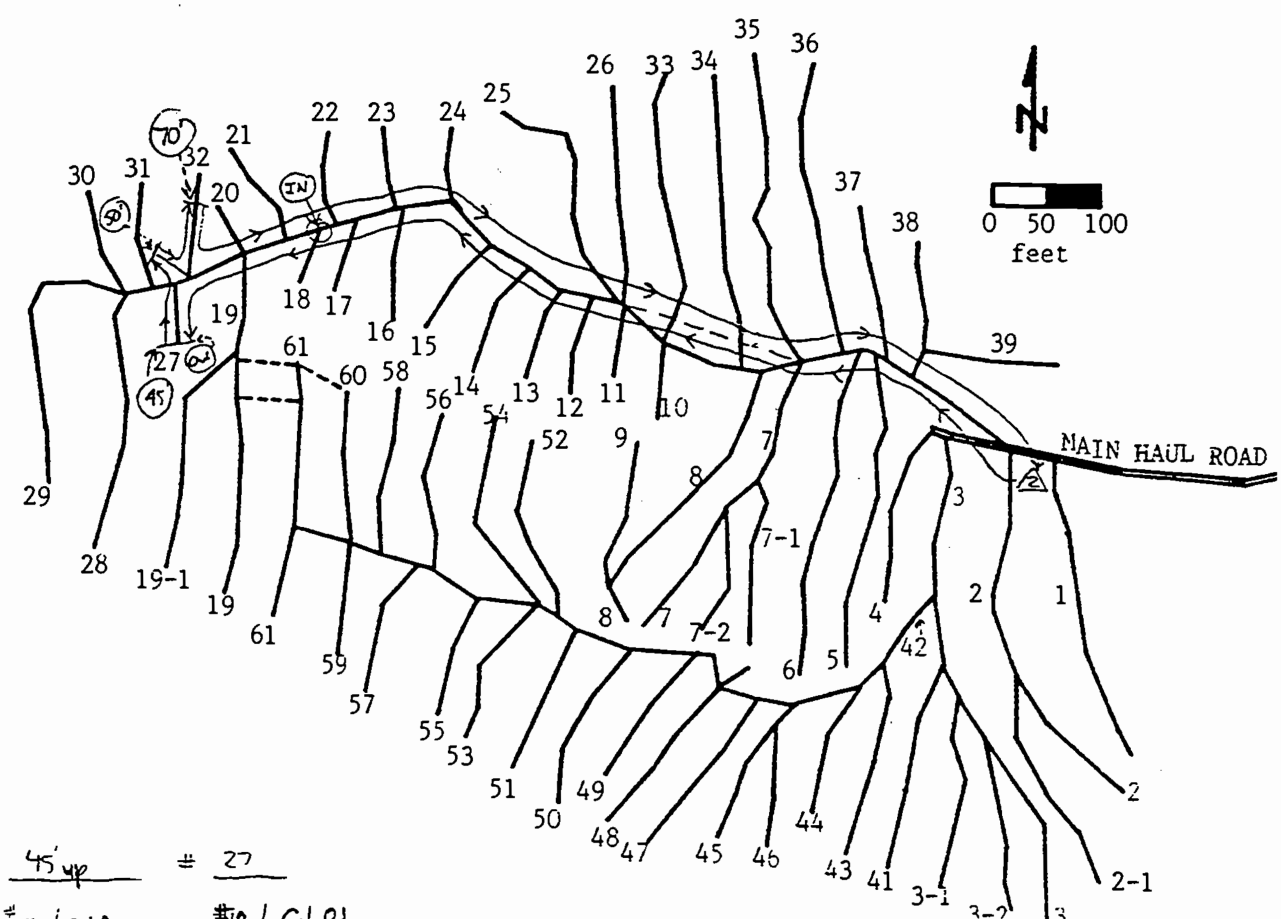
HARVESTER / FORWARDER STUDY - SUMMER 1992

(2 saw trailer/pup)
Off-load:
卌 卌

Date	7-22-92	Start Time	0725
Location	Avery	End Time	0820
Operator	Shawn		
Machine	FMG 910 Forwarder		
Cycle No.	152		
Dist. Out		Distance In	

Weather Conditions Cool / Overcast / wet ground

Comments Single Product ⇒ Saw Logs



Out 45' up # 27

In # 18 / Cat Rd junc #18 / Cat Rd

Appendix E
Measurement Point Data

PLOT NUMBER	STRATUM	0-4 in.	0-8 in.	0-12 in.	O HORIZ.	SLD	SLS	SLQ	% SLOPE	MOIST. CONT.
BASE-2	BG	0.3731	0.5235	0.6579	1	0	0	0	35	0.3872
BASE-4	BG	0.4581	0.6548	0.7162	1	0	0	0	23	0.4890
BASE-6	BG	1.0750	1.0255	1.0059	0.5	0	0	0	29	0.3488
BASE-8	BG	0.8918	0.8234	0.8781	1	0	0	0	52	0.4141
BASE-10	BG	0.6208	0.6920	0.7781	1	0	0	0	12	0.3389
BASE-12	BG	0.7504	0.7664	0.8452	0.5	0	0	0	28	0.3874
BASE-14	BG	0.9456	0.9703	0.9614	0.5	0	0	0	28	0.2542
BASE-16	BG	1.0764	1.0594	0.9940	1	0	0	0	26	0.3458
BASE-18	BG	0.7980	0.9465	0.9245	2	0	0	0	22	0.3807
BASE-20	BG	0.6241	0.8231	0.8724	1	0	0	0	18	0.3953
BASE-22	BG	0.6277	0.7814	0.7835	3	0	0	0	16	0.4396
BASE-24	BG	0.5486	0.7925	0.8902	2	0	0	0	55	0.3772
BASE-26	BG	0.7602	0.8077	0.7100	7.5	0	0	0	24	0.3316
BASE-28	BG	0.4947	0.6208	0.7354	1.5	0	0	0	27	0.3393
BASE-30	BG	0.5534	0.6506	0.6614	1	0	0	0	36	0.3518
BASE-32	BG	0.7539	0.6187	0.576	2	0	0	0	12	0.3328
7A-1	1-4	0.9023	0.8995	0.9296	1	1	3	1	14	0.4447
7-1A-1	1-4	0.4249	0.5841	0.6278	1	2.5	2	3	24	0.3999
7-1A-2	1-4	0.9065	0.8867	0.8847	1	7	4	3	32	0.4680
7-1A-3 *	1-4	0.3704	0.3061	0.3387	2	5	5	2	35	2.2432
7-1A-4	1-4	0.7798	0.8955	0.9622	3	2.5	3	1	12	0.4770
7-1A-5	1-4	1.0819	0.9706	0.9136	0.5	0	0	0	17	0.3968
23A-1	1-4	0.8796	0.9344	0.9839	1	6.5	5	3	18	0.5526
25-1A-1	1-4	0.9252	0.8749	0.7846	5	4.5	5	3	20	0.4379
26A-1	1-4	0.8212	0.8708	0.8674	7	0	0	0	18	0.5239
26A-2	1-4	0.9091	0.8876	0.8119	0.5	4.5	5	3	12	0.4617
34A-1	1-4	0.6364	0.8332	0.7957	1	2	3	1	28	0.6738
36A-1 *	1-4	0.3394	0.4460	0.4264	2	0	0	0	15	1.2941
36A-2	1-4	0.7582	0.8433	0.8923	0.5	2	4	1	22	0.5019
52A-1	1-4	0.8527	0.9742	0.9989	1	7	6	3	28	0.4543
54A-1	1-4	1.0227	1.0687	1.0082	5	4	5	2	31	0.5842
54A-2	1-4	1.0364	1.0159	0.9405	4	3.5	3	3	9	0.4556
56A-2	1-4	0.9006	0.9687	0.9035	1	2.5	3	2	6	0.5086
58A-1	1-4	0.7472	0.9466	0.9022	0.5	1	3	3	10	0.3958
58A-2	1-4	0.9230	0.8348	0.8724	2	6	3	3	31	0.5101
60A-1	1-4	0.8175	0.8720	0.8257	1	2	3	1	25	0.4557
9-1B-1	5-6	0.9486	0.9957	1.0307	0	0	0	0	31	0.3830
9-1B-2	5-6	0.9063	0.9529	0.9135	1	5.5	6	3	22	0.4162
10B-1	5-6	0.7846	0.8137	0.8589	1.5	0	0	0	25	0.4343
11B-1	5-6	0.8362	0.9674	0.9394	1	0	0	0	24	0.4410
12B-1	5-6	0.7924	0.9169	0.9356	4	7	6	3	28	0.3906
16B-1	5-6	1.0360	1.0504	0.9970	6	3	4	1	23	0.4406
17B-1	5-6	0.6922	0.7359	0.7456	3	0	0	0	28	0.6616

PLOT NUMBER	STRATUM	0-4 in.	0-8 in.	0-12 in.	O HORIZ.	SLD	SLS	SLQ	% SLOPE	MOIST CONT
19B-1	5-6	0.6458	0.8751	0.9069	2.5	2	5	1	30	0.4747
19-1B-1	5-6	0.9066	0.9182	0.9576	0	0	0	0	25	0.4082
20B-1	5-6	0.6217	0.6074	0.7049	8	2.5	3	1	15	0.4377
21B-1	5-6	0.7425	0.6450	0.7131	1	7.5	6	3	12	0.4820
25B-1	5-6	0.7959	0.9096	0.8992	1	0	0	0	45	0.6418
26B-1	5-6	0.7801	0.8405	0.8528	4.5	0	0	0	28	0.5460
27B-1 *	5-6	1.0088	1.3100	1.1767	0	0	0	0	50	0.5691
28B-1	5-6	0.8138	0.9474	0.9360	2	0	0	0	28	0.4643
28B-2	5-6	0.5372	0.8779	0.9391	2	0	0	0	33	0.5802
32B-1	5-6	0.3578	0.4982	0.6812	0.5	0	0	0	22	0.7296
33B-1	5-6	0.8305	0.9089	0.9371	0.5	0	0	0	30	0.4585
33B-2	5-6	0.6992	0.8261	0.8594	10	2.5	3	2	24	0.4678
34B-1	5-6	0.7659	0.8212	0.8156	1	7	6	3	36	0.4323
37B-1	5-6	0.8102	0.9508	0.9490	0	0	0	0	20	0.3955
38B-1	5-6	0.5640	0.5943	0.6768	0.5	8.5	6	3	9	0.4949
55B-1	5-6	1.1466	1.0147	1.1166	2	2	3	1	22	0.4270
56B-1 *	5-6	0.1848	0.1382	0.4442	8	4	3	3	12	0.7613
56B-2	5-6	0.8182	0.9598	0.9190	6	0	0	0	14	0.6936
57B-1	5-6	0.9506	0.9932	0.9629	0.5	0	0	0	30	0.3798
57-1B-1	5-6	0.9922	1.1416	1.0689	2	3.5	5	2	35	0.3822
60B-1	5-6	0.5034	0.5936	0.5622	2	4.5	5	1	9	0.6498
61B-1	5-6	0.8134	0.9473	0.9102	7	8	3	3	40	0.5010
61B-2	5-6	0.6039	0.7637	0.7305	1	8.5	2	2	20	0.4235
61/60B-1	5-6	0.8008	0.8926	0.8006	8	1	2	1	18	0.4725
14C-1	7-8	1.0110	1.0693	1.0401	1	3	3	2	18	0.5645
15C-1	7-8	0.9104	0.9508	0.8091	0.5	1	3	1	38	0.6732
19C-1	7-8	0.9711	0.9218	0.9921	8	1.5	3	1	28	0.4452
19-1C-1	7-8	0.8944	0.9227	0.9764	1.5	5	4	3	23	0.4986
19-1C-2	7-8	0.9907	1.0950	0.9887	1.5	0	0	0	30	0.5048
22C-1	7-8	0.6183	0.8285	0.7921	2	0	0	0	20	0.9385
28C-1	7-8	0.8225	1.0937	1.1400	0	0	0	0	42	0.5971
29C-1	7-8	0.6372	0.5841	0.7092	1	0	0	0	40	0.4847
29C-2	7-8	1.1071	1.0067	0.9238	1	1	3	2	36	0.5690
30C-1	7-8	0.9790	1.0138	0.9757	1.5	3	5	2	21	0.5070
33C-1	7-8	0.8510	0.8764	0.7722	0.5	5	2	3	18	0.5119
33C-2	7-8	0.3957	0.6630	0.7510	0.5	0	0	0	24	0.5874
34C-1	7-8	1.0157	0.9873	0.9423	1	7.5	5	3	14	0.3962
35C-1	7-8	0.7961	0.8706	0.9265	1.5	0	0	0	22	0.4135
35C-2	7-8	0.8745	0.8830	0.8777	1	5	5	3	28	0.5185
36C-1	7-8	0.7775	0.9051	0.9364	2	0	0	0	28	0.5383
59C-1	7-8	0.4120	0.7459	0.8071	1.5	2.5	3	1	25	0.5469
8D-2	9-12	0.4476	0.5691	0.6445	1	4	5	1	14	0.8636
19D-1	9-12	0.8152	0.8467	0.8275	1.5	4	4	2	8	0.7777
19D-2	9-12	0.9377	1.0128	1.0103	1	0	0	0	10	0.4598
35D-1	9-12	0.6419	0.6925	0.7022	1.5	7.5	3	3	20	0.4377
36D-1	9-12	1.0063	1.0220	1.0322	0.5	1	2	1	12	0.5594

PLOT NUMBER	STRATUM	0-4 in.	0-8 in.	0-12 in.	O HORIZ.	SLD	SLS	SLQ	% SLOPE	MOIST CONT
52D-1	9-12	1.0254	1.0397	1.0235	0.5	2.5	3	1	10	0.4617
60D-1	9-12	0.8128	0.7653	0.8448	3.5	5	5	2	12	0.3353
61D-1	9-12	0.8360	0.8807	0.9086	1	4.5	4	2	25	0.4621
8E-1	13-20	1.2139	1.1953	1.0778	1	3	5	1	21	0.4110
8E-2	13-20	0.7166	0.8291	0.8887	1.5	0	0	0	18	0.5250
8E-3	13-20	1.0038	1.0700	1.0092	0	0	0	0	21	0.3990
19E-1 **	13-20	0.4438	0.5511	0.6728	1.5	2.5	5	2	36	0.7660
19E-2	13-20	0.9680	0.9484	0.9768	0.5	0	0	0	35	0.6170
7G-1	30+	1.1144	1.1093	1.0781	0	1.5	3	1	16	0.4654
7G-2	30+	0.7466	0.7542	0.8363	0.5	1.5	4	1	34	0.7534
7G-3	30+	1.0110	1.0658	1.0421	1	0	0	0	22	0.4321
7-2G-1	30+	0.9823	0.9531	0.9714	1	3.5	5	3	18	0.4270
7-2G-2	30+	1.1063	1.1799	1.0767	1	1.5	4	1	26	0.6216
42G-1	30+	0.9501	1.0201	0.9645	0	0	0	0	3	0.5654
42G-2	30+	1.1552	0.9648	1.0925	0	0	0	0	0	0.5339
42G-3	30+	0.6282	0.8025	0.8560	0	0	0	0	0	0.7921
42G-4	30+	0.9973	1.1175	1.0876	0	0	0	0	0	0.4929
42G-5	30+	0.4325	0.6626	0.7007	0	0.5	1	2	6	1.0090

SLD = Slash depth (inches)
SLS = Slash size (index value)
SLQ = Slash quantity (index value)
* = Outliers removed for ANOVA analysis
** = Additional outlier removed for regression analysis