Soil Bulk Density and Penetrometer Measurements After Harvester and Forwarder Traffic Over Different Slash Depths in the Oregon Cascades

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ABSTRACT

Bulk density and penetrometer (cone index) measurements taken after logging traffic over different slash depths were compared to pre-treatment values in two cut-to-length system commercial thinning units in the Oregon Cascade Range. Data collection was concurrent with thinning activities from September - November 1996. Non-random plots on designated skid trails measured the combined effect of harvester and forwarder traffic while those on short side-loops off the trails isolated the impacts of the forwarder alone. The harvester operator was asked to create a prescribed amount of slash (zero, low, moderate or high) by modifying the number of trees processed directly over the plots. The average slash depth after one harvester pass was measured for each plot.

Harvest unit, equipment pass category, slash treatment, soil moisture content, pre-harvest bulk density or cone index and skid trail location (rut or center) were tested for significance in predicting post-treatment bulk density or cone index with multiple linear regression. After 3-5 harvester-forwarder passes skid trail ruts increased by an average of 0.14 g/cm^3 ($p = 0.0073$) at the four-inch depth and 0.09 g/cm^3 ($p = 0.0302$) at eight inches above pre-treatment levels. The maximum compaction occurred after 6-10 passes with increases of 0.19 and 0.11 g/cm^3 at four and eight inches, respectively ($p = 0.0004$ and 0.0126). Increased bulk density in the center of harvester-forwarder skid trails became evident after 11-20 equipment passes and only at the four-inch depth. Harvester-forwarder traffic ruts with a high level of slash (8 - 18 in) were found to have 0.07 g/cm^3 lower bulk densities than ruts with low slash levels (4 - 7 in) at the four-inch depth. In contrast, the high slash treatment was associated with slightly higher bulk densities than the low slash treatment in the center of skid trails at both depths. Slash did not appear to have an affect in ruts at the eight-inch depth. Regression models utilizing penetrometer data produced similar results about the significance of treatments at both sampling depths in skid trail ruts. A clear picture of the effects of forwarder traffic alone on soil compaction was not produced by the data collected.

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Authors' Disclaimer

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Table 20: Estimated areal extent of compaction in skid trails, Unit 82. *Only pass categories found to be significantly different from zero pass level according to multiple linear regression model are considered compacted.

1. GENERAL OBJECTIVE

- Clarify how key operational and site variables influence soil compaction from mechanized thinnings (cut-to-length system) in western Oregon young conifer forests.

1.1. Specific Objectives

- Determine if and how machine traffic levels affect compaction
- Determine if and how slash affects compaction levels
- Determine if penetrometer measurements are adequate predictors of soil bulk density
- Compare conclusions from the bulk density and penetrometer data analyses regarding the significance of logging equipment traffic and slash treatments.

2. BACKGROUND

The shift to dependence on second-growth timber has increased interest in mechanizing forest harvest systems in the Pacific Northwest. Mechanization offers many advantages, including improved safety conditions, optimization of log lengths, and improved utilization of marketable timber (Howe 1994). It has been estimated that approximately 60% of western Oregon and 85% of eastern Oregon have ground slopes favorable for mechanized systems (Bettinger et al. 1993a). The degree of soil compaction associated with mechanized harvesting has been identified, however, as an area needing research (Bettinger et al. 1993b).

The cut-to-length (CTL) system (Kellogg et al. 1993) is becoming a particularly popular alternative for small-diameter stands in the region. Because both the harvester and forwarder used in a CTL system travel over slash deposited on skid trails by the harvester, it is possible that overall levels of soil compaction and disturbance are reduced. Froehlich (1978) suggested that the presence of a litter layer reduced the degree and depth of compaction following skidding with a low-ground-pressure, torsion suspension vehicle in three sites located throughout Oregon.

Seixas et al. (1995) examined the soil bulk density of Alabama loamy sands after forwarder passes at two traffic levels (one and five passes), three slash densities (0, 10, and 20 kg/m^2), and two moisture contents. The same degree of protection was offered by the 10 and 20 kg/m^2 slash treatments with dry soils, although on wet soils the higher slash treatment had significantly lower bulk densities than either the zero or 10 kg/m^2 slash treatment.

In a thinned, young-growth stand in the Oregon Coast Range, stepwise regression did not identify a trend of decreased compaction with increasing slash depth or diameter following skidding with a rubber-tired skidder and small crawler tractor (Hogervorst 1994). Skid trails without slash, however, were found to have a significantly greater mean bulk density than those with slash ($p<0.05$).

The effect of tractor skidder traffic (low-ground-pressure, torsion suspension vehicle and Caterpillar D-7) on bare or slash-covered soils (18 kg/m^2) on soil bulk density and penetrometer resistance was tested in Australia by Jakobsen and Moore (1981). Some protection was provided by the slash mat but only for a few logging cycles. No difference between the two vehicles was observed.

Another Australian study (Wronski 1990) concluded that the slash mat increased the apparent soil strength by 25% for every additional 10 kg/m^2 of slash placed above a base of 10 kg/m^2. A noticeable reduction in rut formation was also observed. Other Oregon studies (Armlovich 1995, Zaborske 1989) reported a trend of lower bulk densities associated with logging equipment traffic over slash.

Because of its reported negative affects on tree growth and the duration of the impact, compaction is a significant concern for the land manager. Geist et al. (1989) found compaction to persist in ash soil of the Blue Mountains up to 20 years, and Wert and Thomas (1981) observed significantly higher bulk densities than undisturbed soil on 32 year-old skid trails of the Oregon Coast Range. Compaction impedes root penetration and alters the supply of air, water and nutrients (Adams and Froehlich 1981). Reduced root and/or shoot growth in conifers has been associated with an increase in bulk density (Froehlich 1979, Heilman 1981, Minore et al 1969, Pearse 1958, Youngberg 1959). Though growth response has been found to vary with absolute bulk density and soil texture, Froehlich and McNabb (1983) found a consistent relationship between the percent change in bulk density and height growth of conifer seedlings and saplings (see Figure 1).

The association between growth response and the spatial extent of compaction in the rooting zone is an important but little-studied subject. Northwest Oregon Douglas-fir stands thinned in the previous 5 to 15 years were placed in one of three disturbance classes: light - <10% of the root zone affected by compaction, moderate - ≤40% of the root zone affected by increased bulk density (0-10% increase) and heavy - >40% of the root zone impacted by bulk densities increased by at least 10% (Froehlich and Berglund 1979). Though there was a net growth increase as a result of the thinning, the basal area growth of moderately disturbed trees was found to be reduced by 14% and heavily disturbed trees by 30% as compared to lightly disturbed trees. In a similarly structured study, the growth rate of eastern Oregon ponderosa pine in the moderate and heavy impact classes was reduced by 6 and 12%, respectively (Froehlich 1979). Helms and Hipkin (1986) averaged the bulk density from four points in the rooting zone of 16-year-old ponderosa pines in a California plantation in order to assign each tree to a compaction level group. Of the five groups (1.20, 1.10, 1.00, 0.90 and 0.80 g/cm^3), the tree

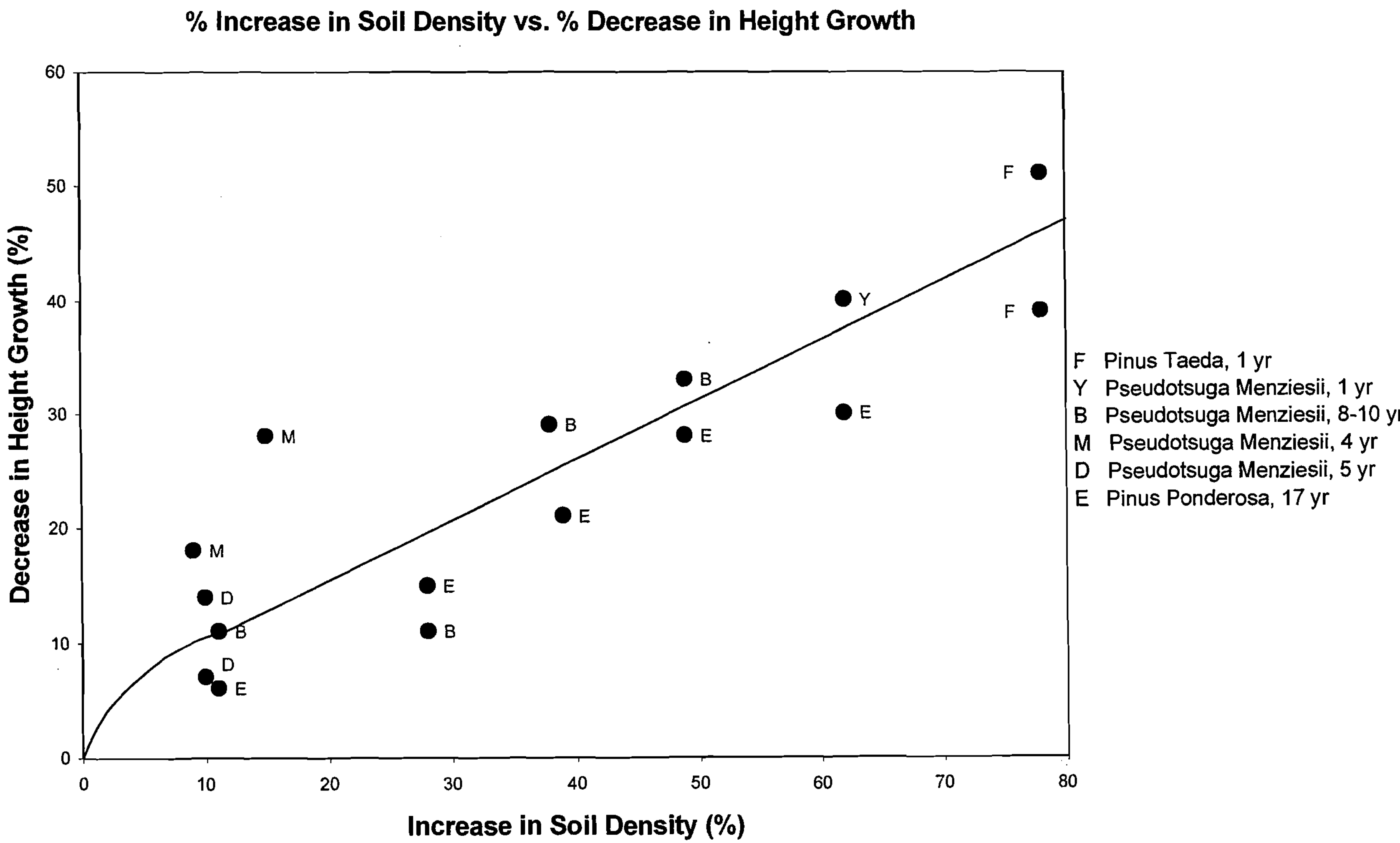

Figure 1: Relationship between the increase in bulk density and the decrease in conifer height growth. From F-Foil and Ralston (1967); Y-Youngberg (1959); B-Bureau of Land Management; and D, M, E-Froehlich (1979). Line is fitted visually. (Source: Froehlich and McNabb 1983.)

heights of the four highest bulk densities were reduced by 14, 13, 1 and 0% as compared to the 0.8 g/cm^3 level.

Though bulk density itself may not affect tree growth, it is correlated with less easily measured parameters such as soil strength and porosity which can be directly tied to growth rates. Soil core samples have been the traditional means of determining soil bulk density (Klute 1986). After taking a core sample of a known volume, the soil is dried and weighed in order to calculate a dry bulk density. Nuclear densimeters have become more common in forest soils research and have the advantage of non-destructively measuring a relatively large volume of soil. This device operates on the principle that the amount of radiation that can pass through a soil is inversely proportional to its density.

Another approach to assessing compaction is to estimate changes in the soil shear strength (Klute 1986). Penetrometers measure resistance as a metal rod with a cone tip is pushed into the soil. It has been suggested that "penetrometers provide the best estimate of resistance to root growth in soil, short of direct measurement of root force" (Bengough and Mullins 1990). In addition, penetrometers allow relatively rapid evaluations of large areas. Though the amount of research tying penetrometer measurements to the growth of woody, perennial tree species is limited, there is an extensive body of literature concerning annual agricultural plants (Misra and Gibbons 1996). Generally, root penetration of annual plants appears to cease at resistances of about 1 MPa (Bengough and Mullins 1990).

The primary objectives of this study were to determine the degree of compaction associated with a CTL harvester-forwarder thinning operation in a second-growth conifer stand in the Oregon Cascades. Particularly, an understanding of if and how soil can be affected by traffic levels and logging slash was desired. In addition, the adequacy of penetrometer readings for predicting soil bulk density was examined and conclusions about slash and logging traffic treatments using the two different dependent variables (i.e., soil bulk density and cone index) were compared. Estimates of total areal compaction were also made.

3. STUDY SITES AND SILVICULTURAL TREATMENTS

Bulk density and slash depth data were collected in two harvest units (81 and 82) of the Flatthin Timber Sale from September through November of 1996. Penetrometer data was collected only in Unit 81. This sale was located on the Willamette National Forest, Oakridge Ranger District near Westfir, Oregon (Sections 19 and 20, T. 19 S., R. 4 E.). The units were composed of 50-year-old Douglas-fir (Pseudotsuga menziesii) with an average diameter at breast height of 13 inches ranging up to 23 inches. Stocking was estimated at 277 trees per acre. Understory species included western redcedar (Thuja plicata), western hemlock (Tsuga heterophylla), cherry (Prunus spp.), and bigleaf maple (Acer macrophylla). The silvicultural prescription for Unit 82 (96 ac.) was a light thin (residual 100-110 trees per acre) with half-acre clearcuts at a 330 foot spacing. Unit 81 (50 ac.) was a heavy thin to 50-55 trees per acre. Total harvest volumes for Units 81 and 82 were estimated at 800 and 1300 MBF, respectively.

Soils on both units were classified as Mapping Unit 14 in the Willamette National Forest Soil Resource Inventory. These soils are deep to very deep, slightly plastic to plastic and are derived from residual and colluvial materials. Surface soils are thin shotty loams and silt loams. Subsoils are thick silt loams, silty clay loams, and clay loams. The landtype is well drained with rapid permeability in the surface soils and moderate to slow in the subsoils. Study plots were kept to areas with slopes less than 10%. An additional complication was presented by the presence of old skid trails from the original harvest entry. Plots were located where these old tractor trails were not apparent. Plots on less obvious old skid trails, however, may be included in the sample and add to the overall variability.

The harvest was conducted with a CTL system using two Timberjack[1] vehicles. The harvester, a model 2618 with a tracked carrier and hydraulic harvesting head (estimated static ground pressure: 7.9 psi), felled, processed and stacked the logs beside skid trails for transport. An eight-wheel drive model 1210 forwarder with bogie tracks on the rear tires took the logs to the landing. Front and rear ground pressures for this vehicle are estimated to be 7.0 and 3.8 psi unloaded, increasing to 8.2 and 10.5 psi when fully loaded. Short-log trucks were used to transport logs to the mills.

Data from Unit 82 reflects harvest with relatively dry soil conditions. The fall rains began as the operators moved to Unit 81, thus sampling took place over a period of highly variable soil moisture conditions. Though a second harvester-forwarder pair introduced in Unit 81 was of the same make and model, data from this unit reflects both a different operator and equipment than Unit 82. Skid trails were flagged prior to thinning and approved by the timber sale administrator in order to minimize the areal extent of soil affected.

4. METHODS

The methods used were modeled after previous soil compaction/slash studies (Froehlich et al 1980, Jakobsen and Moore 1981, Seixas et al. 1995). Soil bulk density was collected on two plot types, the first located on designated skid trails with both harvester and forwarder traffic, the second on short loops off the designated trails with forwarder traffic only. Soil cone index data was collected only in Unit 81 as soil strength in Unit 82 during the dry sampling period was too high to consistently allow measurements. Each plot was assigned a slash treatment of zero, low, moderate, or high. The number of equipment passes was closely monitored.

For the slash treatments, the harvester operators were instructed to create the desired level of slash by varying the number of trees processed over the plot and to keep control plots free of debris. The zero slash treatments were created by manually clearing the plots to mineral soil prior to equipment traffic. To measure slash depth, a wooden dowel graduated in inches was pushed vertically through the slash to the soil surface. A 6x12 inch board with a hole in the center was then placed over the dowel and the depth in inches read from the point at which the board came to rest on the slash. Measurements were recorded after one harvester pass to represent the initial depth as well as with each subsequent bulk density measurement. Average plot slash depths were based on the average of six measurements taken from two transects across the width of the skid trail (three points per transect). The equipment passes were not controlled but were recorded and are representative of the range of operational traffic for this harvest volume, unit and stem size, topography and machinery.

Plots were 20 feet in length and spanned the width of the trail. Each plot was divided into ten, two-foot sections (see Fig. 2). Before treatment, a random sampling order was assigned to each plot section. Three measurements were possible in each section, two in the rut and one in the center, for a total of 30 per plot (10 sections x 2 ruts + 10 sections x 1 center). Sampling was limited by equipment turn time and total number of passes, thus not all 30 possible points were sampled in every plot. Measurements of the same number of passes were repeated in another

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[1] Mention of trade names throughout this manuscript does not constitute endorsement.

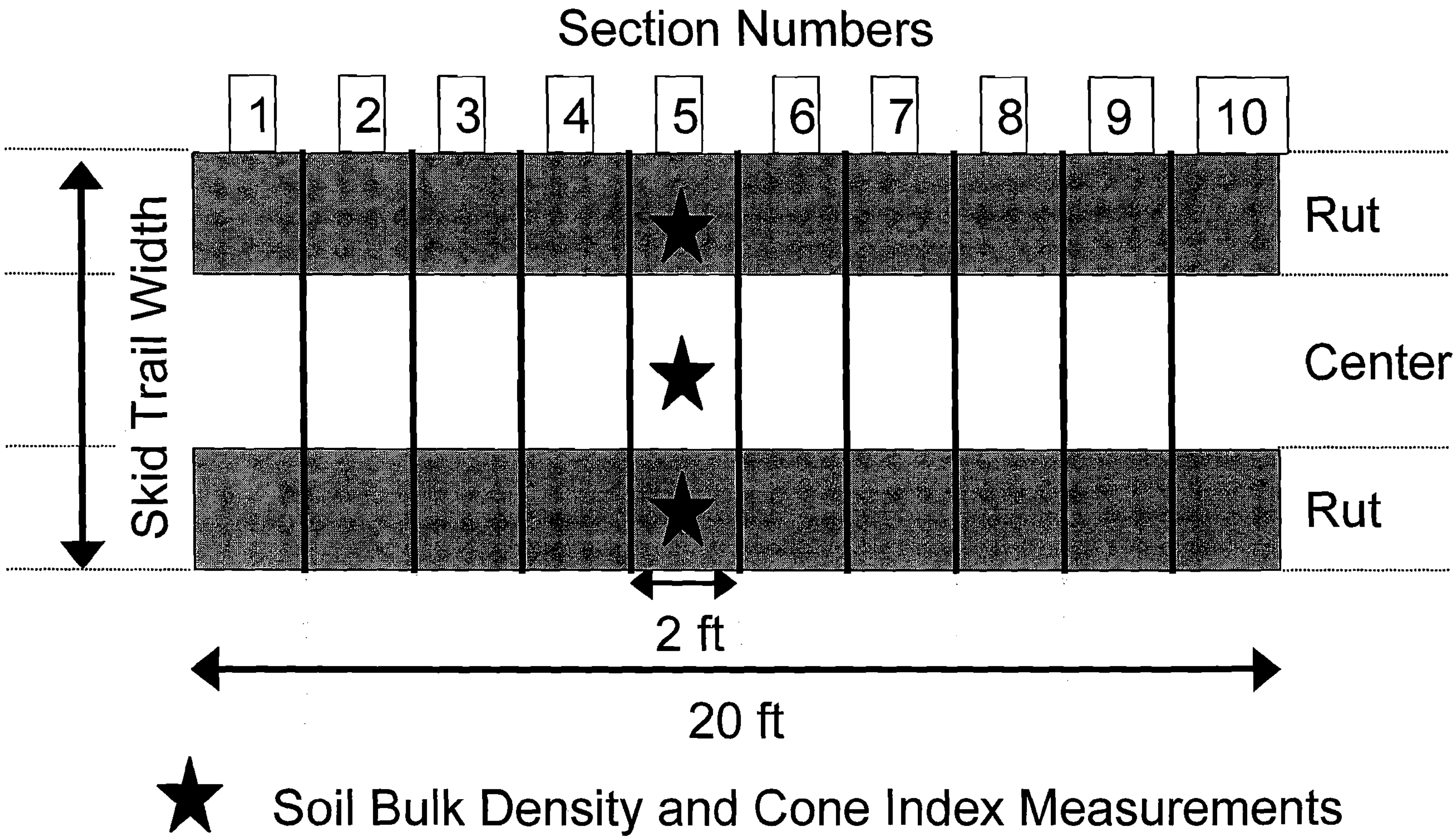

Figure 2: Plot design diagram.

section where time allowed, to increase measurement precision. Wet bulk density was measured at four- and eight-inch depths with a Campbell Pacific Nuclear Densimeter with a stratagage attachment to allow lateral measurements at a specific depth. Bulk soil samples were collected and analyzed in the lab for gravimetric moisture content in order to convert values to dry bulk density. Soil cone index data was collected with a Rimik CP 20 Recording Cone Penetrometer (12.83 mm cone diameter) which records penetration resistance at regular depth intervals in millimeters. Three resistance profiles were collected within 30 cm of each other at each measurement point and the average of these measurements (kPa) at the depth closest to four and eight inches was used for the analysis. Statistical evaluations focused on multiple linear regression analyses using the computer package Statgraphics.

5. RESULTS

5.1. Pre-Treatment Bulk Density

A total of 330 data points in 13 plots were collected at each sampling depth for this analysis. The plot pre-harvest bulk density was the average of ten measurements adjacent to the plot prior to treatment. A statistical summary and scatterplots of the pre-harvest data are provided in Figures 3 and 4 and Table 1.

Of the 13 plots, nine experienced both harvester and forwarder traffic and four received only forwarder traffic. Two control plots (cleared to mineral soil) were created, of which one was treated with forwarder traffic only. A summary of treatment by plot is provided in Table 2.

5.2. Moisture Content

Fractional gravimetric soil moisture content during the data collection period ranged from 0.21 to 0.80 g_w/g_s. Figure 5 shows a scatterplot of moisture content by plot, where plot numbers

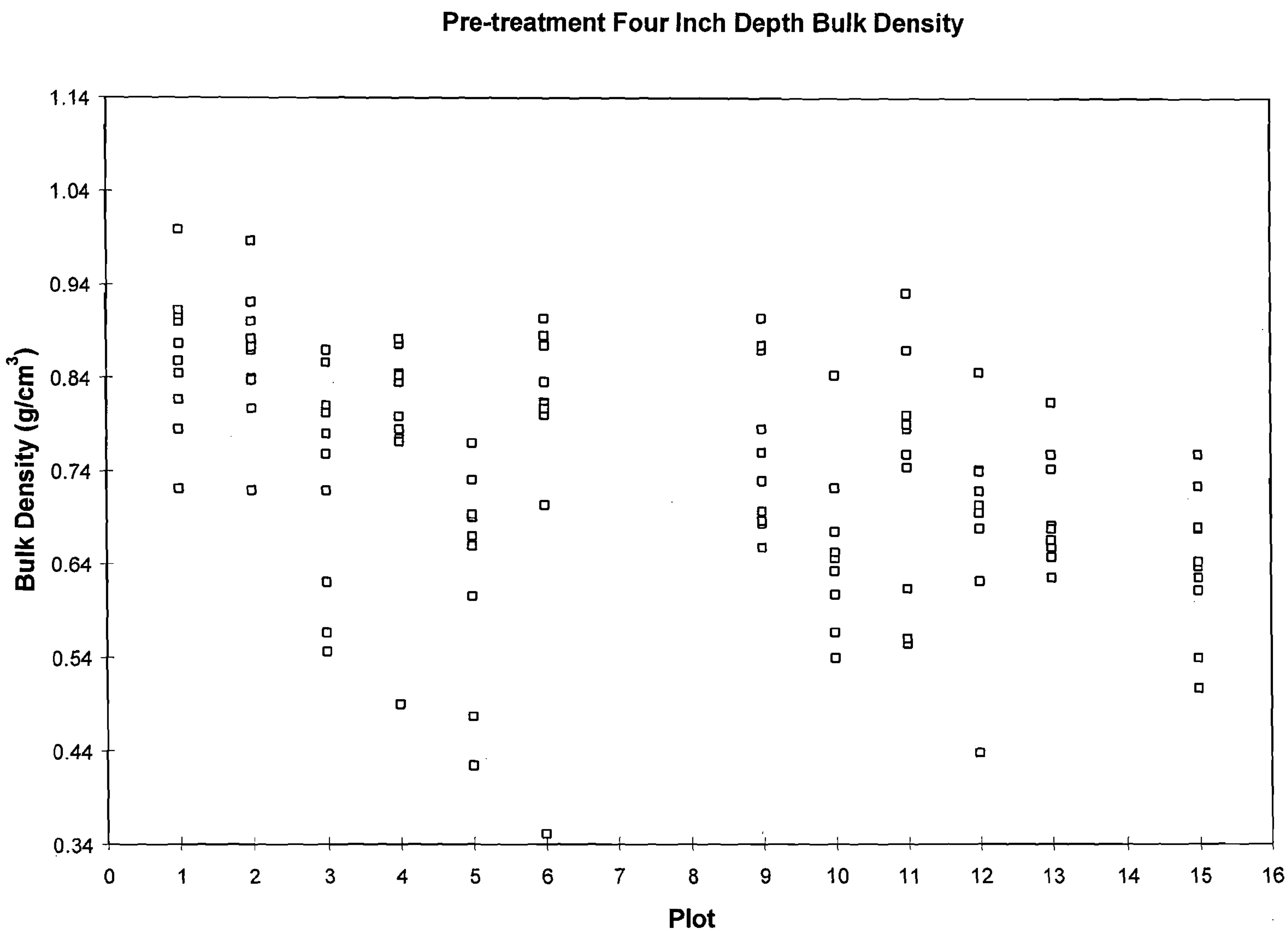

Figure 3: Four-inch depth pre-treatment bulk density by plot.

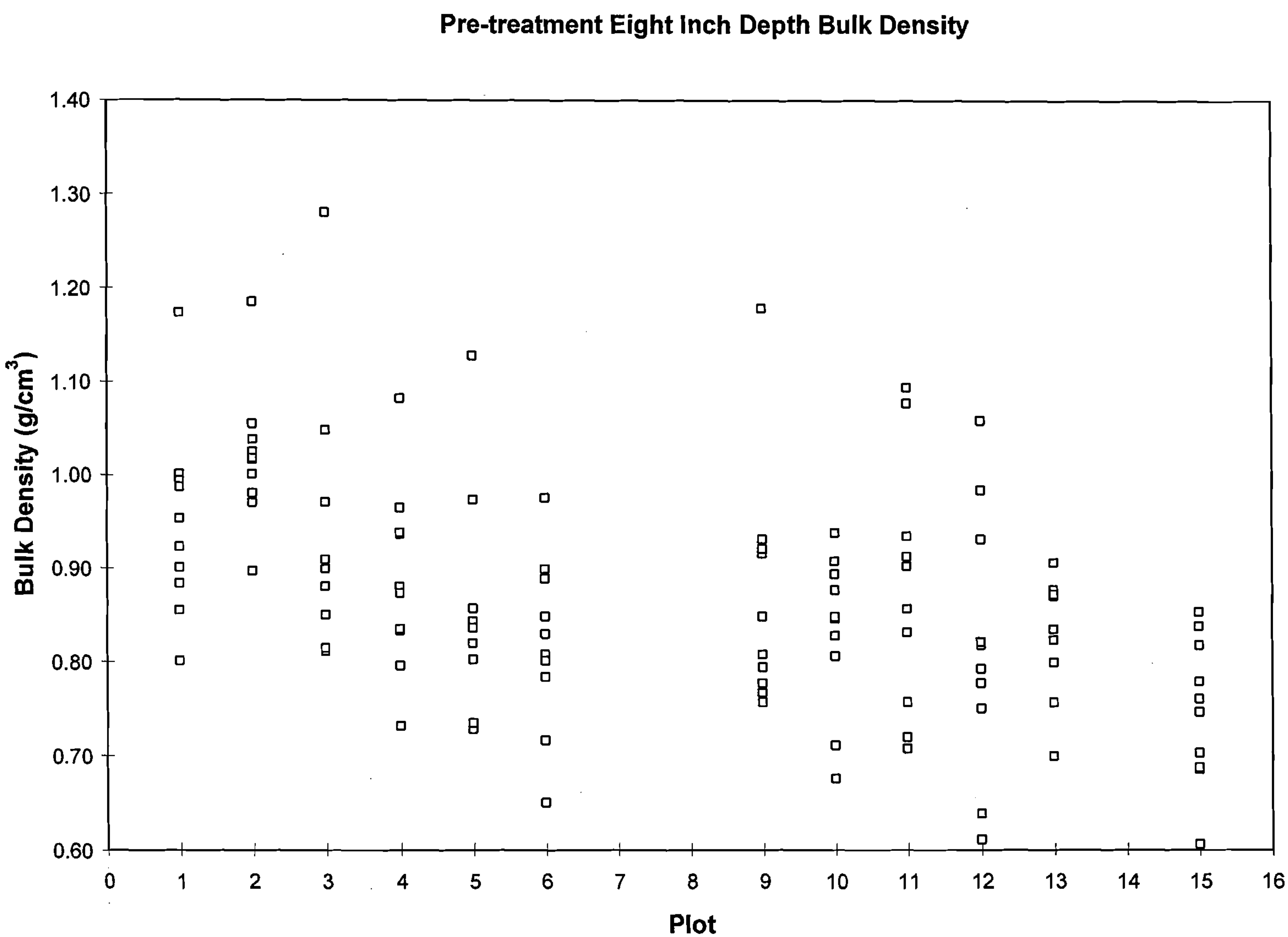

Figure 4: Eight-inch depth pre-treatment bulk density by plot.

			4 Inch Depth Bulk Density (g/cm^3)			8 Inch Depth Bulk Density (g/cm^3)		
Plot	Unit	n	$\bar{x}$	s^2	CV	$\bar{x}$	s^2	CV
1	82	10	0.86	0.006	0.09	0.95	0.011	0.11
2	82	10	0.86	0.005	0.08	1.02	0.005	0.07
3	82	10	0.73	0.014	0.16	0.94	0.020	0.15
4	82	10	0.79	0.013	0.14	0.89	0.010	0.11
5	82	10	0.64	0.013	0.02	0.83	0.021	0.17
6	82	10	0.78	0.026	0.21	0.82	0.008	0.11
9	81	10	0.76	0.008	0.12	0.87	0.016	0.15
10	81	10	0.65	0.007	0.13	0.84	0.007	0.10
12	81	10	0.68	0.011	0.16	0.82	0.020	0.17
13	81	9	0.70	0.003	0.08	0.83	0.004	0.08
15	81	10	0.64	0.006	0.12	0.75	0.006	0.10

Table 1: Summary statistics for pre-treatment bulk density by plot.

Plot	Unit	Traffic (F or H/F)*	Traffic Range (Passes)	Avg. Slash Depth (in)	Prescribed Slash Treatment (0, L, M, H)	# Bulk Density Measures at Each Depth	
						Rut	Center
1	82	H/F	1-23	0	0	8	4
2	82	H/F	7-37	10	M	14	9
3	82	H/F	2-24	4	L	18	9
4	82	H/F	2-16	8	M	11	6
5	82	H/F	2-25	10	H	15	8
6	82	F	1-10	0	0	20	10
9	81	H/F	4-12	2	L	8	4
9.5	81	F	2	9	L	4	2
10	81	H/F	3-19	10	M	15	5
10.5	81	F	2-8	18	M	6	0
12	81	F	1	7	H	4	1
13	81	H/F	1-36	11	H	17	6
15	81	H/F	5	13	L	2	1

Table 2: Summary information of treatment data by plot. *Harvester and forwarder (H/F) traffic or forwarder traffic only (F).

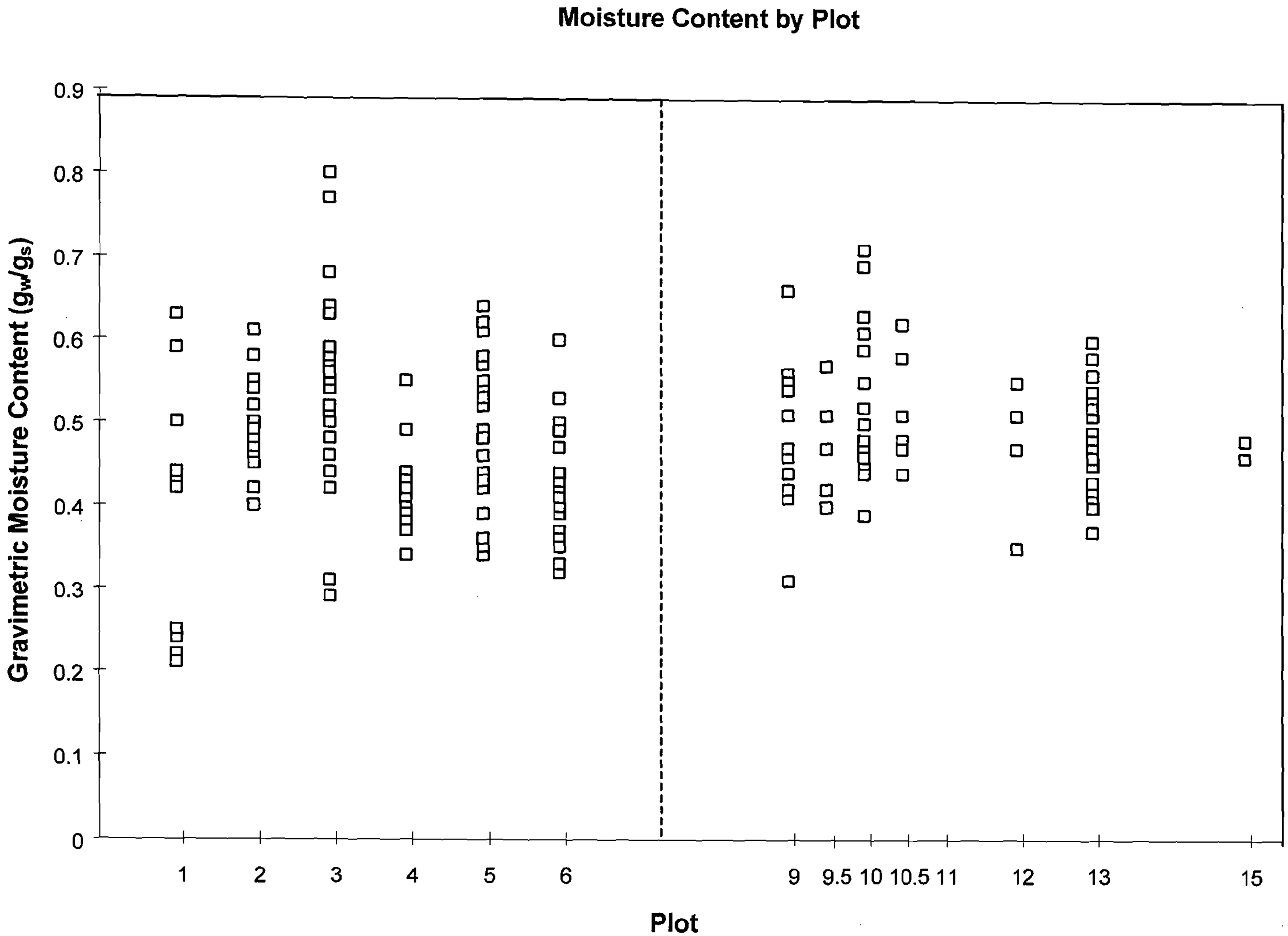

Figure 5: Gravimetric moisture content by plot.

Plot	1	2	3	4	5	6	9	9.5	10	10.5	12	13	15
Unit	82	82	82	82	82	82	81	81	81	81	81	81	81
$\bar{x}\ \theta_g$ (g_w/g_s)	0.37	0.49	0.54	0.41	0.50	0.41	0.48	0.46	0.51	0.52	0.47	0.48	0.47

Table 3: Average gravimetric moisture content by plot.

follow approximately consecutive sampling through time (Sept. - Nov.). However, there is no clear trend of increasing soil moisture over time. Average values by plot are presented in Table 3.

5.3. *Points Removed from Analysis*

Review of the moisture content scatterplots highlighted some anomalies in the data from Unit 82, such as observations with moisture contents of over 300%. Field notes about these suspicious points indicated that the samples contained a high amount of rotten log material. As the nuclear densimeter is not accurate at very high moisture contents (manufacturer's notes), and these sample points are considered to be from a different population than the rest of the data, these points were excluded from the compaction analysis. Table 4 lists the excluded points and their moisture contents.

5.4. *Regression Models*

Separate linear regression models were tested for the predicted bulk density of the rut and center of skid trails at both sampling depths. Averages were used where multiple measurements of the same traffic level within a plot occurred. The parallel lines regression models tested followed this general form:

$$BD_p = \beta_0 + \beta_1 * \text{Unit} + \beta_2 * BD_o + \beta_3 * MC + {}_4\beta_{-5} * \text{Slash Treatment} + \beta_{6\text{-}10} * \text{Pass Category}$$

where

BD_p	=	Predicted bulk density (g/cm^3)
Unit	=	Harvest unit (Unit 81 or Unit 82)
BD_o	=	Average pre-harvest bulk density (g/cm^3)
MC	=	Moisture content (g_w/g_s)
Slash Treat.	=	Slash treatment (zero, low, high)
Pass Category	=	Number of passes (0, 1-2, 3-5, 6-10, 11-20, >20)

Plot	2	2	2	2	4	4	4	4	4	4	4	4	4	5
Moisture Content (%)	78	133	96	397	325	271	189	116	120	89	122	91	188	246

Table 4: Points excluded from analysis, Unit 82.

To control for unit differences, data from Unit 81 were given a value of one for the unit variable and Unit 82 a value of zero. Slash was also tested using indicator variables for three levels (zero, low and high) in the regression, with zero slash as the reference. For example, the low slash variable would be assigned a value of one if that treatment was assigned to the measurement in question and would otherwise equal zero. Indicator variables also were used to denote six categories of traffic (0, 1-2, 3-5, 6-10, 11-20 and >20 passes) with zero passes as the reference. Recall that where there are more than two categories in a set of indicator variables, the model must contain one fewer variable than the total number of levels. The level whose indicator variable is omitted is the reference level. Since actual slash levels were not consistent with the amount prescribed, data in the regression analysis was grouped by average slash depth after one harvester pass (see Figure 6). Moderate and high levels of slash were combined in the high category since there was not a distinct break between the two. Slash depths in the low treatment ranged from 4 - 7 inches while heavy slash included values from 8 - 18 inches.

Gravimetric moisture content (unitless) and pre-harvest bulk density (g/cm^3) were included as continuous variables where significant ($p>0.10$). Since the data are observational there is no causal interpretation of the statistical results. Scatterplots of the data are provided in Figures 7-14.

The final regression equations to predict bulk density after treatment (g/cm^3), p-values, degrees of freedom and r-squared are summarized in Tables 5 and 6. Interaction terms between slash treatment and traffic level were tested but excluded ($p>0.10$).

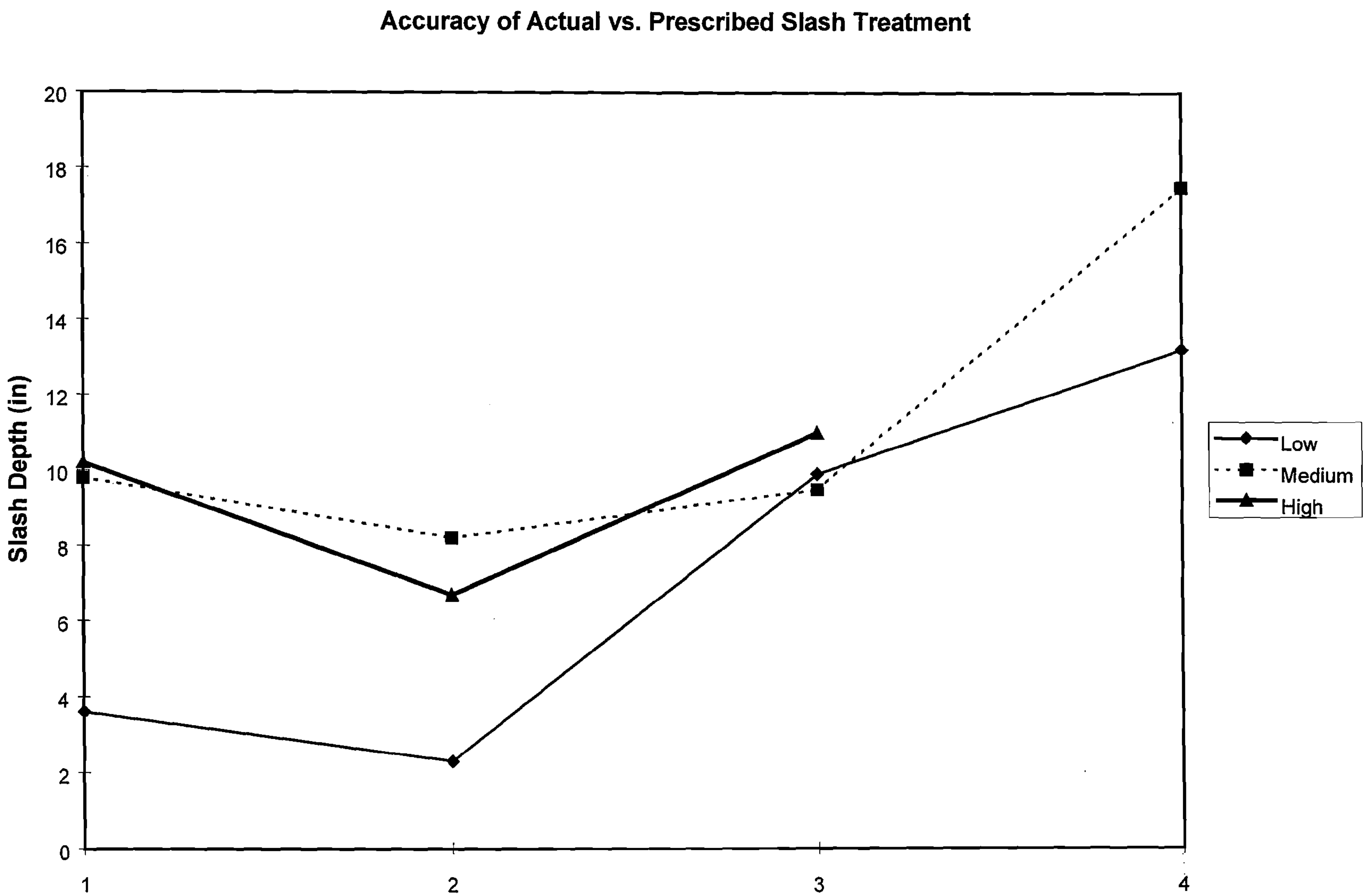

Figure 6: Average plot slash depth plotted by prescribed slash treatment group.

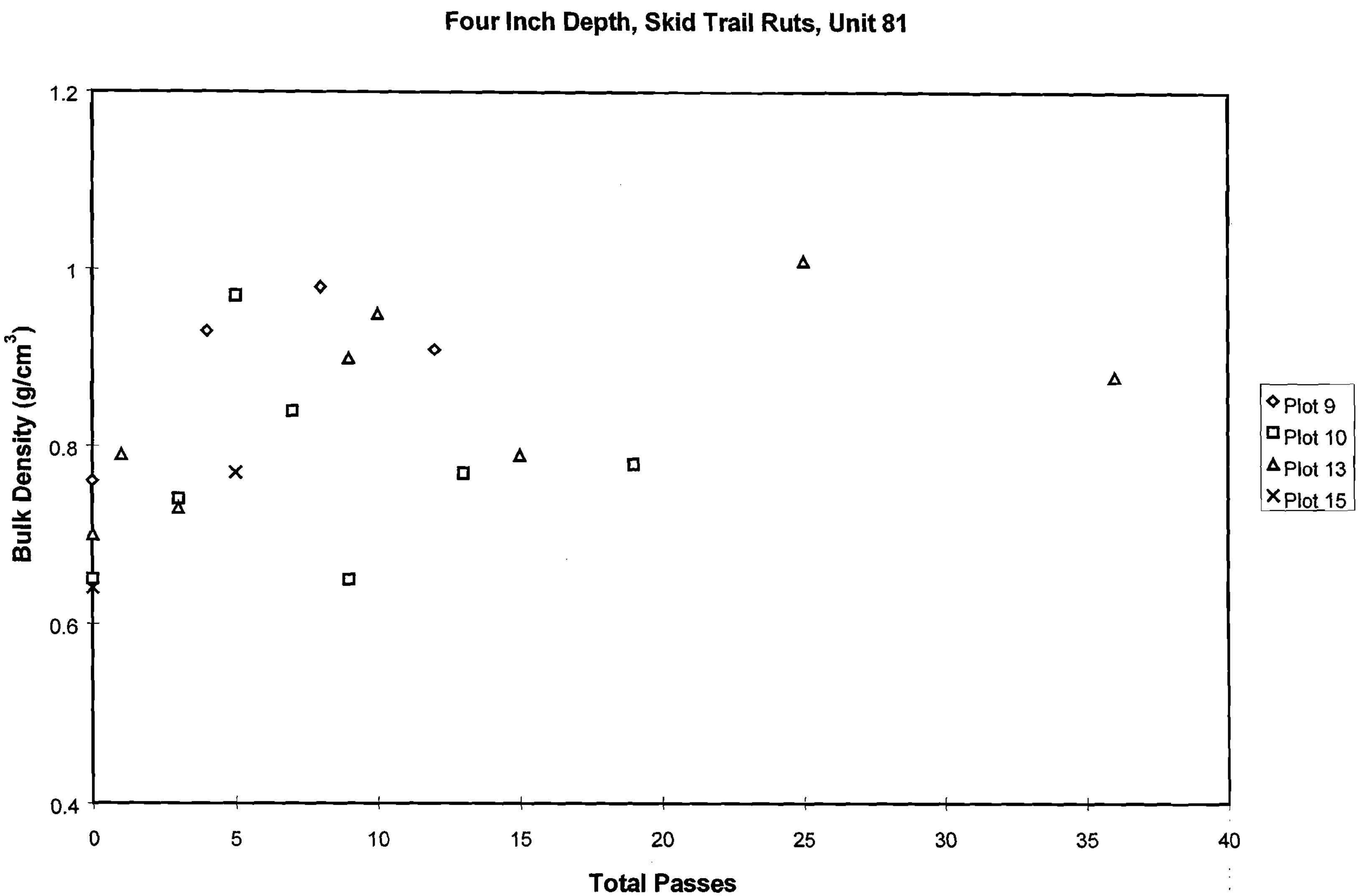

Figure 7: Four-inch depth bulk density in skid trail ruts vs. total equipment passes, Unit 81.

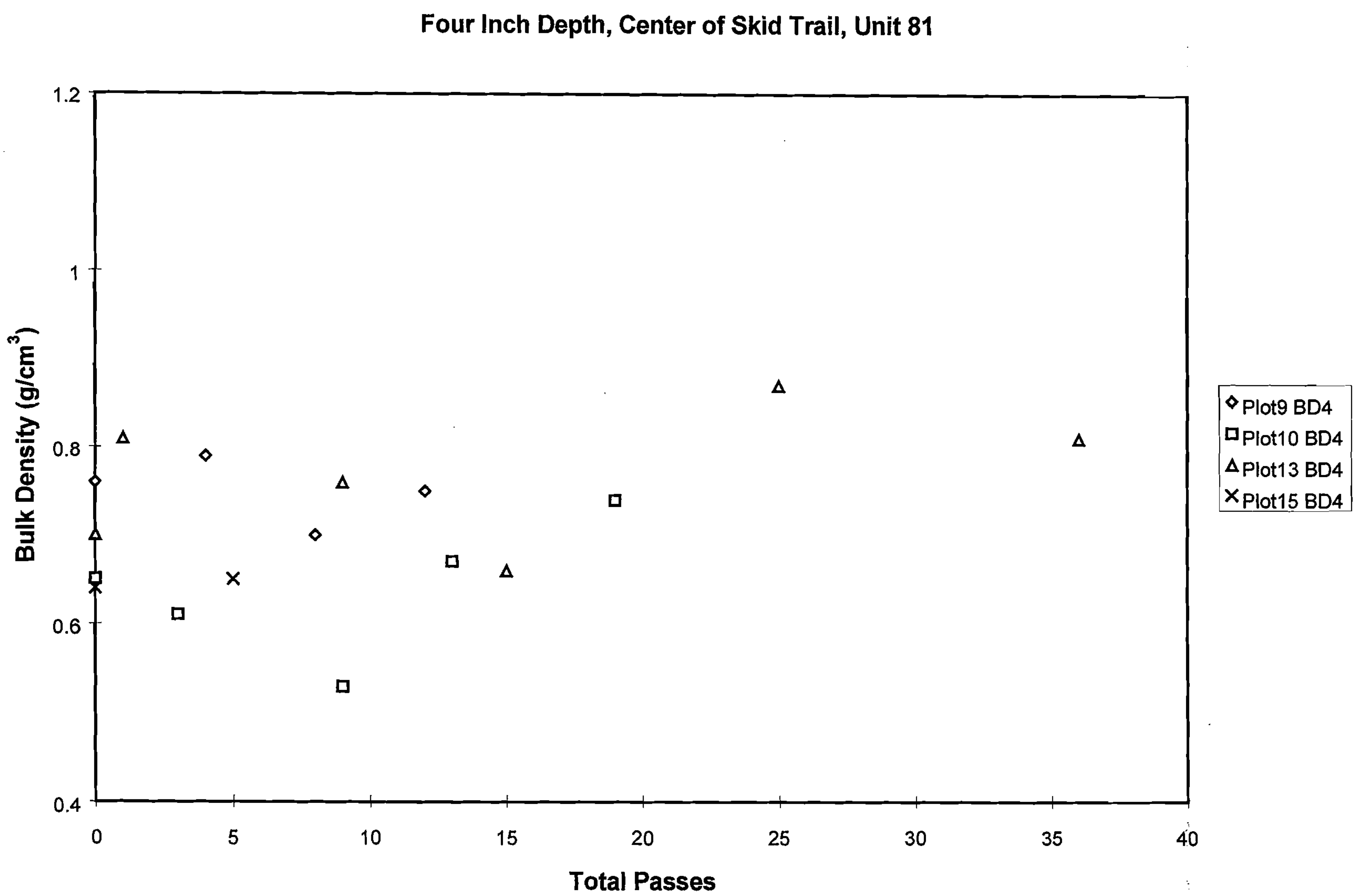

Figure 8: Four-inch depth bulk density in center of skid trail vs. total equipment passes, Unit 81.

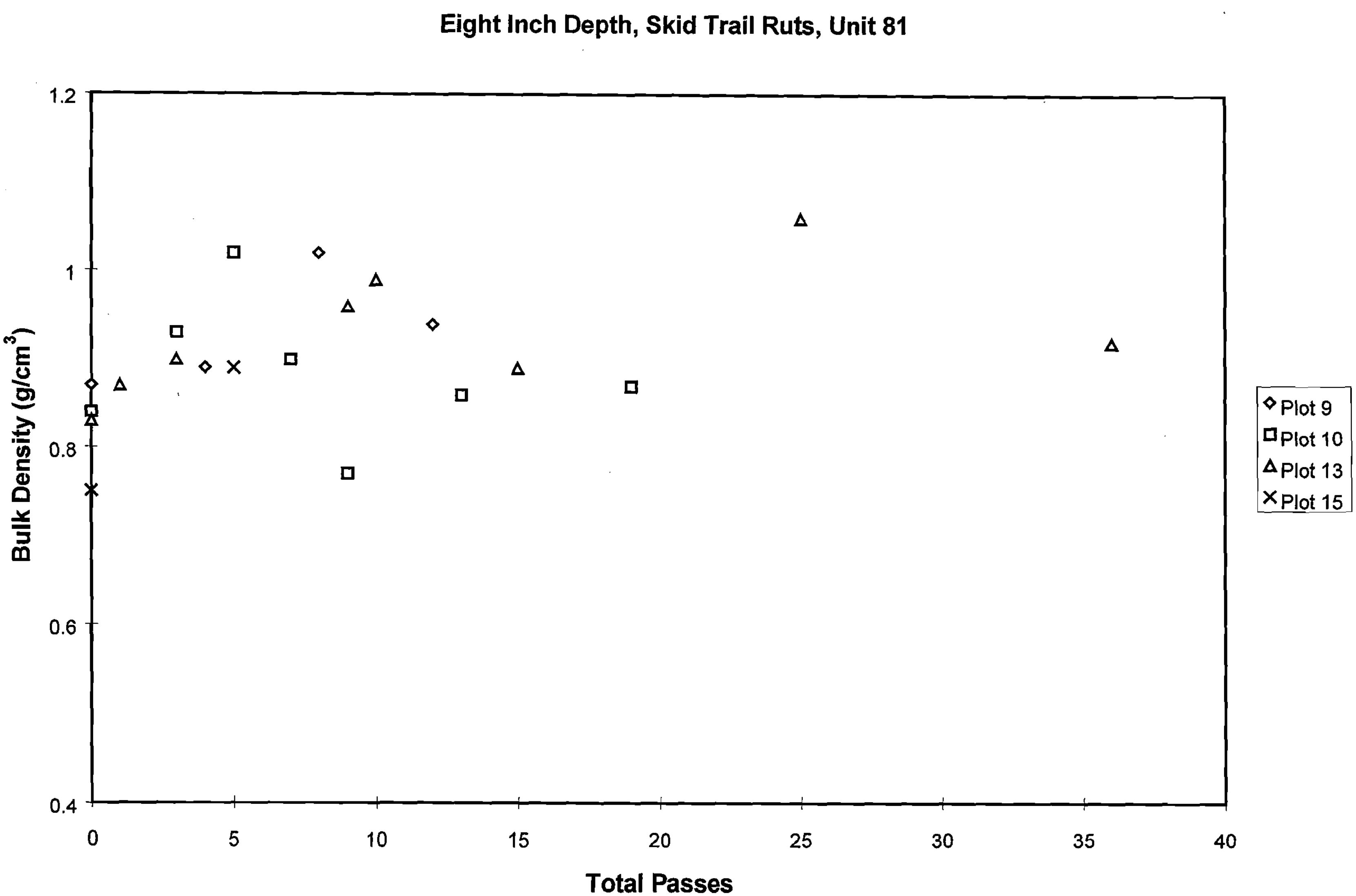

Figure 9: Eight-inch depth bulk density in skid trail ruts vs. total equipment passes, Unit 81.

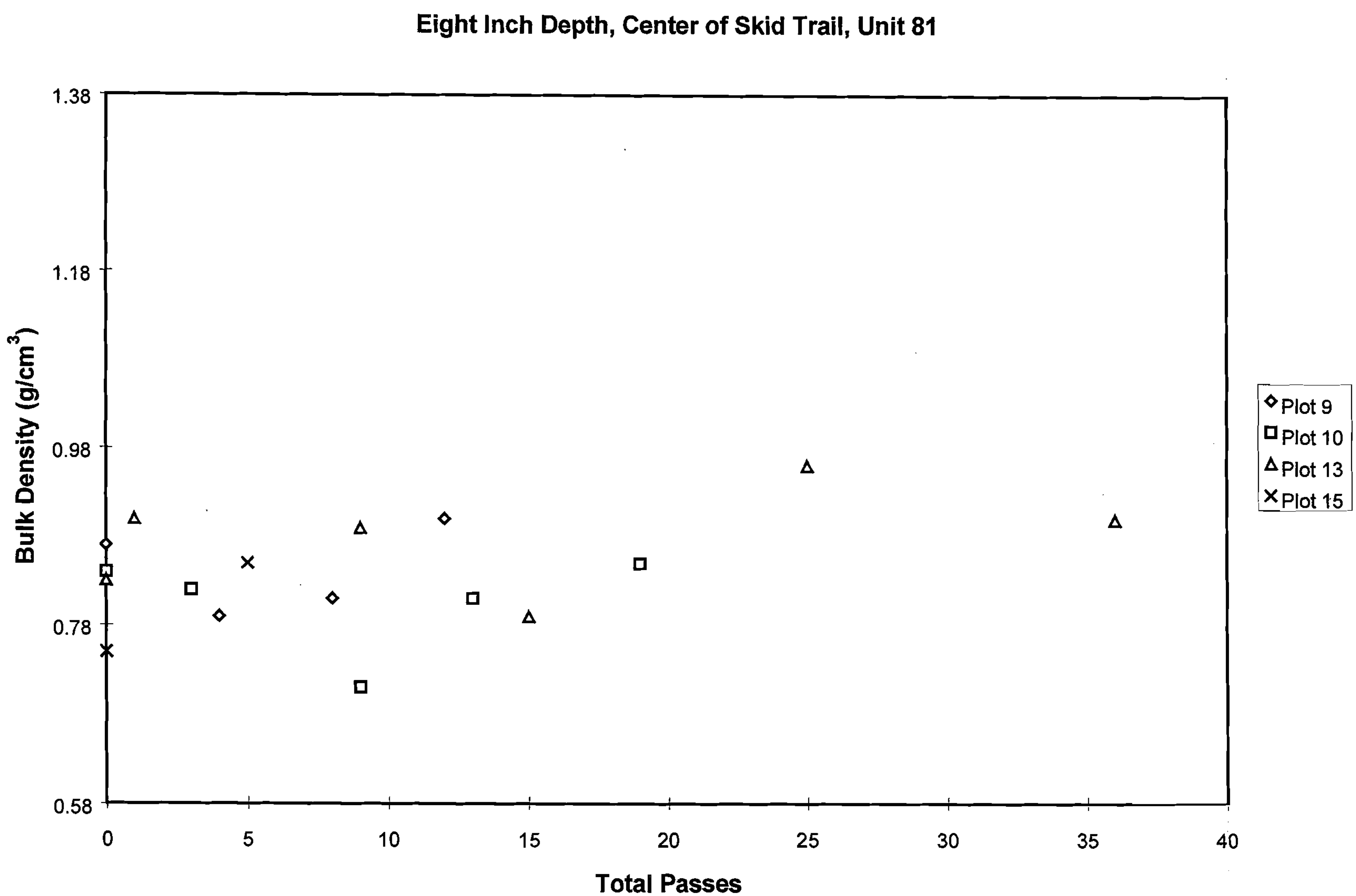

Figure 10: Eight-inch depth bulk density in center of skid trail vs. total equipment passes, Unit 81.

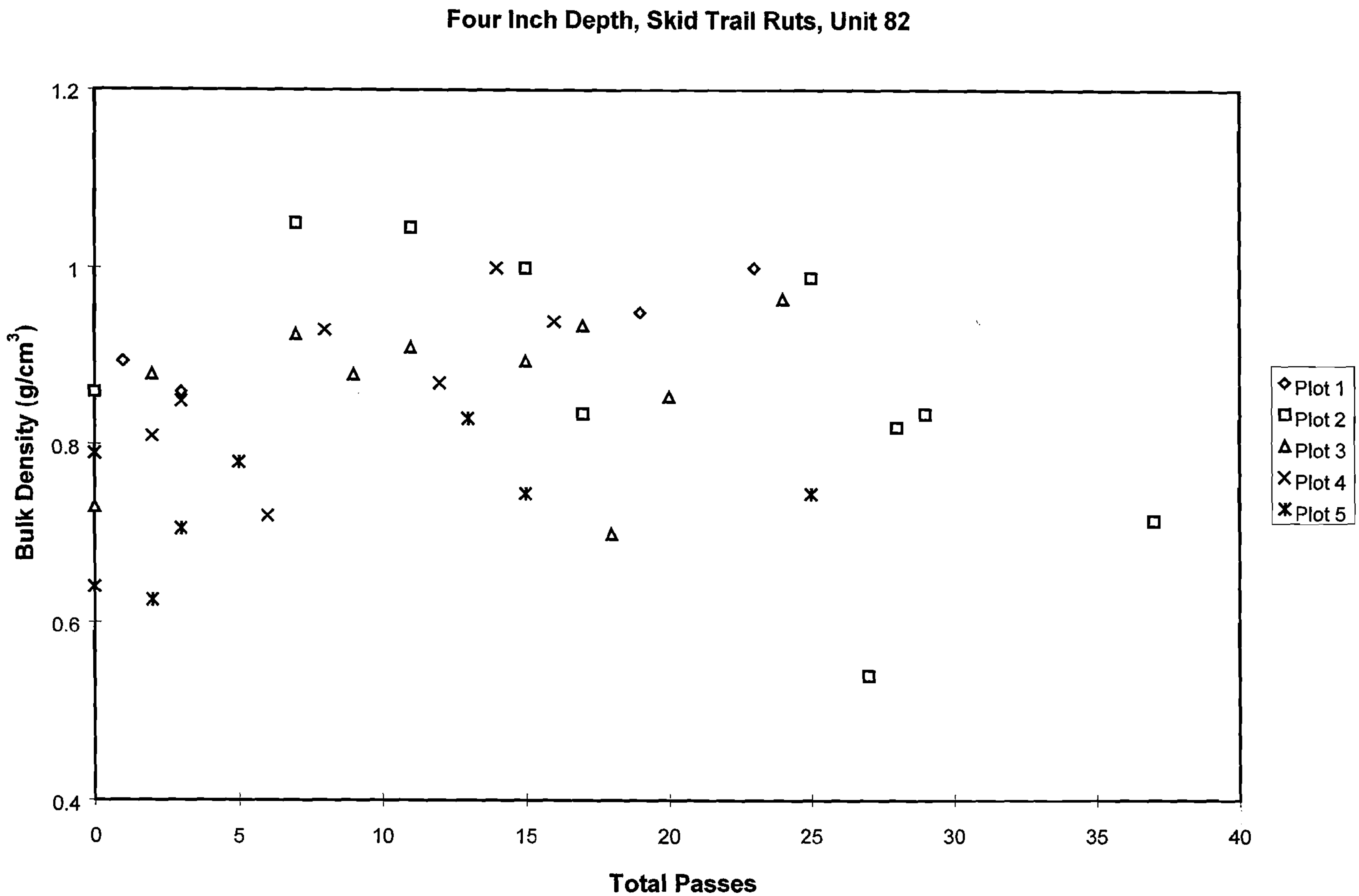

Figure 11: Four-inch depth bulk density in skid trail ruts vs. total equipment passes, Unit 82.

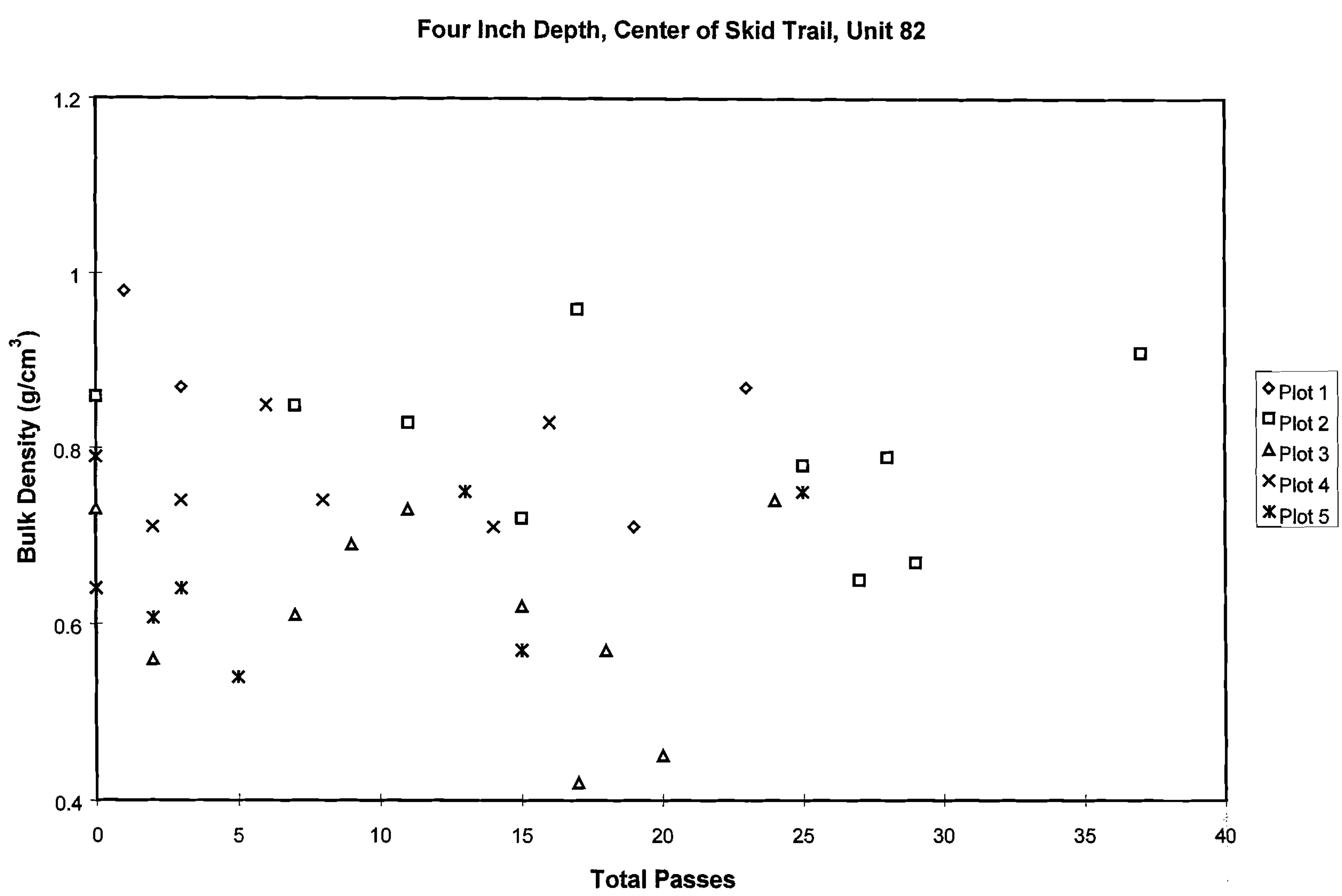

Figure 12: Four-inch depth bulk density in center of skid trail vs. total equipment passes, Unit 82.

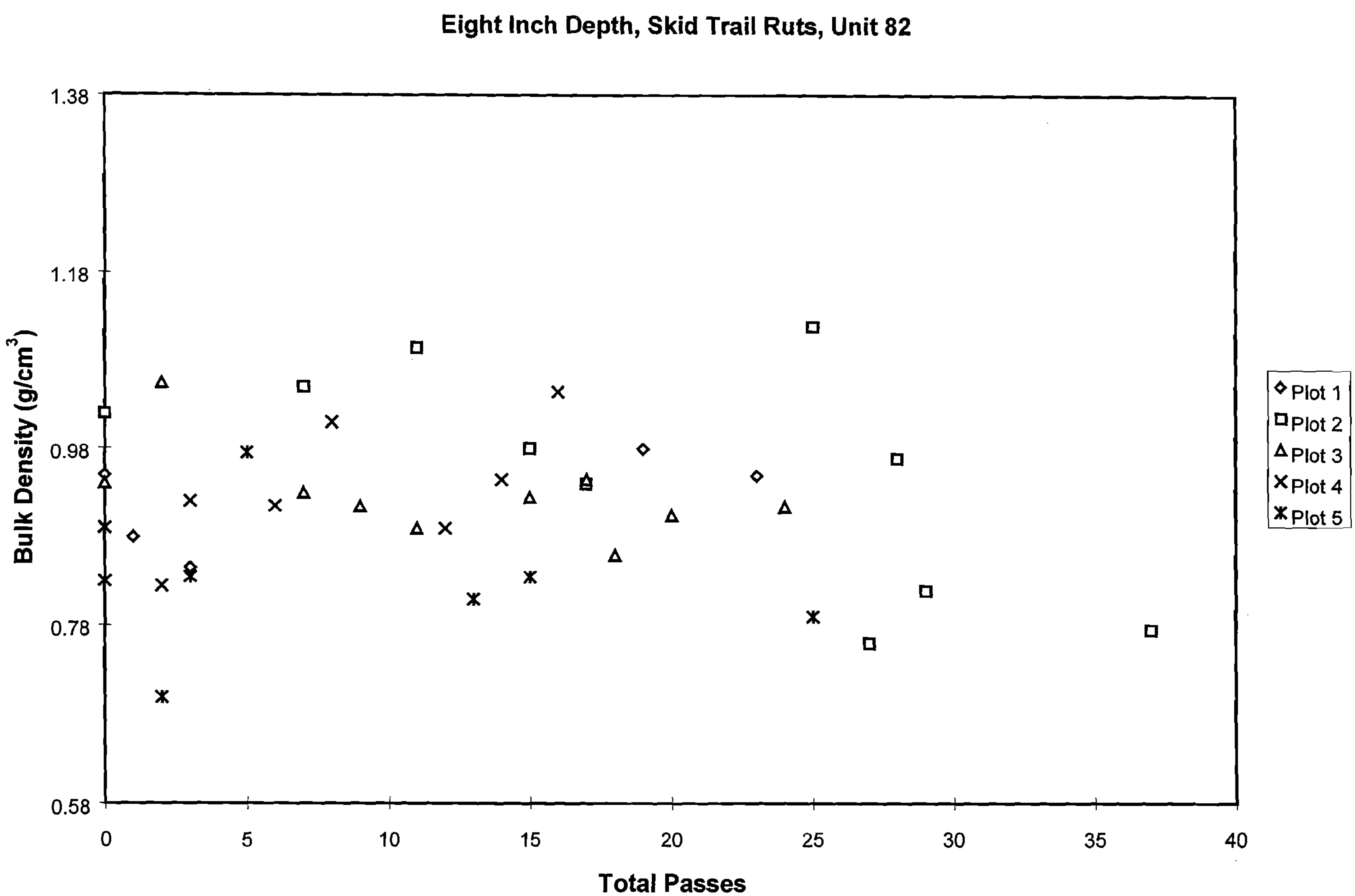

Figure 13: Eight-inch depth bulk density in skid trail ruts vs. total equipment passes, Unit 82.

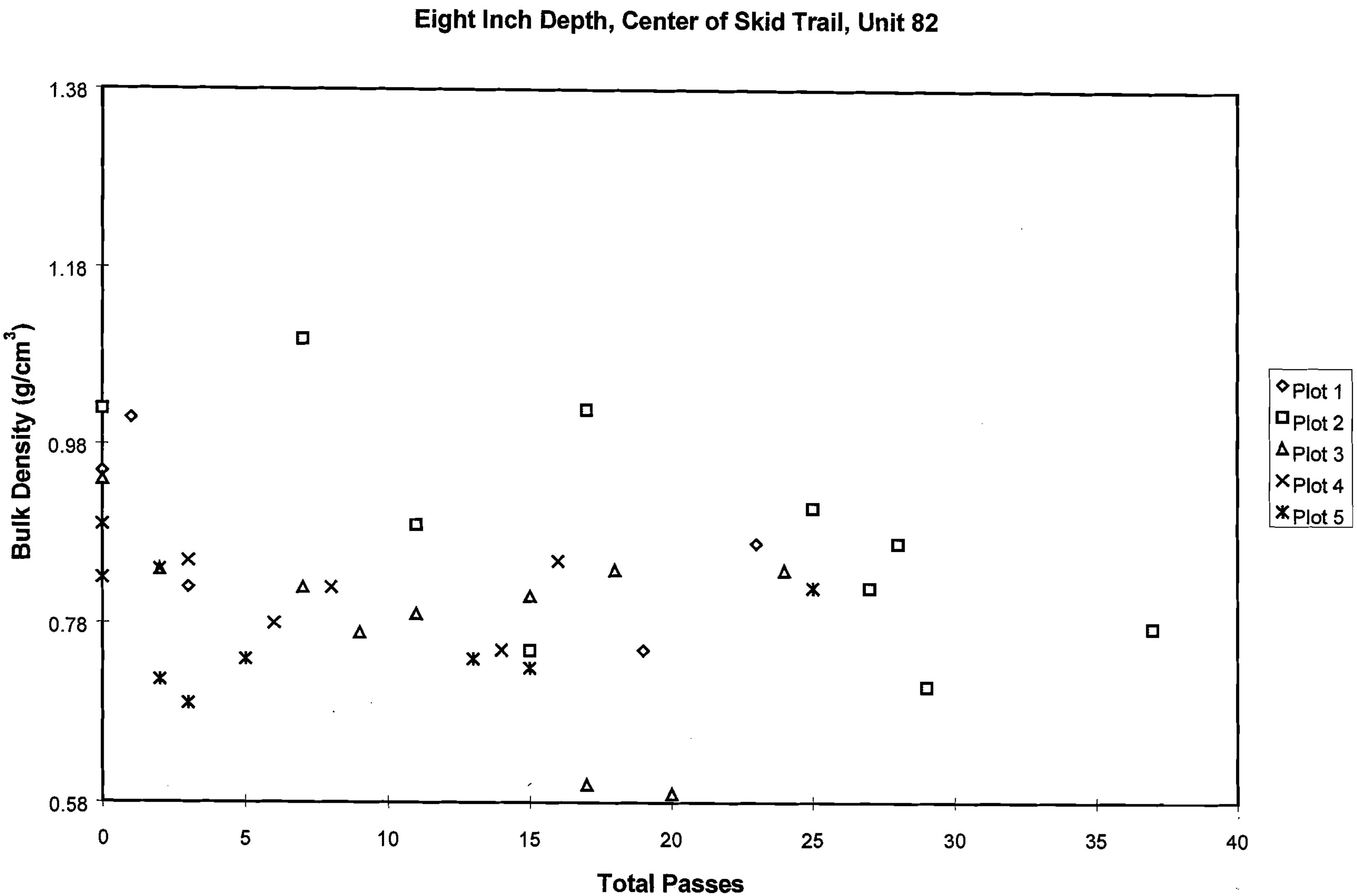

Figure 14: Eight-inch depth bulk density in center of skid trail vs. total equipment passes, Unit 82.

5.4.1. Vehicle Traffic and Bulk Density in Ruts

The bulk density of skid trail ruts with 1-2 equipment passes was not significantly different from the density of undisturbed soil at the four- or eight-inch sampling depth. At three or greater equipment passes, bulk densities were significantly different from the undisturbed level ($p<0.03$) at both sampling depths except for the greater than twenty passes category at eight inches ($p=0.19$). The greatest absolute change in density occurred after 6-10 passes for both the four-inch (+0.19 g/cm^3) and eight-inch (+0.11 g/cm^3) depth. There is no significant difference, however, between bulk densities in the 3-5 passes category and subsequent traffic levels at either depth ($p>0.10$). This may suggest that bulk density reaches a plateau at this traffic level. Overall, unit differences were not found to be significant ($p>0.15$).

5.4.2. Slash Treatment and Bulk Density in Ruts

Neither a low or high amount of slash appears to influence bulk density when compared to the zero slash treatment at either sampling depth ($p>0.20$). However, it was questionable if the zero slash treatment adequately reflected the response of unprotected mineral soil for two reasons. First, the zero slash treatment was not replicated. Secondly, the one plot representing the zero slash treatment had a substantial amount of organic matter incorporated into the soil from a partially decayed stump at the plot edge with each equipment pass. When compared to the low slash treatment, a high amount of slash was associated with bulk densities that were 0.07 g/cm^3 lower at the four-inch depth ($p=0.039$). Slash level did not contribute significantly to the eight-inch depth regression. Table 7 provides a summary of the regression-estimated mean bulk density in skid trail ruts by pass category and slash treatment, which

Location and Sampling Depth in Skid Trail	Regression Equation
Ruts, 4 Inch Depth	Bulk Density (g/cm^3) = 0.490245 + 0.0389907*Unit + 0.618427*BD_0-0.581469*MC - 0.0722464*SlashLow - 0.0152149*SlashHigh + 0.0534425*Pass1-2 + 0.00587013*Pass3-5 + 0.0501411*Pass6-10 + 0.0729367*Pass11-20 + 0.0824168*Pass>20
Ruts, 8 Inch Depth	Bulk Density (g/cm^3) = 0.454811 + 0.0416942 *Unit + 0.561576 * BD_0 - 0.384723 *MC + 0.0647552*SlashLow - 0.045895*SlashHigh + 0.018777*Pass1-2 + 0.0916816*Pass3-5 + 0.105753*Pass6-10 + 0.0922904*Pass11-20 + 0.0608763*Pass>20
Center, 4 Inch Depth	Bulk Density (g/cm^3) = 0.490245 + 0.0389907*Unit + 0.618427*BD_0 - 0.581469*MC - 0.0722464*SlashLow - 0.0152149*SlashHigh + 0.0534425*Pass1-2 + 0.00587013*Pass3-5 + 0.0501411*Pass6-10 + 0.0729367*Pass11-20 + 0.0824168*Pass>20
Center, 8 Inch Depth	Bulk Density (g/cm^3) = 0.306522 + 0.0726081*Unit + 0.79586*BD_0 - 0.547098*MC - 0.00138399*SlashLow - 0.043483*SlashHigh + 0.0468289*Pass1-2 - 0.0372972*Pass3-5 + 0.0087721*Pass6-10 + 0.00919632*Pass11-20 + 0.0312219*Pass>20

Table 5: Regression equations for predicting bulk density at either sampling depth in the rut and center of skid trails receiving both harvester and forwarder traffic.

Variables	Indicator (I) or Continuous (C) Variable	P-Values Skid Trail Ruts 4 Inch Depth	P-Values Skid Trail Ruts 8 Inch Depth	P-Values Center of Skid Trail 4 Inch Depth	P-Values Center of Skid Trail 8 Inch Depth
Intercept	--	0.0327	0.0310	0.0026	0.1292
Unit	I	0.2471	0.1543	0.1208	0.0169
Moisture Content (g/g)	C	0.0666	0.0106	0.0000	0.0000
Pre-Bulk Density (BD_0, g/cm^3)	C	0.0133	0.0087	0.0004	0.0002
Low Slash	I	0.4364	0.1960	0.1056	0.9746
High Slash	I	0.7476	0.2993	0.7052	0.2772
1-2 Passes	I	0.1168	0.6836	0.2126	0.2952
3-5 Passes	I	0.0073	0.0302	0.8755	0.3455
6-10 Passes	I	0.0004	0.0126	0.1918	0.8238
11-20 Passes	I	0.0003	0.0258	0.0529	0.8104
>20 Passes	I	0.0083	0.1878	0.0331	0.4317
r^2 (adj.)	--	33	18	62	50
DF	--	60	60	55	55
Model P-Value	--	0.0005	0.0225	0.0000	0.0000

Table 6: P-values, r^2, and degrees of freedom for harvester-forwarder traffic regression models with bulk density as the dependent variable.

of those groups is significantly different from the zero pass category and the calculated percentage change from the zero pass category.

5.4.3. Influential Data Points in the Skid Trail Rut Model

Certain data points were found to influence the skid trail rut model results at both sampling depths. Exclusion of the Plot 2 data point at 27 equipment passes resulted in moisture content becoming non-significant ($p=0.197$). Removing the eight-inch data points from both Plot 5 (5 passes) and 10 (9 passes) resulted in unit becoming significant ($p<0.08$). The greater than twenty pass category at eight inches also became significant (+0.08 g/cm^3, $p=0.071$) when the same Plot 5 point was excluded. Neither field nor lab notes, however, revealed a legitimate reason to remove these points from the data set.

5.4.4. Vehicle Traffic, Slash Treatment and Bulk Density in the Center of Skid Trails

Soil bulk densities in the center of skid trails at the four-inch depth did not change from the zero pass level until 11-20 equipment passes had occurred (+0.07 g/cm^3, $p=0.053$). Measurements beyond twenty passes showed greater bulk densities than the zero pass level ($p=0.033$), but were no different from the 11-20 pass category ($p=0.759$). At the eight-inch depth, none of the tested pass categories had significantly different bulk densities from the zero pass level ($p>0.29$). Neither low nor high levels of slash were found to affect bulk densities at either sampling depth when compared to the zero slash treatment ($p>0.10$). The high slash treatment was found to associated with 0.06 g/cm^3 higher bulk densities than the low slash treatment at the four-inch depth ($p=0.020$) and 0.04 g/cm^3 greater at eight inches (0.102). The unit variable was not found to be significant at the four-inch depth ($p=0.121$), but did contribute

			Mean Bulk Density (g/cm^3) for Equipment Pass Category					
Unit	Slash Treatment	Sampling Depth (in)	0	1-2	3-5	6-10	11-20	>20
81	Low	4	0.76	0.85 (11)	0.90 (16)*	0.95 (20)*	0.95 (20)*	0.91 (16)*
81	High	4	0.69	0.78 (12)	0.83 (17)*	0.88 (22)*	0.88 (22)*	0.85 (19)*
82	Zero	4	0.68	0.76 (12)	0.81 (16)*	0.86 (21)*	0.86 (21)*	0.83 (18)*
82	Low	4	0.72	0.81 (11)	0.86 (16)*	0.91 (21)*	0.91 (21)*	0.88 (18)*
82	High	4	0.66	0.75 (12)	0.80 (18)*	0.85 (22)*	0.85 (22)*	0.81 (19)*
81	Low	8	0.87	0.89 (2)	0.96 (9)*	0.97 (10)*	0.96 (9)*	0.93 (6)*
81	High	8	0.85	0.87 (2)	0.94 (10)*	0.96 (11)*	0.94 (10)*	0.91 (7)*
82	Zero	8	0.76	0.78 (3)	0.85 (11)*	0.87 (13)*	0.85 (11)*	0.82 (7)*
82	Low	8	0.83	0.85 (2)	0.92 (10)*	0.93 (11)*	0.92 (10)*	0.89 (7)*
82	High	8	0.81	0.83 (2)	0.90 (10)*	0.91 (11)*	0.90 (10)*	0.87 (7)*

Table 7: Summary of regression estimates of mean bulk density in skid trail ruts by harvester-forwarder traffic level, percent change from pre-harvest (in parentheses), and significant difference from 0 passes at the 90% level (denoted with *). (Values used in regression: Pre-harvest Bulk Density = (4") 0.73 and (8") 0.87 g/cm^3, Moisture Content = 0.47.)

to the model variance at eight inches (p=0.017). Mean bulk density by traffic level and slash treatment, the estimated percent change from the undisturbed level, and significant differences from the undisturbed level in skid trail centers are summarized in Table 8.

5.4.5. Influential Points in the Skid Trail Center Model

Results of the skid trail center model at the four-inch depth were influenced by three points: the nine-pass sample from Plot 10, the 13-pass sample from Plot 5, and the Plot 2 sample at 17 passes. Omitting the Plot 5 point resulted in the Unit parameter becoming significant (p=0.041, +0.05 g/cm^3). When the Plot 10 point was excluded, the 6-10 pass category became significantly different from the zero pass level (p=0.044, +0.08 g/cm^3). In addition, the low slash treatment was found to have approximately 0.09 g/cm^3 lower bulk densities than the zero slash treatment ($p<0.06$) after removing the Plot 2 and 10 points. However, because there are no field or lab observations to suggest that these points are different from the other measurements, they were kept in the data set. No influential points were observed at the eight-inch depth.

5.4.6. Forwarder Traffic Only, Slash Treatment and Bulk Density in Skid Trails

Results were analyzed using either multiple linear regression or a comparison of confidence intervals. A comparison of confidence intervals was utilized where there were insufficient data points to perform a multiple linear regression (i.e. the low and high slash treatments). Four plots were treated with forwarder traffic only. As treatments were not replicated between units, each plot was analyzed separately.

Multiple linear regression was utilized to determine the effects of traffic on the zero-slash treatment (Plot 6, Unit 82). Scatterplots of the data are displayed in Figures 15 and 16. The

			Mean Bulk Density (g/cm^3) for Equipment Pass Category					
Unit	Slash Treatment	Sampling Depth (in)	0	1-2	3-5	6-10	11-20	>20
81	Low	4	0.64	0.69 (7)	0.63 (-2)	0.69 (7)	0.71 (10)*	0.72 (11)*
81	High	4	0.69	0.75 (8)	0.69 (0)	0.74 (7)	0.77 (10)*	0.77 (10)*
82	Zero	4	0.67	0.72 (7)	0.66 (-2)	0.72 (7)	0.74 (9)*	0.75 (11)*
82	Low	4	0.60	0.65 (8)	0.59 (-2)	0.65 (8)	0.67 (10)*	0.68 (12)*
82	High	4	0.65	0.71 (8)	0.65 (0)	0.70 (7)	0.73 (11)*	0.74 (12)*
81	Low	8	0.82	0.86 (5)	0.78 (-5)	0.82 (0)	0.82 (0)	0.85 (4)
81	High	8	0.86	0.90 (4)	0.82 (-5)	0.87 (1)	0.87 (1)	0.89 (3)
82	Zero	8	0.74	0.79 (6)	0.70 (-6)	0.75 (1)	0.75 (1)	0.77 (4)
82	Low	8	0.74	0.79 (6)	0.71 (-4)	0.75 (1)	0.75 (1)	0.78 (5)
82	High	8	0.79	0.83 (5)	0.75 (-5)	0.79 (0)	0.79 (0)	0.82 (4)

Table 8: Summary of skid trail center regression estimates of mean bulk density by harvester-forwarder traffic level, percent change from pre-harvest (in parentheses), and significance at 90% level (denoted with *). Pre-harvest Bulk Density = (4") 0.73 and (8") 0.87 g/cm^3, Moisture Content = 0.47.

resulting regression equations with model and coefficient significance are summarized in Tables 9 and 10.

Forwarder traffic levels were not significantly related with soil bulk density of the zero-slash treatment except at the eight-inch sampling depth in skid trail ruts. In this case, 3-5 forwarder passes were found to increase bulk density above the pre-harvest level by 0.20 g/cm^3 (p=0.049), though 6-10 passes did not affect the level of compaction (p=0.139).

The regression estimates of soil bulk density, percentage change from pre-harvest levels, and where the density significantly differs from the zero pass level for ruts at the eight-inch depth are summarized in Table 11.

Scatterplots of the data collected in low and high slash treatment plots receiving forwarder traffic only are provided in Figures 17 and 18.

Mean bulk density and confidence intervals or maximum and minimum values per traffic level per plot are provided in Table 12.

No difference was observed between bulk densities pre- and post-forwarder except for the 1-2 pass category in the center of skid trails at the four-inch depth of Plot 9.5 (high slash) and at the eight-inch depth in Plot 12 (low slash). Increases of 17 and 23% were observed in this traffic category (Plots 9.5 and 12, respectively). As this was only a visual assessment of confidence intervals, the difference in not considered statistically significant.

Overall, forwarder traffic did not appear to affect soil bulk densities after ten or less passes regardless of slash depth. There is some evidence that bulk density increases occurred after 1-2 passes in the skid trail center with both the high (4 inch sampling depth) and low (8 inch sampling depth) slash treatments. These results should be viewed as preliminary, however, as they reflect relatively limited sampling.

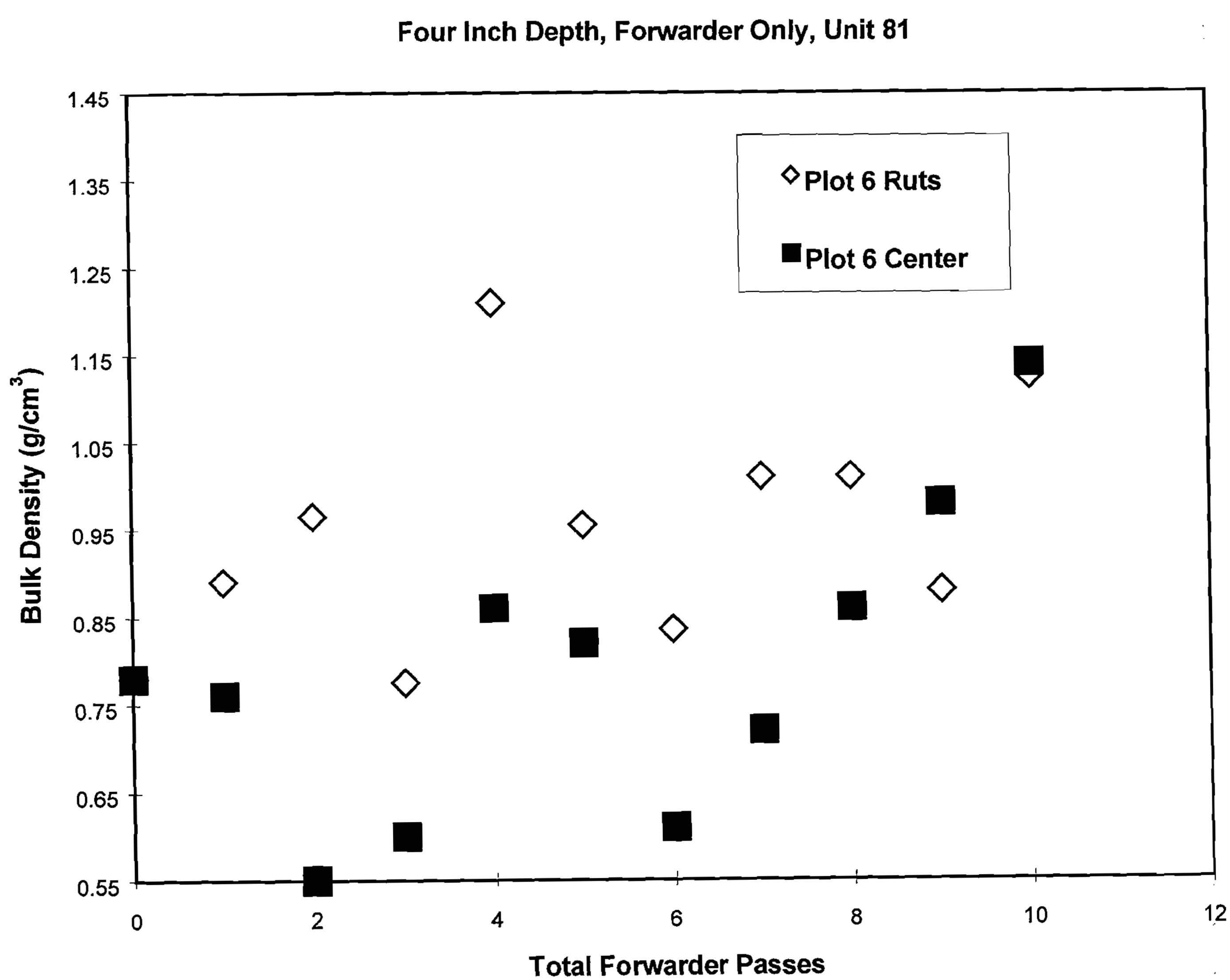

Figure 15: Four-inch depth bulk density vs. total forwarder passes, zero slash.

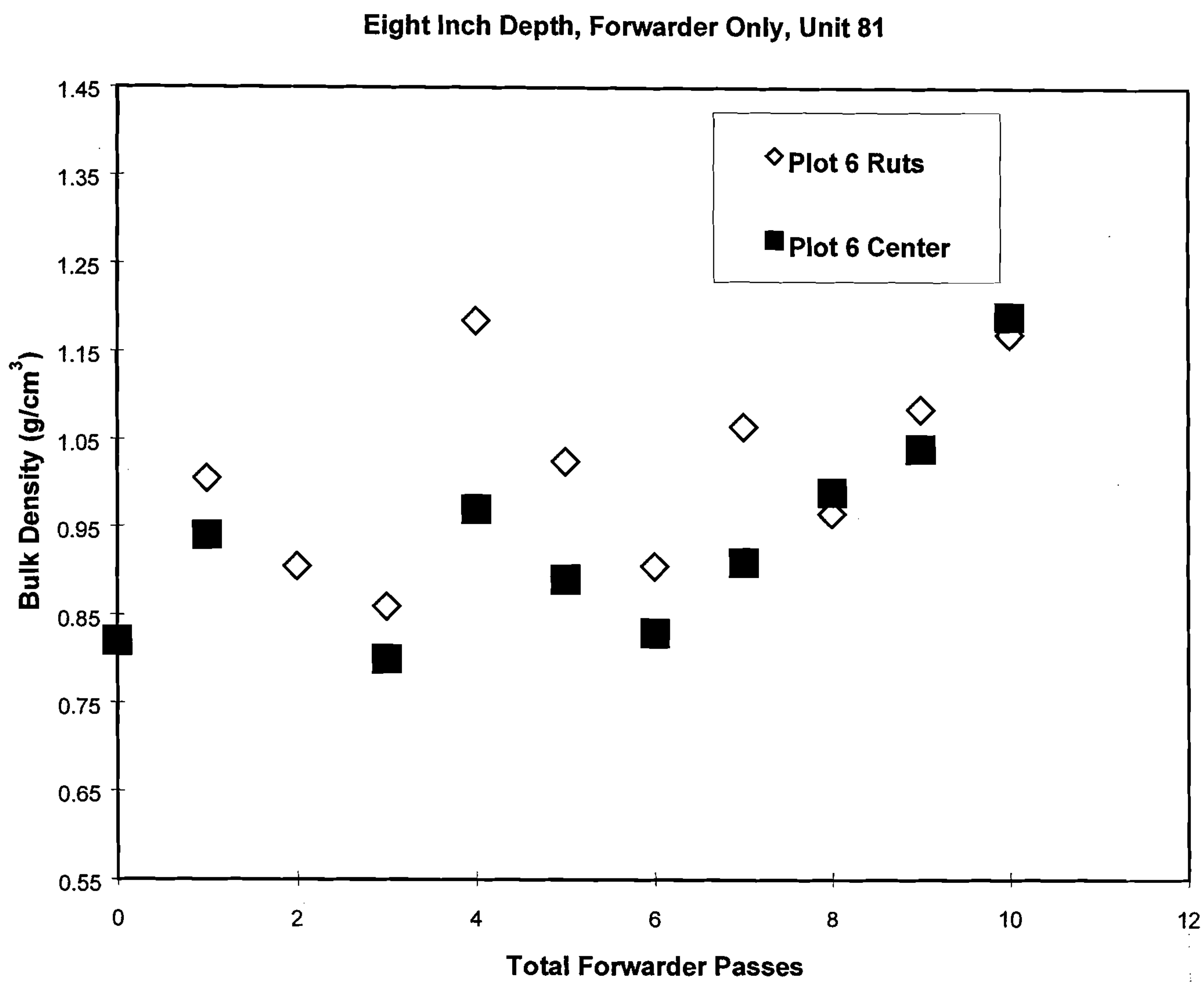

Figure 16: Eight-inch depth bulk density vs. total forwarder passes, zero slash.

Location and Sampling Depth in Skid Trail	Regression Equation
Ruts, 4 Inch Depth	Bulk Density (g/cm^3) = 0.78 + 0.1475*1-2Pass + 0.2*3-5Pass + 0.192*6-10Pass
Ruts, 8 Inch Depth	Bulk Density (g/cm^3) = 1.56072 - 1.7226*MC + 0.0144182*1-2Pass + 0.203333*3-5Pass + 0.138761*5-10Pass
Center, 4 Inch Depth	Bulk Density (g/cm^3) = 1.56921 - 1.83537*MC - 0.0240548*1-2Pass + 0.0778862*3-5Pass + 0.0379512*5-10Pass
Center, 8 Inch Depth	Bulk Density (g/cm^3) = 1.45951 - 1.48722*MC - 0.0132027*1-2Pass + 0.145985*3-5Pass + 0.136307*5-10Pass

Table 9: Regression equations for predicting bulk density at either sampling depth in the rut and center of skid trails with only forwarder traffic, zero slash treatment.

Variables	P-values			
	Skid Trail Ruts		Center of Skid Trail	
	4 Inch Depth	8 Inch Depth	4 Inch Depth	8 Inch Depth
Intercept	0.0011	0.0003	0.0031	0.0034
Moisture Content (g/g)	--	0.0101	0.0395	0.0659
1-2 Passes	0.4405	0.8826	0.8923	0.9374
3-5 Passes	0.2781	0.0493	0.6452	0.3744
6-10 Passes	0.2729	0.1390	0.8078	0.3720
r^2 (adj.)	0	65	39	43
DF	10	10	10	10
Model P-Value	0.6712	0.0313	0.1414	0.1151

Table 10: Variable and total model p-values, r^2, and degrees of freedom forwarder-traffic only regression model, zero slash treatment.

	Mean Bulk Density (g/cm^3) for Equipment Pass Category			
Model	0	1-2	3-5	6-10
8" Rut	0.75	0.77 (3)	0.95*(21)	0.89 (16)

Table 11: Summary of forwarder-traffic, zero-slash treatment, showing percent change from pre-harvest (in parentheses), and significance at 95% level (denoted with *).

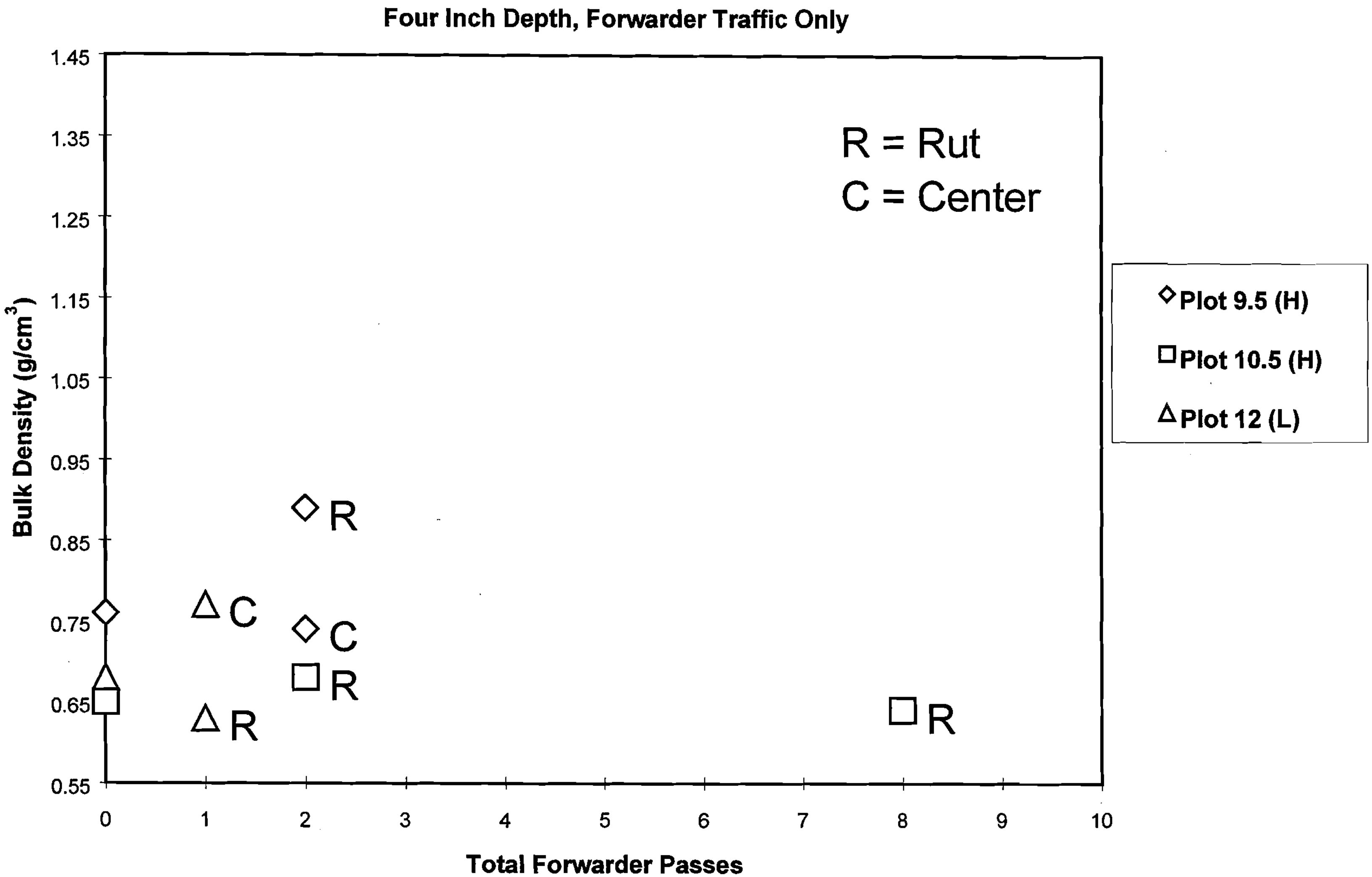

Figure 17: Four-inch depth bulk density vs. total forwarder passes. Low (L) and high (H) slash treatment with forwarder traffic only.

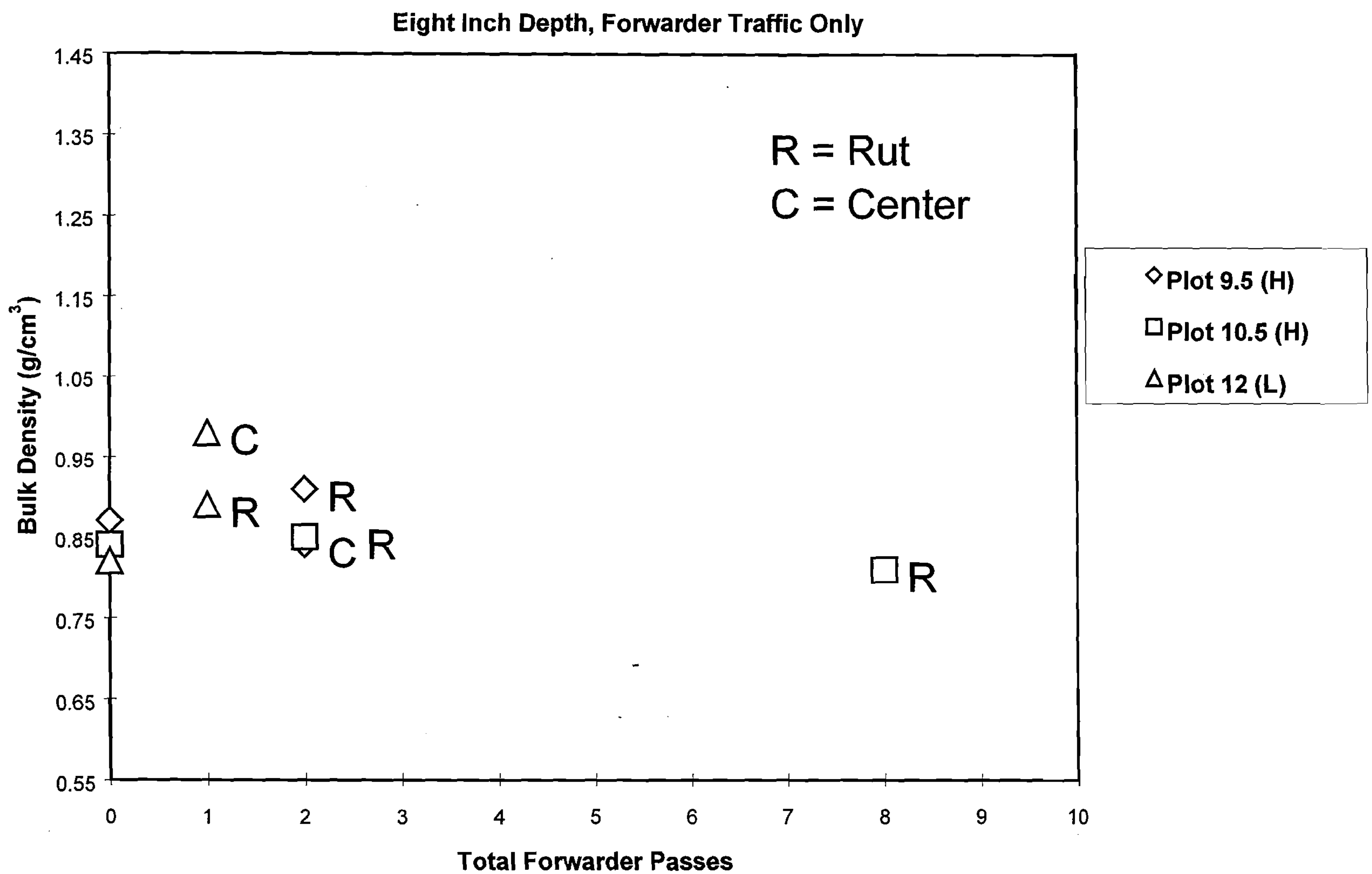

Figure 18: Eight-inch depth bulk density vs. total forwarder passes. Low (L) and high (H) slash treatment with forwarder traffic only.

	Mean Bulk Density (g/cm^3) for Equipment Pass Category (95% Confidence Interval,(NA) Not Available)		
Model	0	1-2	6-10
Low Slash, 4 Inch Ruts (Plot 12)	0.68 (0.60 - 0.76)	0.63 (0.55 - 0.71)	--
Low Slash, 8 Inch Ruts (Plot 12)	0.82 (0.72 - 0.92)	0.89 (0.78 - 1.00)	--
Low Slash, 4 Inch Center (Plot 12)	0.68 (0.60 - 0.76)	0.73 (NA)	--
Low Slash, 8 Inch Center (Plot 12)	0.82 (0.72 - 0.92)	1.06 (NA)*	--
High Slash, 4 Inch Ruts (Plot 9.5)	0.76 (0.70 - 0.83)	0.78 (0.69 - 0.88)	--
High Slash, 8 Inch Ruts (Plot 9.5)	0.87 (0.78 - 0.96)	0.84 (0.76 - 0.91)	--
High Slash, 4 Inch Ruts (Plot 10.5)	0.65 (0.59 - 0.71)	0.68 (0.36 - 0.99)	0.64 (0.44 - 0.84)
High Slash, 8 Inch Ruts (Plot 10.5)	0.84 (0.78 - 0.89)	0.85 (-0.04 - 1.74)	0.81 (0.64 - 0.98)
High Slash, 4 Inch Center (Plot 9.5)	0.76 (0.70 - 0.83)	0.92 (0.85 - 0.98)*	--
High Slash, 8 Inch Center (Plot 9.5)	0.87 (0.78 - 0.96)	0.99 (0.67 - 1.30)	--

Table 12: Mean bulk density and 95% confidence intervals by treatment, forwarder traffic only. * Denotes non-overlapping confidence intervals as visually compared to zero pass category.

5.4.7. Pre-Treatment Penetrometer Data

A total of 40 and 42 penetrometer profiles were collected to represent the pre-harvest soil condition at four and eight inches, respectively. No pre-harvest data was collected for Plot 12. Data from plots with whole numbers are used for those with half numbers (i.e. Plots 10 and 10.5). Sixty-four penetrometer profiles were collected for post-harvest analysis. A statistical summary of the pre-harvest data is given in Table 13.

Cone index measurements were collected with pre- and post-treatment bulk density samples in Unit 81, but high soil strength during data collection in Unit 82 precluded sampling.

5.4.8. Vehicle Traffic, Slash Treatment and Penetrometer Measurements

Cone index data was analyzed using multiple linear regression models similar to those used for the bulk density data to facilitate comparison of the results. As before, where there were multiple measures within the same plot at a given number of passes, the values were averaged. Scatterplots of the cone index data versus total equipment passes are provided in Figures 19 - 22.

The resulting regression equations and related statistics are provided in Tables 14 and 15. Moisture content and pre-harvest cone index were tested for significance in all models, but were excluded for lack of significance ($p>0.10$).

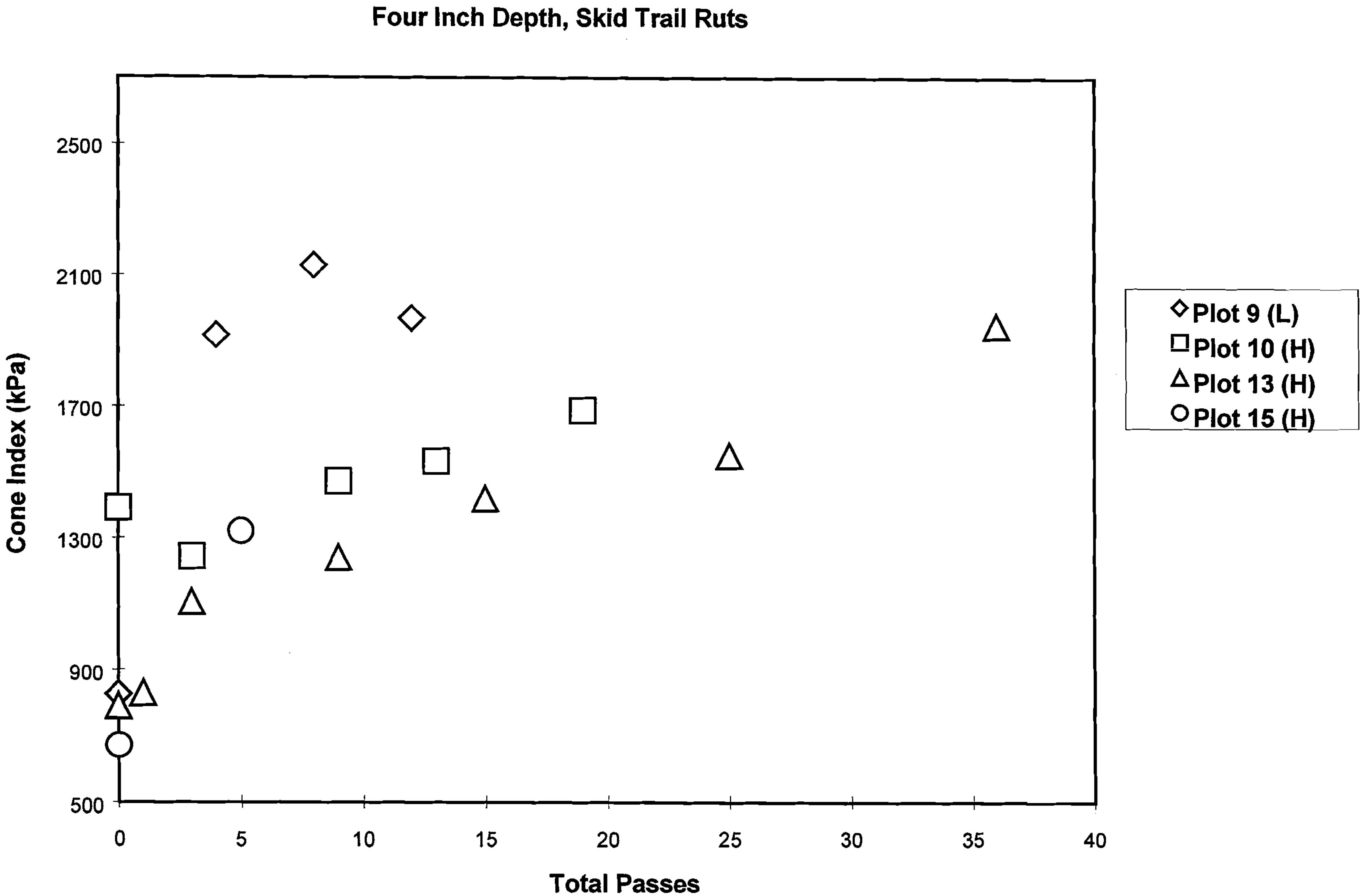

Figure 19: Four-inch depth cone index vs. total equipment passes, skid trail ruts, Unit 81.

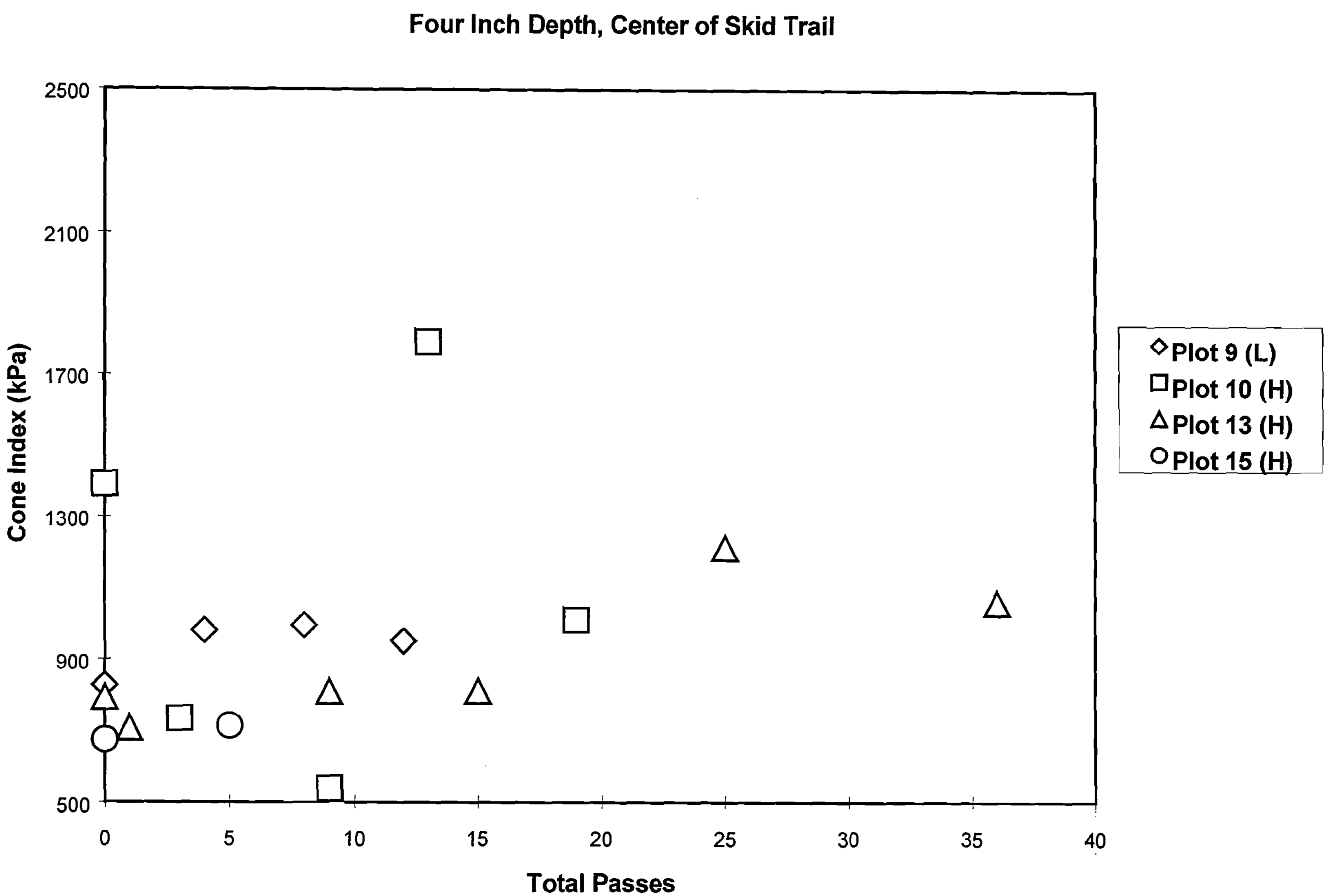

Figure 20: Four-inch depth cone index vs. total equipment passes, center of skid trail, Unit 81.

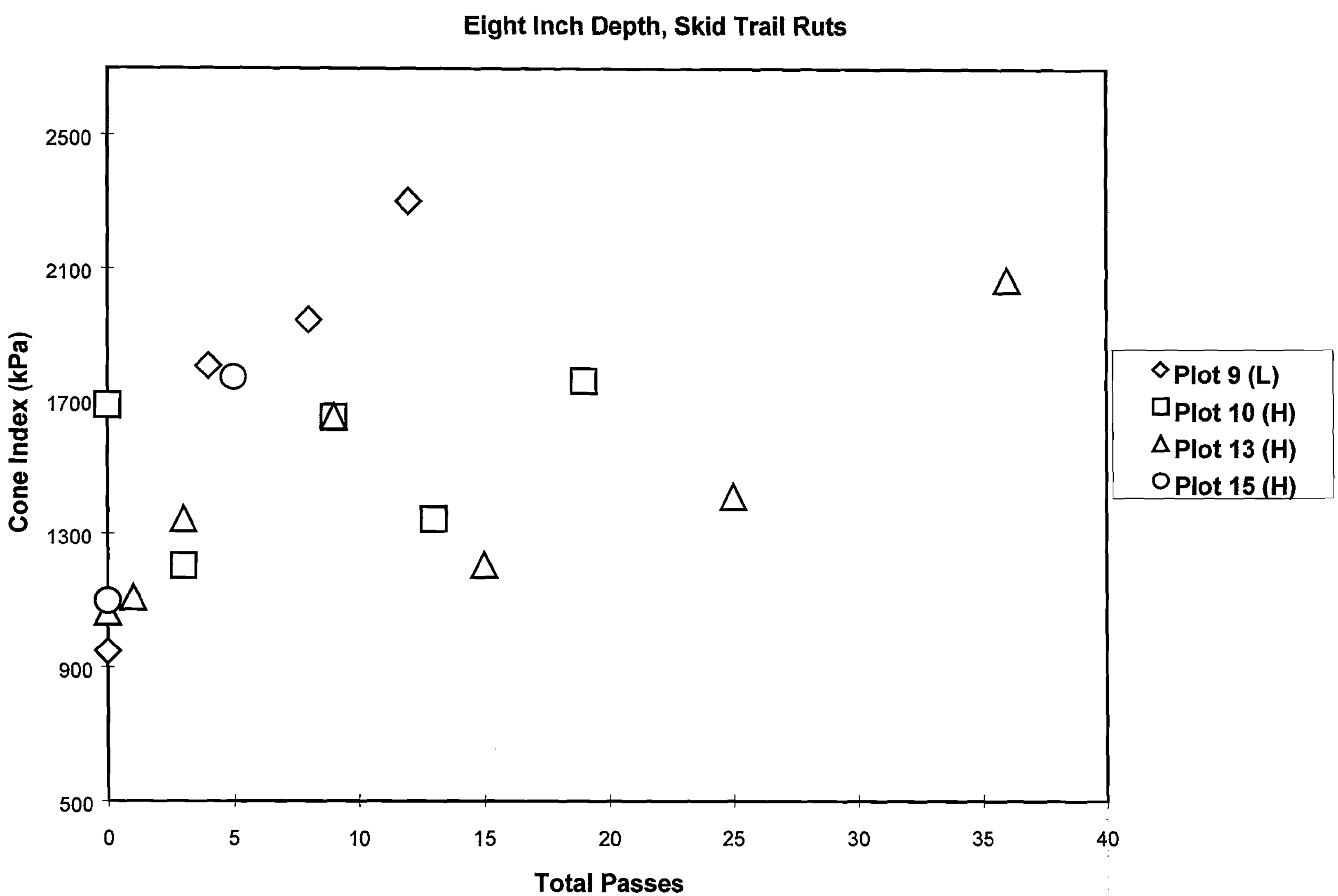

Figure 21: Eight-inch cone index vs. total equipment passes, skid trail ruts, Unit 81.

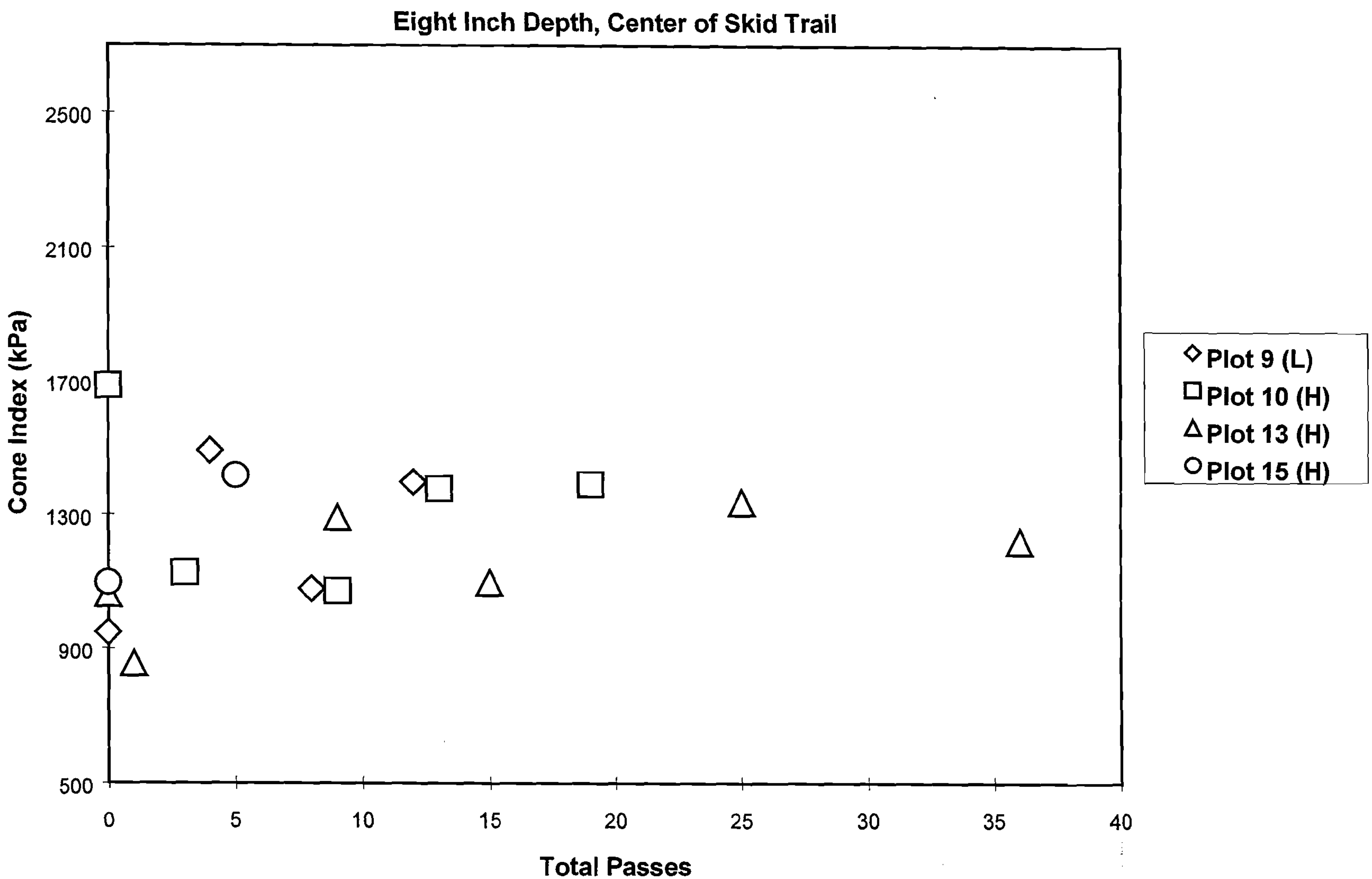

Figure 22: Eight-inch depth cone index vs. total equipment passes, center of skid trail, Unit 81.

			4 Inch Depth Cone Index (kPa)			8 Inch Depth Cone Index (kPa)		
Plot	Unit	n	Avg.	s^2	CV	Avg.	s^2	CV
9	81	4	825	36625	0.23	947	80339	0.30
10	81	4	1390	22157	0.11	1686	136935	0.22
13	81	4	791	84149	0.36	1063	28939	0.16
15	81	9/8	672	114166	0.50	1097	189231	0.40

Table 13: Summary of pre-harvest penetrometer (cone index) data.

Location and Sampling Depth in Skid Trail	Regression Equation
Ruts, 4 Inch Depth	Cone Index (kPa) = 1242.76 - 430.978*SlashHigh + 17.7168*Pass1-2 + 477.097*Pass3-5 + 658.447*Pass6-10 + 732.66*Pass11-20 + 936.217*Pass>20
Ruts, 8 Inch Depth	Cone Index (kPa) = 1420.69 - 296.755*SlashHigh - 16.4362*Pass1-2 + 332.563*Pass3-5 + 525.922*Pass6-10 + 455.25*Pass11-20 + 615.314*Pass>20
Center, 4 Inch Depth	Cone Index (kPa) = 946.465 - 35.9167*SlashHigh - 205.549*Pass1-2 - 114.521*Pass3-5 - 142.187*Pass6-10 + 222.097*Pass11-20 + 227.451*Pass>20
Center, 8 Inch Depth	Cone Index (kPa) = 1173.44 + 32.9118*SlashHigh - 350.353*Pass1-2 + 151.284*Pass3-5 - 47.049*Pass6-10 + 119.0*Pass11-20+ 74.6471*Pass>20

Table 14: Regression equations for predicting cone index at either sampling depth in the rut and center of skid trails with harvester and forwarder traffic.

Soil resistance to penetration increased from the zero pass level in skid trail ruts at the four-inch depth after 3-5 equipment passes (p=0.031) and after 6-10 passes at the eight-inch depth (0.08). Subsequent equipment passes also had greater cone index values than the undisturbed state at both sampling depths, but none of these traffic levels were significantly different from each other (p>0.10).

A high level of slash was found to reduce overall cone index values in skid trail ruts by 431 kPa as compared to the low slash treatment at the 4 inch depth (p=0.021). Slash did not appear to influence bulk densities in skid trail ruts at the eight-inch depth. Neither equipment pass nor slash treatments, however, were observed to affect bulk density in the center of skid trails. Estimates of the mean cone index in skid trail ruts are provided in Table 16.

5.4.9. Influential Data Points on Penetrometer Models

It is important to note that for the rut models at both depths the coefficient for the 1-2 pass category is based on a single and thus influential value. Though no unusual residuals were observed in the four-inch depth skid trail center model, the pre-harvest value from Plot 10 at the eight-inch depth was found to influence the statistical results. If this point is excluded from the analysis, the 3-5, 11-20, and >20 pass categories all become significantly different from the zero pass level (p=0.0272, 0.0306 and 0.0933 respectively). As no valid reason for excluding this data point was found in the field notes, it remained part of the data set.

5.4.10. Forwarder Traffic Only, Slash Treatment and Penetrometer Measurements

Scatterplots of the cone index data collected on Unit 81 plots receiving forwarder traffic only are provided in Figures 23 and 24. As there were insufficient data points to perform a

Variables	Indicator (I) or Continuous (C) Variable	P-values Skid Trail Ruts 4 Inch Depth	 8 Inch Depth	 Center of Skid Trail 4 Inch Depth	 8 Inch Depth
Intercept	--	0.0000	0.0001	0.0014	0.0000
High Slash	I	0.0211	0.1757	0.8560	0.8101
1-2 Passes	I	0.9552	0.9675	0.5869	0.1966
3-5 Passes	I	0.0314	0.2063	0.6547	0.3994
6-10 Passes	I	0.0093	0.0755	0.5797	0.7898
11-20 Passes	I	0.0030	0.0931	0.3560	0.4708
>20 Passes	I	0.0025	0.0707	0.4437	0.7131
r^2 (adj.)	--	61	17	0	0
DF	--	17	17	16	16
Model P-Value	--	0.0080	0.2401	0.6697	0.5888

Table 15: Variable and total model p-values, r^2, and degrees of freedom for harvester-forwarder traffic regression models with cone index as the dependent variable.

		Mean Cone Index (kPa) at Equipment Pass Category					
Slash Treatment	Sampling Depth (in)	0	1-2	3-5	6-10	11-20	>20
Low	4	1243	1261	1720*	1901*	1976*	2179*
High	4	812	830	1289*	1470*	1545*	1748*
Low	8	1421	1404	1753	1947*	1876*	2036*
High	8	1124	1107	1456	1650*	1579*	1739*

Table 16: Summary of mean cone index in skid trail ruts with harvester and forwarder traffic and two slash treatments (Unit 81 only, significant difference from zero passes at 90% level denoted with *).

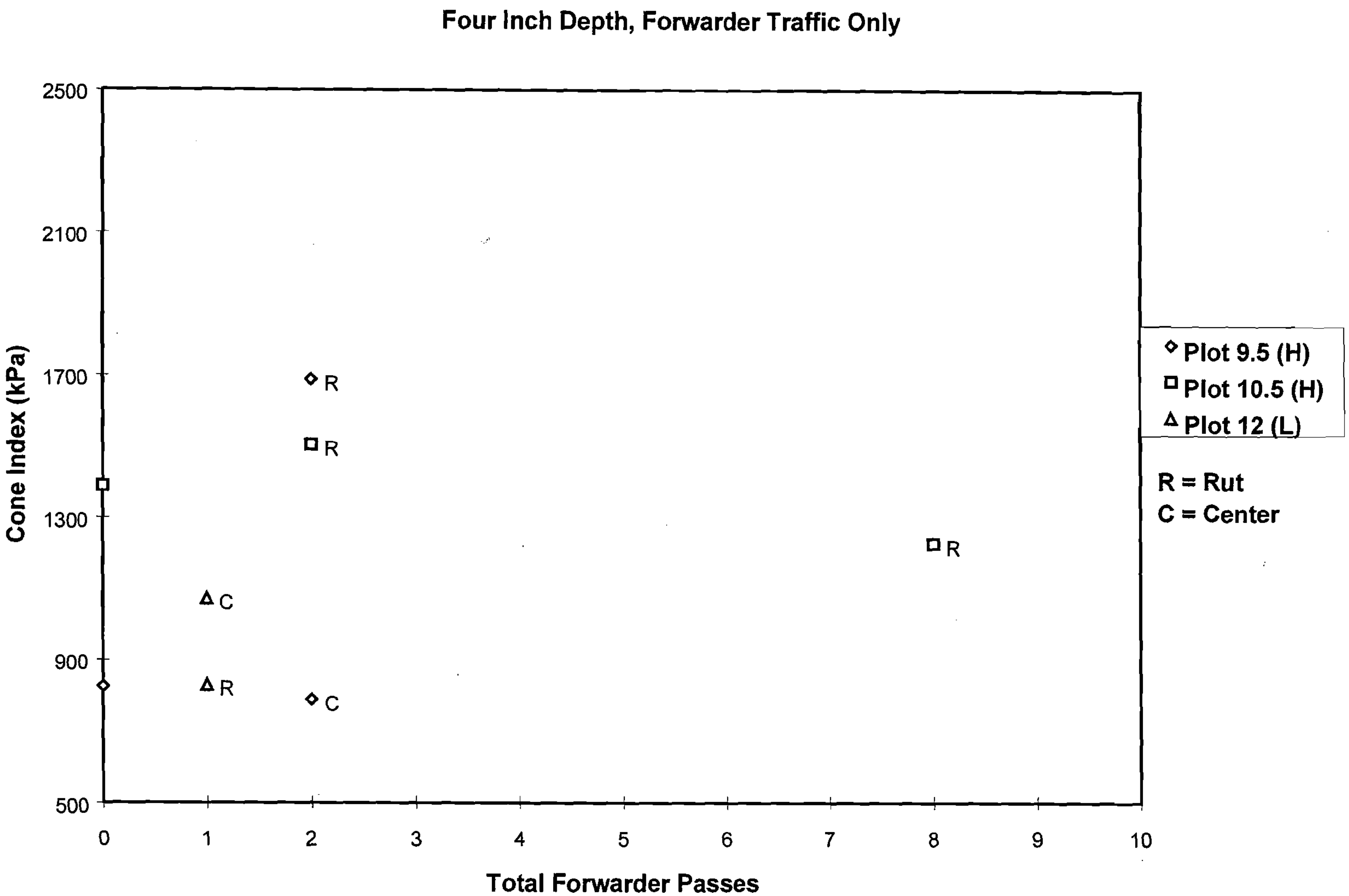

Figure 23: Four-inch depth cone index vs. forwarder passes, Unit 81. (H) and (L) indicate high and low slash treatments, respectively.

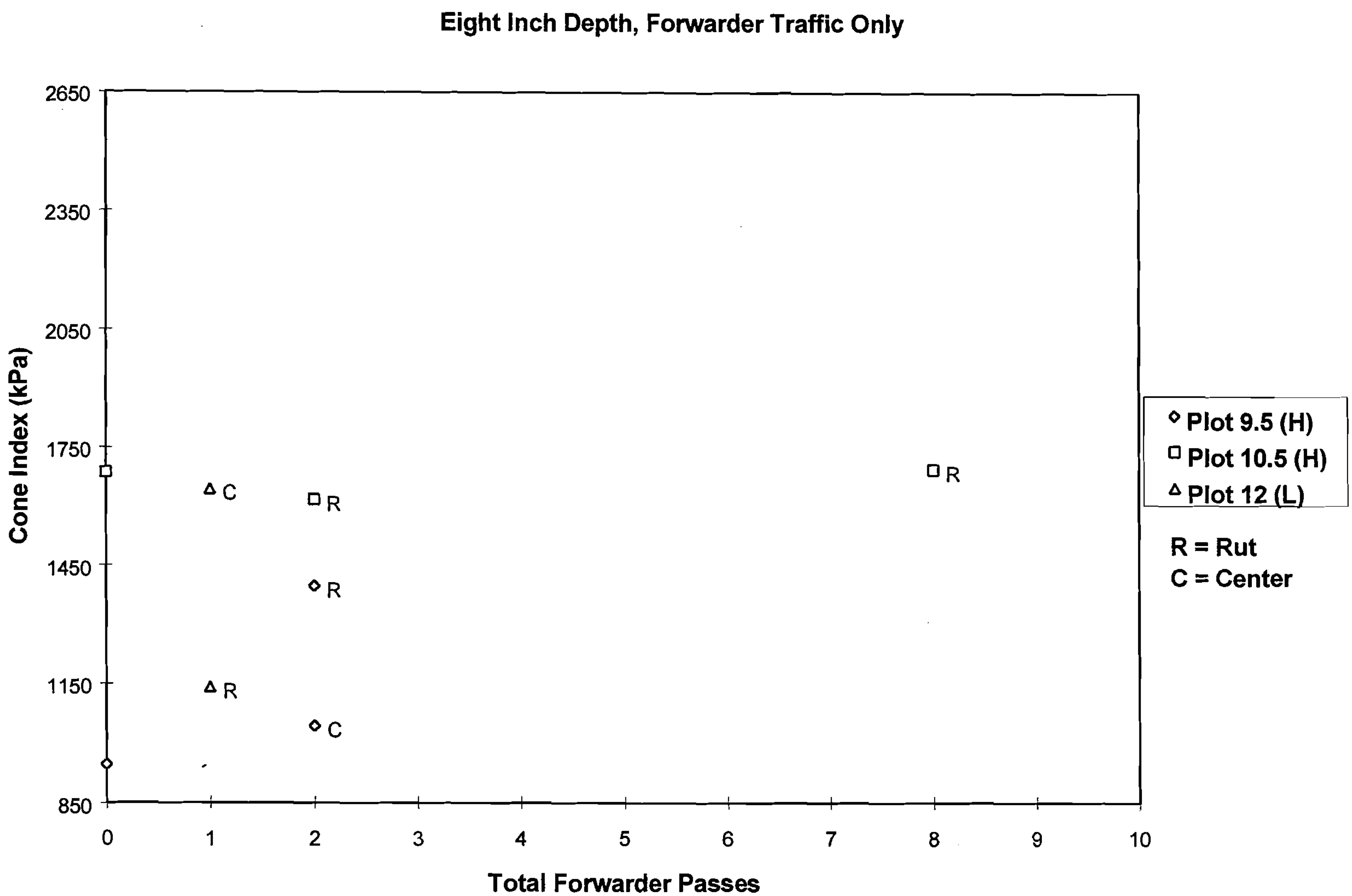

Figure 24: Eight-inch depth cone index vs. forwarder passes, Unit 81. (H) and (L) indicate high and low slash treatments, respectively.

multiple linear regression, a visual comparison of confidence intervals was utilized to identify notable differences in means (see Table 17).

Only cone indices of skid trail ruts at the four-inch depth of the high slash treatment after 1-2 passes showed qualitative evidence of a change (+823 kPa) from the zero pass category. Overall, it appears that forwarder traffic or slash treatments had any effect on soil cone index values.

5.4.11. Penetrometer Measurements and Prediction of Bulk Density

Linear regression was utilized to determine how effective penetrometer data was for predicting soil bulk density (Figures 25 and 26). At both the four- and eight-inch depth, the cone index is significantly related to bulk density (p=0.0003 and 0.006), but appears to have little value as a prediction tool ($r^2 \leq 10\%$).

5.5. *Estimates of Total Areal Compaction*

The spatial distribution and degree of compaction in each of the thinning units was estimated from skid trail maps, the total number of forwarder loads per unit and from the previous analysis of bulk density changes associated with traffic levels. Skid trail maps were hand-drawn by the USDA Forest Service timber sale administrator and the number of forwarder loads was obtained from shift level data collected from the logging operator as part of a time and motion study conducted concurrently at the site[2]. Dividing the estimated length of skid trails in a

[2] Miller, M. Personal communication. Time and motion study. Department of Forest Engineering, Oregon State University, Corvallis

	Mean Cone Index (kPa) at Equipment Pass Category (95% Confidence Interval in parentheses)		
Model	0	1-2	6-10
Low Slash, 4 Inch Ruts (Plot 12)	--	830 (788 - 872)	--
Low Slash, 8 Inch Ruts (Plot 12)	--	1141 (881 - 1401)	--
Low Slash, 4 Inch Center (Plot 12)	--	1071 (--)	--
Low Slash, 8 Inch Center (Plot 12)	--	1645 (--)	--
High Slash, 4 Inch Ruts (Plot 9.5)	825 (637 - 1013)	1688 (1192 - 2184)*	--
High Slash, 8 Inch Ruts (Plot 9.5)	947 (669 - 1225)	1397 (917 - 1877)	--
High Slash, 4 Inch Ruts (Plot 10.5)	1390 (1244 - 1536)	1229 (127 - 2331)	1505 (1073 - 1937)
High Slash, 8 Inch Ruts (Plot 10.5)	1686 (1323 - 2049)	1696 (-285 - 3677)	1617 (1140 - 2094)
High Slash, 4 Inch Center (Plot 9.5)	825 (637 - 1013)	788 (710 - 866)	--
High Slash, 8 Inch Center (Plot 9.5)	947 (669 - 1225)	1043 (1009 - 1077)	--

Table 17: Mean cone index and 95% confidence intervals by treatment, forwarder traffic only. * Denotes non-overlapping confidence intervals in a visual comparison to zero pass category.

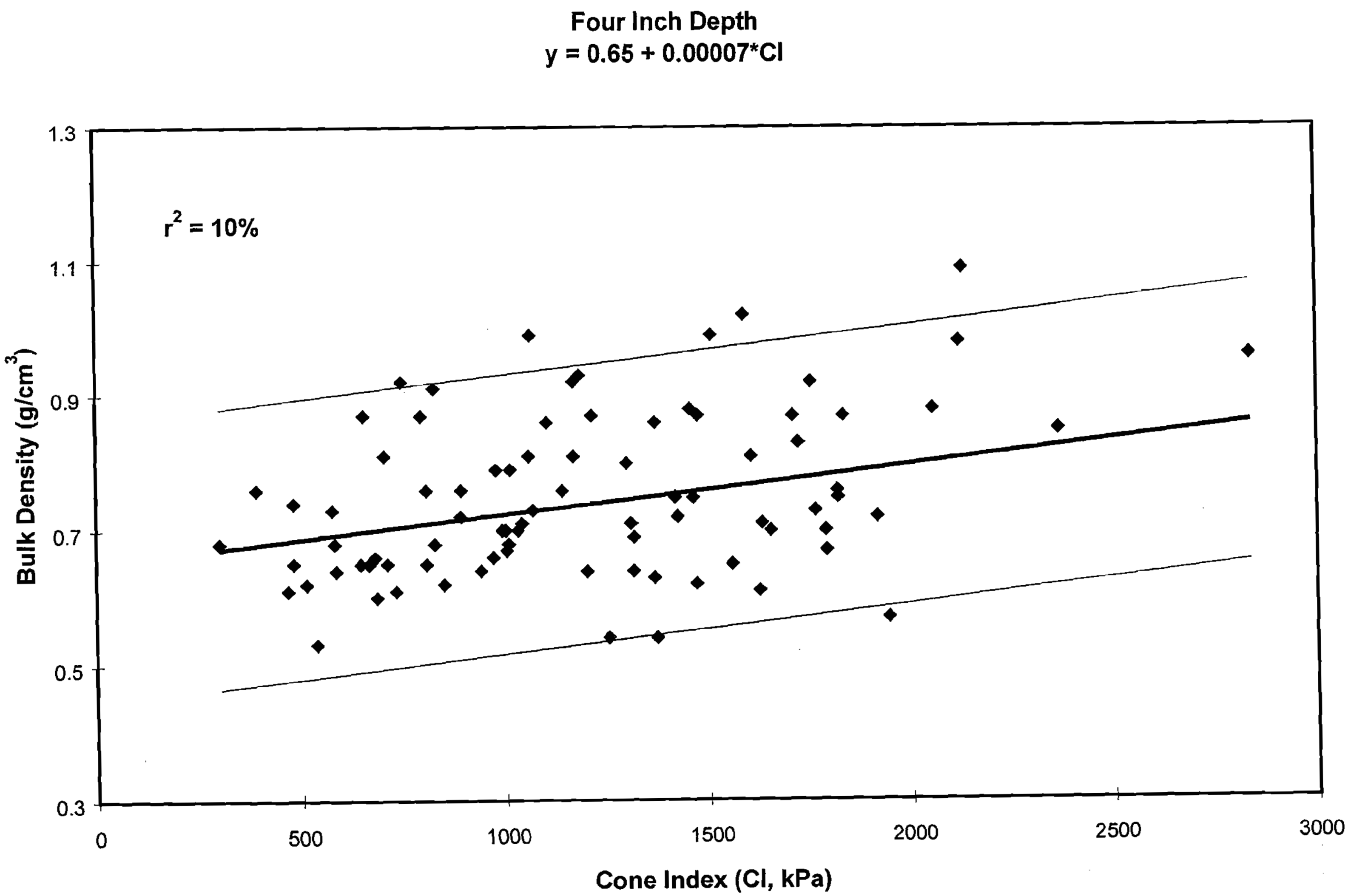

Figure 25: Four-inch depth bulk density vs. cone index regression with 95% prediction limits. Regression equation and r-squared values are also shown.

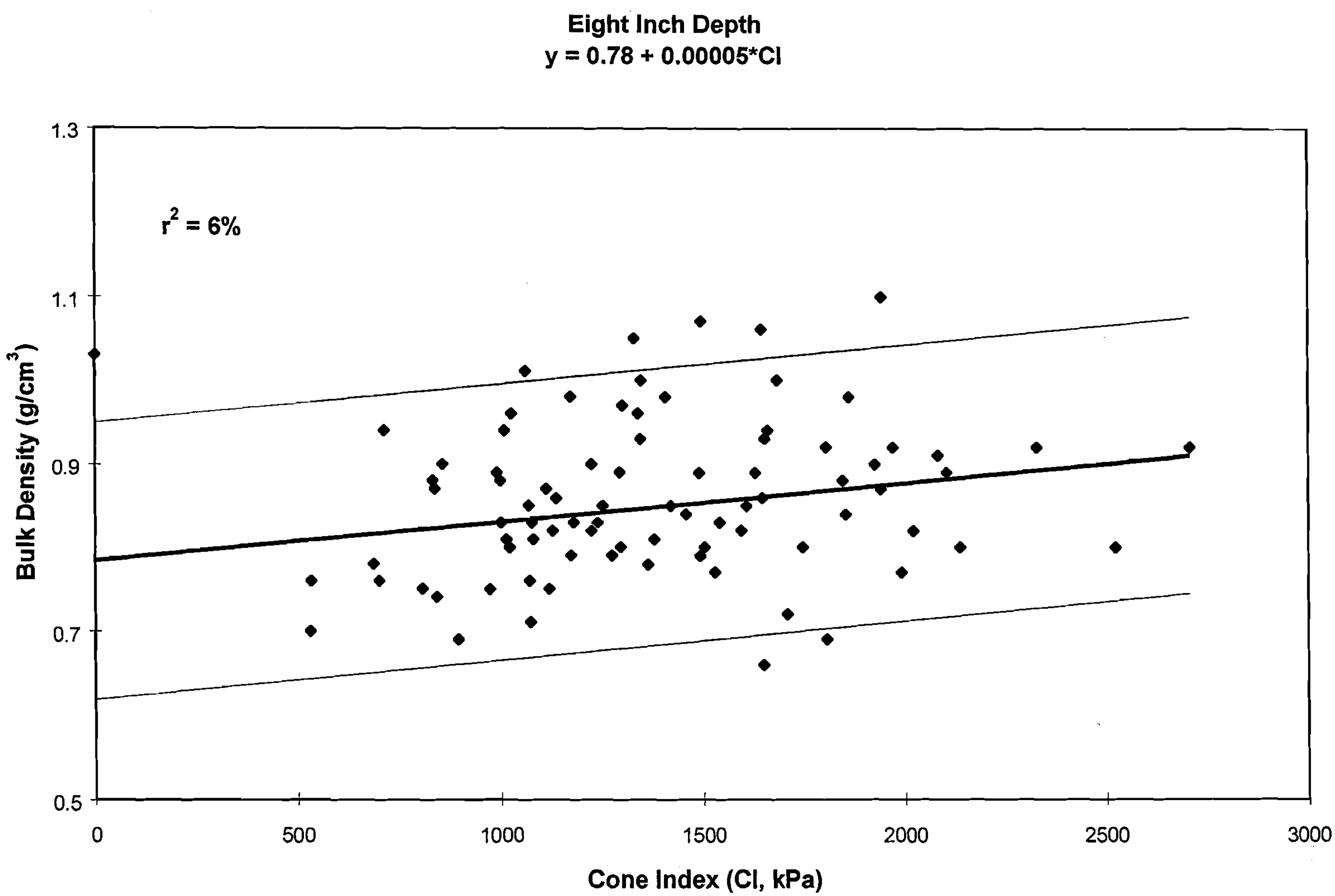

Figure 26: Eight-inch depth bulk density vs. cone index regression with 95% prediction limits. Regression equation and r-squared values are also shown.

	(A) Estimated No. Forwarder Loads (Round Trips)	(B) Estimated Total Skid Trail Length (ft)	(C) Feet of Skid Trail per Forwarder Load (B/A)
Unit 81	349	31012	89
Unit 82	638	41382	65

Table 18: Estimated total skid trail length, total forwarder loads and length of trail for one forwarder load per unit.

unit by the tallied number of forwarder loads provided the average length of skid trail necessary to produce one forwarder load (Table 18). The estimated feet of skid trail per forwarder load (one round trip or two passes), plus an assumed harvester traffic level of two passes per skid trail, allowed the traffic pattern to be distributed across the skid trail maps (Figures 27 and 28). For example, in Unit 81 an 89 foot long skid trail would have four vehicle passes (two harvester passes plus two forwarder passes), while a skid trail twice that length would support two forwarder loads or a total of six vehicle passes (two harvester passes plus four forwarder passes). Example calculations as performed with a Visual Basic program in Excel are provided in Appendix A. Finally, the bulk density corresponding to the estimated traffic level on each skid trail was determined from the results of the previous multiple linear regression analysis of harvester- forwarder traffic (Tables 7 and 8). Assuming an average skid trail width of ten feet and a track/tire width of 2.5 feet (equipment specifications), half of the skid area is estimated to be in ruts and half in the center classification. The total length, area and proportion of the unit in each traffic and density category are summarized in Tables 19 and 20.

It is estimated that bulk density was increased significantly across 11% of Unit 81 and 7% of Unit 82 at the four-inch depth. A pass category and location (i.e. rut or center) was considered compacted if the variable p-value showed a significant difference from the zero pass level in the harvester-forwarder traffic multiple regression model. These values decreased to 7 and 5% of the total unit area at eight inches. The estimated minimum density increase above the undisturbed level at the four-inch depth ranges from 10 (center) to 16% (ruts) in Unit 81 and 9 to 16% in Unit 82 (degree of compaction is ±1 or 2% depending on slash treatment). Rut bulk

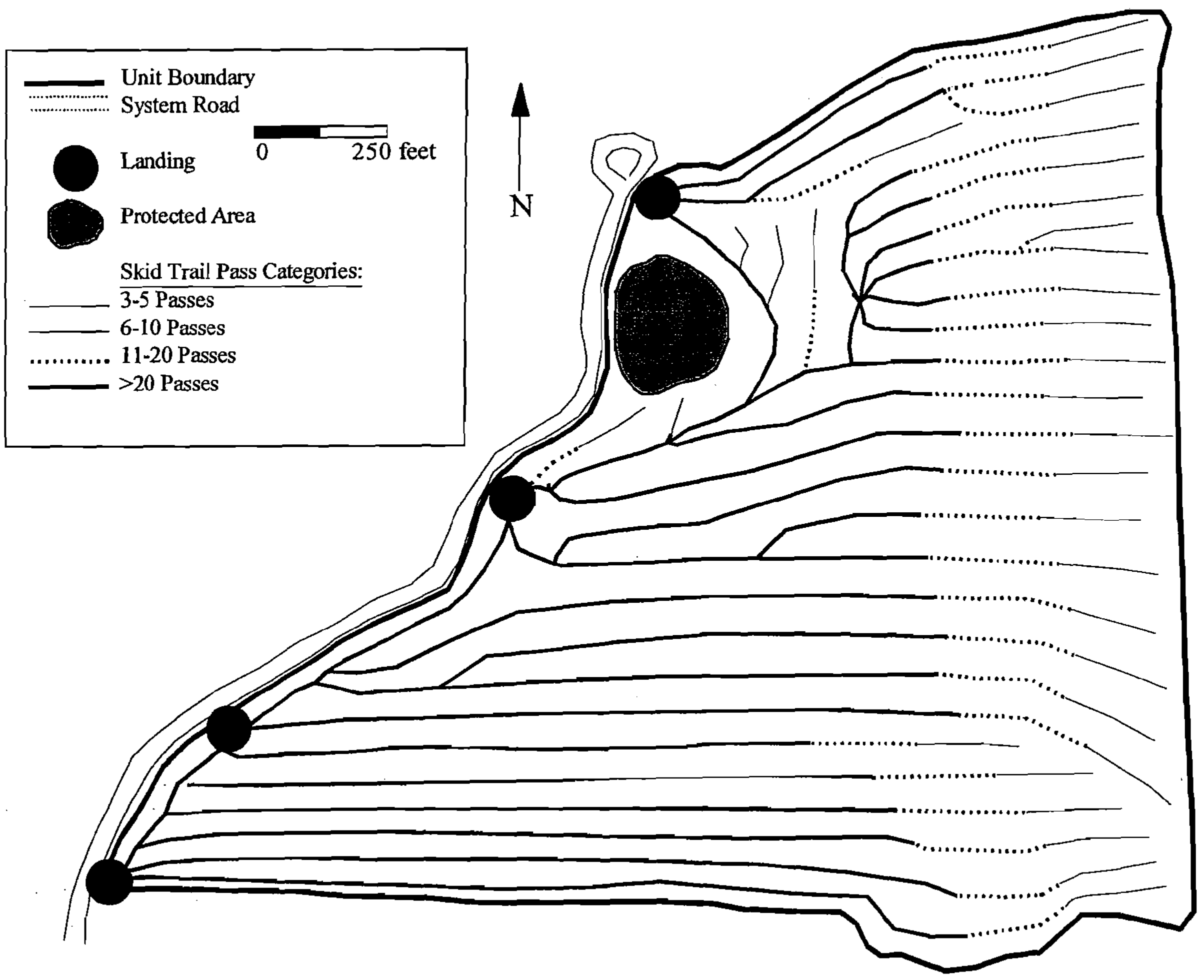

Figure 27: Unit 81 skid trail and traffic intensity map.

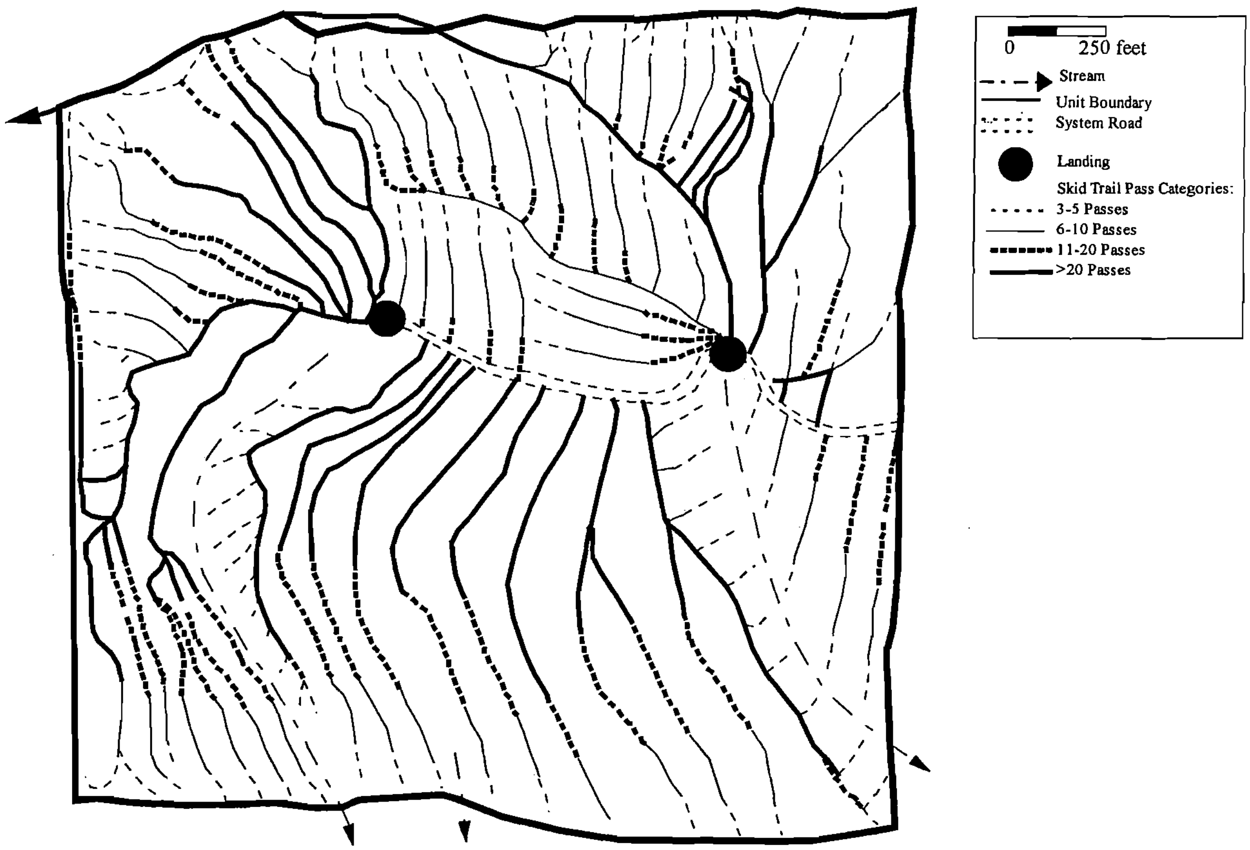

Figure 28: Unit 82 skid trail and traffic intensity map.

densities at eight inches were likely to be elevated by at least 9% in Unit 81 and 10% in Unit 82. Significant compaction was not detected at this depth in the center of skid trails.

It is estimated that the total skid trail area in Unit 82 was four percent less than that of Unit 81. Average skidding distances in Unit 81 (1027 ft) were also much longer than Unit 82 (461 ft), which increased the total length of skid trails expected to have greater than 11 passes[3]. This is pertinent as the center of skid trails at the four-inch depth appears to become compacted at these higher traffic levels. Greater than half of the area in Unit 82 was thinned using a herringbone-like skid trail pattern. This reduced the overall skidding distance and probably minimized compaction in the center of skid trails. The parallel skid trail pattern in Unit 81 increased the average skidding distance and thus the amount of compaction predicted to occur in the center of skid trails. Landing or road location may have also influenced skidding distances.

This is a low estimate of total unit compaction for two reasons. First, it was common for the harvester to make more than two passes over a skid trail in order to make repairs or complete unfinished trails. Secondly, the existing network of old skid trails from previous entries is not considered in this analysis.

6. DISCUSSION

6.1. Bulk Density

Field data and estimates from the regression equations suggest that the combination of harvester and forwarder traffic produced significant soil compaction in skid trail ruts. Compaction apparently becomes significant after 3-5 passes at both the four- and eight-inch

[3] Miller, M. Personal communication. Time and motion study. Department of Forest Engineering, Oregon State University, Corvallis.

Pass Category	Total Skid Trail Length (ft.)	Total Area (ft^2) Rut	Total Area (ft^2) Center	% of Unit Rut	% of Unit Center	% of Unit Compacted* 4 Inch Depth Rut	% of Unit Compacted* 4 Inch Depth Center	% of Unit Compacted* 8 Inch Depth Rut	% of Unit Compacted* 8 Inch Depth Center
3-5	3375	16875	16875	0.8	0.8	0.8	0	0.8	0
6-10	8520	42600	42600	2	2	2	0	2	0
11-20	10461	52305	52305	2	2	2	2	2	0
>20	8657	43285	43285	2	2	2	2	2	0
Sub-Total	31013	155065	155065	7	7	7	4	7	0
Grand-Total	31013	310130		14%		11%		7%	

Table 19: Estimated areal extent of compaction in skid trails, Unit 81. *Only pass categories found to be significantly different from zero pass level according to multiple linear regression model are considered compacted.

Pass Category	Total Skid Trail Length (ft.)	Total Area (ft^2)		% of Unit		% of Unit Compacted* 4 Inch Depth		% of Unit Compacted* 8 Inch Depth	
		Rut	Center	Rut	Center	Rut	Center	Rut	Center
3-5	7207	36035	36035	0.9	0.9	0.9	0	0.9	0
6-10	13219	66095	66095	2	2	2	0	2	0
11-20	11668	58340	58340	1	1	1	1	1	0
>20	9288	46440	46440	1	1	1	1	1	0
Sub-Total	41382	206910	206910	5	5	5	2	5	0
Grand-Total	41382	413820		10%		7%		5%	

Table 20: Estimated areal extent of compaction in skid trails, Unit 82. *Only pass categories found to be significantly different from zero pass level according to multiple linear regression model are considered compacted.

depths, with 6-10 passes yielding the greatest absolute increase in density. At the four-inch depth, this increase was 0.19 g/cm^3 (+20-22%), and 0.11 g/cm^3 (+11-13%) at eight inches. No difference was noted between the 3-5 pass and subsequent pass categories at either depth, however, suggesting that compaction had leveled off at this point due to sufficient gains in soil strength. At the eight-inch depth, the significance of the difference between the >20 and zero pass category hinges on one influential data point. The change in density was greater at the four- than eight-inch in depth.

Compaction in the center of skid trails with both harvester and forwarder traffic was significant only after 11-20 passes at the four-inch depth, with no change observed at eight inches regardless of traffic level. At four inches, 11-20 passes increased bulk density by 0.07 g/cm^3 (+9-11%) and by 0.08 g/cm^3 (+10-12%) after more than 20 passes. Omission of one influential point also resulted in the 6-10 pass category becoming significant ($p=0.044$, +0.08 g/cm^3).

Results from the forwarder-traffic-only plots conflicted somewhat with results of the harvester-forwarder-traffic plots, but this could be the result of limited sampling. Overall, forwarder traffic alone did not seem to affect soil bulk density. However, a few significant differences in bulk density (+17-23%) were observed between the zero pass and some multiple pass categories. Greater sampling intensities may have revealed more clear associations between forwarder traffic and soil bulk density.

Estimates from the regression analysis suggest that harvester-forwarder plots with a high level of slash (8 – 18 in) had 0.07 g/cm^3 lower absolute compaction levels than the low slash treatment (4 – 7 in) in skid trail ruts at the four-inch depth. A comparison of the regression-estimated bulk density between the low and high slash treatments at the same traffic level suggests that deeper slash reduces compaction by approximately 7%. However, inherent variability in the data may significantly affect the accuracy of such regression-based estimates. For example, comparing the within-slash treatment differences between the pre- and post-treatment bulk density estimates places the reduction in compaction closer to about 2%.

Slash treatment had no apparent effect on bulk density in harvester-forwarder ruts at the eight-inch depth nor at either depth or location in the forwarder-traffic only plots. Slash treatment in the center of harvester-forwarder skid trails at the four-inch depth had results conflicting those of the ruts, with a high level of slash being associated with 0.06 g/cm^3 greater bulk densities than the low slash treatment ($p=0.020$). It is possible that the low slash treatment results in more soil being displaced from the skid trail ruts and deposited in the center and edges of the trail, decreasing the measured bulk density in the center.

A difference between the bulk densities of plots with and without slash was expected but not observed ($p>0.25$). Though the zero-slash treatment plot was cleared to mineral soil, it was noted that with each pass the logging equipment incorporated a substantial amount of partly decomposed organic matter into the soil from a rotten stump at the plot edge. It is believed that this resulted an overall lower bulk density in one of the ruts than would have been expected without the incorporated organic matter (see Figure 29). Buried rotten logs and stumps were common in most plots, but the sample size for the zero slash treatment was small enough to be dominated by the influence of organic matter. Organic matter was observed to reduce soil compactibility in samples collected around Lower Saxony, Germany by Zhang et al (1997). In this study, slightly humified peat was added to clay soils that were then compacted using the standard Proctor procedure. Penetration resistance in the compacted samples was reduced from 0.49 MPa in soils without the additional organic matter to 0.30 MPa in the peat-enriched soils.

The information from both this and Zhang's study suggest that leaving adequate amounts of woody material may be a long-term mitigation against soil compaction associated with ground-based harvesting systems.

Another oddity noted in the regression was the negative relationship between moisture content and bulk density. When bulk density was plotted against moisture content at specific equipment pass levels a strong correlation was noted between the two, most noticeably in Unit 82 (see Figures 31 and 32).

Without further tests, the reason for the negative relationship between bulk density and moisture content is unknown. It is possible that variation in organic matter content may explain this phenomenon. That is, from observation is appears that higher moisture was associated with the presence of significant amounts of organic matter, which in turn reduced the observed dry bulk density values. Again, this suggests the value of decomposed large woody material not only as a mitigating factor against soil compaction, but as a soil moisture reservoir.

The relative changes noted at the four-inch depth are similar to those found in Linn County, Oregon by Armlovich (1995). In this study a harvester-forwarder pair resulted in 20, 17, and 29% increases in bulk density at the same depth for traffic levels of <4, 7-8, and 30+ equipment passes, respectively. Estimates of compaction at eight inches were also comparable, with changes of 15, 16 and 23% at the same traffic levels. In Alabama, Lanford and Stokes (1995) noted an 11-20% increase in bulk density at a two inch depth, decreasing to 7-10% at six inches after operations with a harvester-forwarder pair (Valmet 546 Woodstar). The greater compaction levels were associated with highly disturbed areas where exposure, rutting, or deposition of mineral soil over litter had occurred.

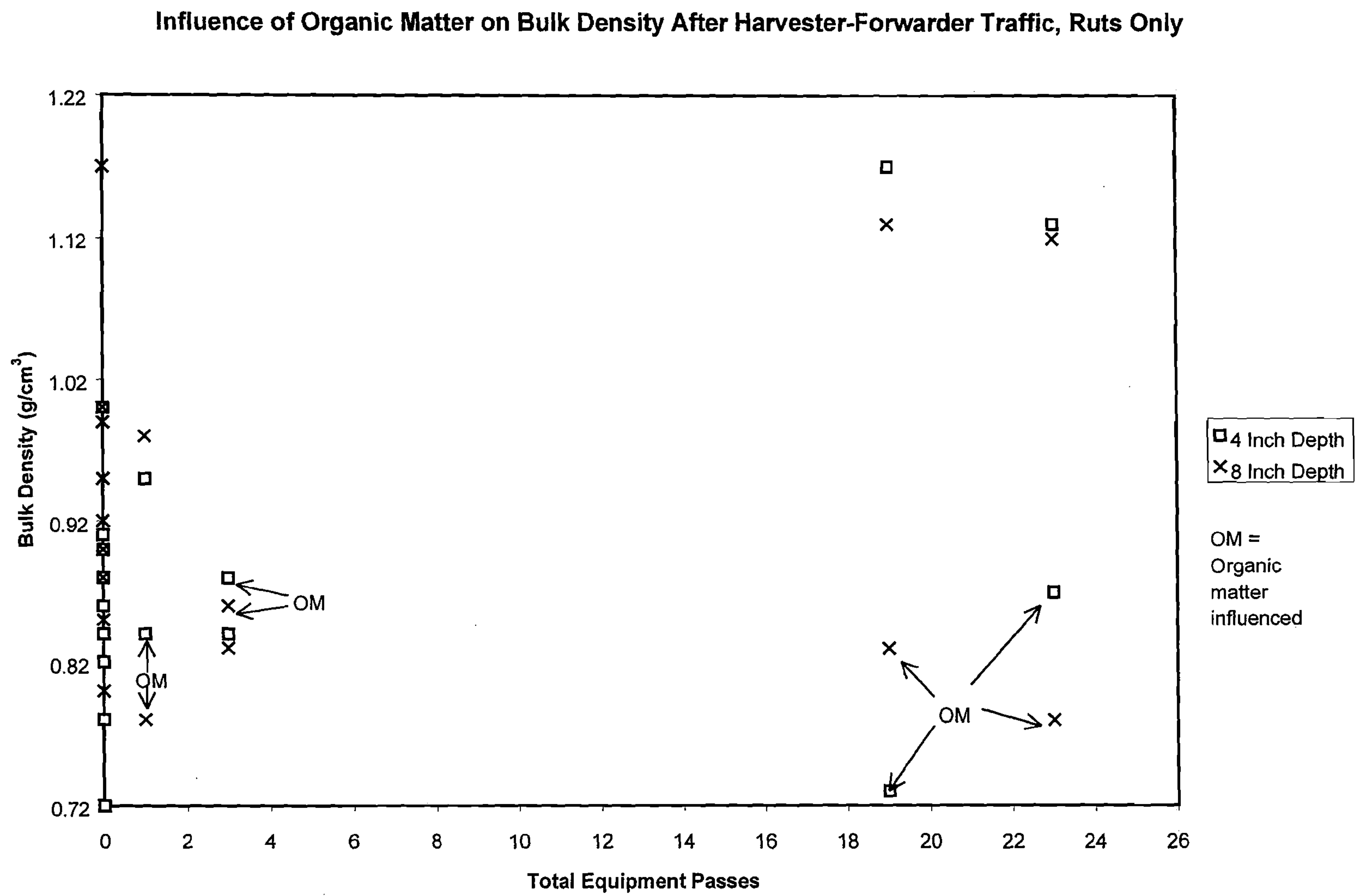

Figure 29: Influence of organic matter inputon bulk density after vehicle traffic on zero slash treatment plot.

These results suggest that compaction in skid trails varies with spatial location, depth, organic matter, moisture content, slash depth, pre-treatment bulk density and number of vehicle passes. Conclusions about vehicle-specific impacts, however, cannot be made from this data set. Ruts become compacted after only 3-5 equipment passes, while the center of skid trails do not increase in bulk density until greater than 11 passes occur. Most compaction occurs in ruts at the four-inch depth. The degree of compaction in the ruts diminishes with depth, with no detectable change in the center of skid trails at eight inches. A high level of slash also appears to provide some measure of protection in harvester-forwarder ruts at the four-inch depth.

6.2. Penetrometer Data (Cone Index)

In general, the multiple linear regression results using bulk density and penetrometer data (cone index) regarding vehicle traffic, slash and was similar in skid trail ruts. The cone index at 3-5 (4 inch depth) or 6-10 (8 inch depth) and greater pass categories was significantly greater than the zero pass level, and values in the high slash treatment were significantly lower than the low slash treatment. Cone index values, however, do not seem to flatten out after 3-5 passes unlike the bulk density data. Neither slash nor equipment pass treatments, however, were significant in the center of skid trails using penetrometer data.

For the analysis of forwarder-traffic-only plots using cone index data, the ruts at the four-inch depth in the high slash treatment after 1-2 passes were found to be greater than the zero pass category. No other differences were observed. This is in contrast to the results with bulk density where the skid trail center in both the high (4 inch depth) and low (8 inch depth) slash treatment was more dense than undisturbed soil after 1-2 passes. As mentioned, however, limited sampling may be primarily responsible for such anomalies.

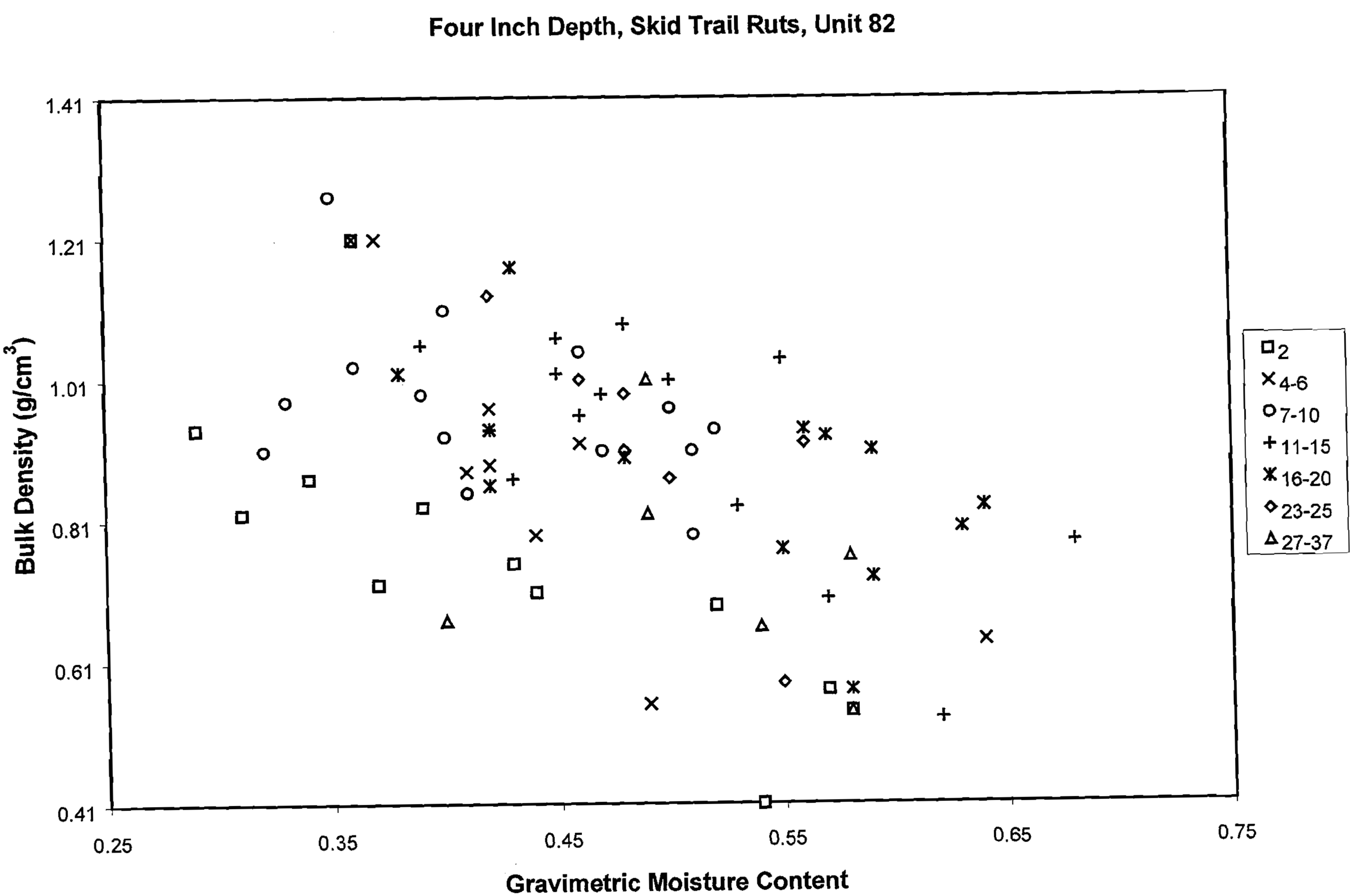

Figure 31: Bulk density at the four-inch depth vs. moisture content, by pass categories, on Unit 82.

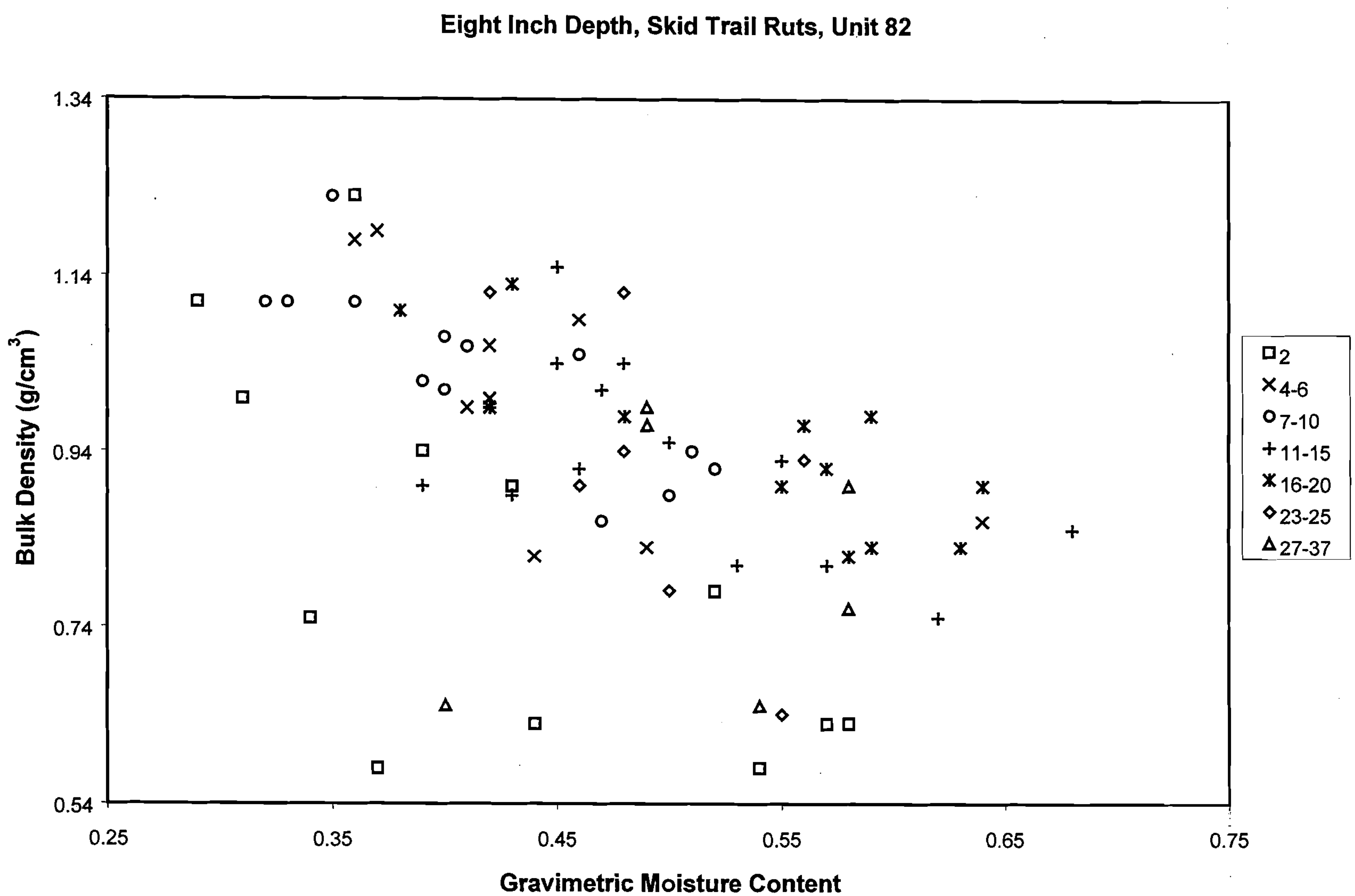

Figure 31: Bulk density at the eight-inch depth vs. moisture content, by pass categories, on Unit 82.

7. MANAGEMENT IMPLICATIONS

Land managers can take several approaches to measuring, mitigating against or alleviating soil impacts associated with forest harvest activities (Adams and Froehlich 1981, Froehlich and McNabb 1983, Klute 1986). One popular means of mitigating against compaction is to define disturbance/damage limits above which remedial or other action is taken. The USDA Forest Service created standards which state that the total acreage of all detrimental soil conditions, including system roads, should not exceed 20% of a logging unit (Forest Service Manual 2520, 2-4, R-6 Supplement 45). With regards to compaction, a detrimental condition is defined as a 20% increase in bulk density above the undisturbed level on volcanic ash or pumice soils, or a 15% increase on all other soils. The Weyerhaeuser Corporation does not use a specific standard for compaction, but relies instead upon four classes of soil disturbance[4]. Only a certain areal percentage of the unit is permitted to be classified in the more severe categories before remedial action is taken. Operators on their land are taught to identify the disturbance classes and receive feedback from the company on inspected units.

As an example, the results of this study were compared against Forest Service standards. The soils in this study fall into the "other" (non-volcanic) category. As bulk density increases as high as 22% were calculated at the four-inch depth, detrimental soil conditions most likely exist in the surface soils (based on regression models of bulk density after harvester and forwarder traffic). The relationship between the relative increase in bulk density and relative decrease in conifer height growth suggested by Froehlich and McNabb (1983) support this conclusion. From Figure 1 it is estimated that compaction after 6-10 passes with harvester-forwarder traffic has the potential to reduce height growth of seedlings and young trees by approximately 10-15%. In addition, if conifer root growth ceases at about 1 MPa as observed in annual non-woody crops, the penetrometer measurements also suggest that root growth may be inhibited in some trail locations and slash levels. Neither unit, however, was estimated to have areal extents of compaction at the four-inch depth that exceeded 20% of the total unit area. Also, detrimental conditions are not likely to exist at the eight-inch depth by this standard since the greatest calculated increase in bulk density was only 13%. Therefore, this entry would not be considered to have resulted in an unacceptable amount of "detrimental" soil compaction with respect to Forest Service standards.

Several factors, however, complicate the use of such a straightforward compaction standard. After such a thinning operation, there is a wide range in proximity of residual trees to compacted soil. Also, it is unknown how deep beyond eight inches this compaction extends or how many trees have a substantial portion of their rooting zone effected. Thus, making an accurate estimation of the areal extent of compaction required to negatively affect conifer growth is difficult. Secondly, because most penetrometer readings of undisturbed soil show values of resistance above or near 1 MPa (0.6 - 1.6 MPa), it is likely that conifer root growth is limited at a higher level of soil strength than non-woody plants. Unfortunately, no information is available as to what cone index levels are either optimal or limiting for tree growth in these soils. Third, the slash layer and soil organic matter further add to the spatial complexity of compaction. Both appear to provide protection against soil compaction, but the benefit relative to conifer growth is

[4] R. Heninger, Field Station Manager, Springfield Office, Weyerhaeuser Corporation. Personal Communication. Note: Soil disturbance standards are currently being revised.

uncertain. Other benefits of the slash layer, however, such as a possible reduction in rut formation, should not eliminate slash placement as a management tool (Wronski 1990).

A second method for land managers to minimize soil compaction and disturbance is in the choice of harvesting system. Where soil impacts is a concern, cable or helicopter systems are commonly chosen over ground-based systems. Because of the high cost associated with such systems there is a need to develop either lower-impact ground-based systems or to reduce the impacts of existing systems. Designating skid trails, as opposed to logger's choice, is commonly used to minimize the areal extent of the skid trail network (Froehlich et al. 1981). On the other hand, the results of this study suggest that unit layout may also result in different soil compaction levels. Designated skid trails were used in both the harvest units in this study. However, upon comparing the total percentage and spatial pattern of compaction between units 81 and 82 (see figures 27 and 28, tables 18 and 19), it appears that a greater percentage of Unit 81 was compacted using long skidding distances with a parallel skid trail pattern as opposed to shorter skidding distances and the mostly herringbone pattern used in Unit 82. This is largely due to minimizing compaction in the center of skid trails that appears to occur at eleven or greater vehicle passes. The different thinning intensities and volume removed between the units, however, is a confounding factor in this conclusion.

Limiting the season in which ground-based equipment can operate has also been used as a management tool to control soil disturbance and compaction levels. Use of ground-based equipment has traditionally been limited to periods of low soil moisture or frozen conditions. Though Unit 82 was harvested in the relatively dry summer period and Unit 81 after the fall rains began, no difference between the units was observed. It is uncertain, however, if this was due to the harvest equipment, the slash layer, or the lack of a significant difference in soil moisture content over time.

Tillage is used as a last resort to alleviate compaction. The success of tillage depends on a number of factors including soil texture, rock content, type of equipment used, the density of residual trees and the depth of compaction (Froehlich and McNabb 1983). As most of the compaction from this CTL system occurred in the first four inches, subsoiling should be a successful endeavor provided none of the previously mentioned factors was a complication.

The option exists, of course, to leave remediation of compaction to natural processes. Again, since compaction in these units occurred mostly in the surface soils where plant, animal or frost-heave process would be more prevalent, natural recovery may occur over an acceptable period of time (Adams and Froehlich 1981).

The results of this study also present the possibility of suiting reforestation practices to the observed spatial pattern of compaction in skid trails. Planting in the center of CTL skid trails in these units where the least compaction has occurred as opposed to the ruts may be an adequate way to maximize the amount of acreage in production. This is, of course, based on the assumption that growth conditions in the ruts were not severe enough or would persist long enough to significantly affect seedling growth once their roots start to spread into these more compacted zones.

Accurately measuring bulk density across the landscape to ascertain compaction levels, however, is a costly and time-consuming process. A faster, more inexpensive means of determining harvest impacts on conifer growth or soil hydrologic properties would be invaluable. Overall, it appears that the penetrometer results were similar to those found with bulk density measurements. For detection of substantial compaction in surface soils where actual bulk density values are not necessary, the penetrometer may be a quick and easy alternative to intensive density sampling. As stated previously, little or no information exists to relate penetrometer readings to actual changes in site productivity or conifer growth.

8. RESEARCH IMPLICATIONS

The results and suggested management implications of this study present the following avenues for future research:

- Quantify any change in growth, yield or health of young to old conifers over time as the result of different levels of compaction within the rooting zone (both horizontal and vertical extents),
- Determine if a relationship exists between penetrometer readings and conifer growth or soil hydrologic properties after accounting for moisture content and soil texture,
- Address the possible role of organic matter, particularly large woody material, as a mitigating factor against compaction. In particular,
  - Does organic matter significantly reduce the spatial extent of compaction along skid trails or in landings?
  - Does organic matter play a significant role as a water reservoir during periods of low soil moisture?
  - If the answer to either or both of these questions is yes, what amount and size of organic matter is required to maintain these properties in forest soils over time?
- Design studies to specifically determine if unit layout (herringbone vs. parallel skid trail patterns, centralized vs. unit-edge landings, short vs. long skidding distances) can significantly affect the degree and spatial arrangement of soil compaction.

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APPENDIX A

Unit 81 Segment Lengths and Traffic Intensities

Segment #	Total Segment Length (in)	Total Segment Length (ft)	Length in 3-5 Pass Category (ft)	Length in 6-10 Pass Category (ft)	Length in 11-20 Pass Category (ft)	Length in >20 Pass Category (ft)	Trips
1	8.1	1887	96	288	480	1023	44
2	7.7	1794	96	288	480	930	42
3	7.5	1748	96	288	480	884	41
4	7.2	1678	96	288	480	814	39
5	6.9	1608	96	288	480	744	38
6	6	1398	96	288	480	534	33
7	7.1	1654	96	288	480	790	39
8	6.3	1468	96	288	480	604	35
9	5.6	1305	96	288	480	441	31
10	6.2	1445	96	288	480	581	34
11	4.1	955	96	288	480	91	23
12	5.2	1212	96	288	480	348	29
13	3	699	96	288	315	0	17
14	4.5	1049	96	288	480	185	25
15	4.9	1142	96	288	480	278	27
16	4.6	1072	96	288	480	208	26
17	3.8	885	96	288	480	21	21
18	2.3	536	96	288	152	0	14
19	2.3	536	96	288	152	0	14
20	2.7	629	96	288	245	0	16
21	1	233	96	137	0	0	7
22	2.4	559	96	288	175	0	14
23	2.2	513	96	288	129	0	13
24	3	699	96	288	315	0	17
25	1.4	326	96	230	0	0	9
26	0.8	186	96	90	0	0	6
27	0.6	140	140	0	0	0	5
28	0.3	70	70	0	0	0	3
29	1	233	96	137	0	0	7
30	0.4	93	93	0	0	0	4
31	1.1	256	96	160	0	0	7
32	4.4	1025	96	288	480	161	25
33	3.1	722	96	288	338	0	18
34	1.6	373	96	277	0	0	10
35	3.8	885	96	288	480	21	21
		total (ft)	3375	8520	10461	8657	

Total Trips	Est Total Trips	Total Length	Est Total Length
754	762	31766	33388

Visual Basic Macro for Determination of Segment Lengths and Traffic Intensities in Unit 81

```
Sub Traffic81()
For i = 8 To 42
   Cells(i, 8) = Int(2 + 2 * (1 / Worksheets("Data").[$f$13]) * Cells(i, 3))
   '   = 2 harvester passes + 2*(1/(ft/forwarder passes)) * Total ft
   Trips = Cells(i, 8)
   If Trips > 20 Then
      Cells(i, 4) = Worksheets("Data").[$e$30]
      'Length 3-5 Passes = Max Length for 2 Harv. + 2 For. Passes 1*(96 feet/for trip)
      Cells(i, 5) = Worksheets("Data").[$e$33] - Worksheets("Data").[$e$30]
      'Length 6-10 Passes = Max Length for 2 Harv. + 8 For. Passes 4*(96 feet/for trip)-
      'Max Length for 2 Harv. + 2 For. Passes 1*(96 feet/for trip)
      Cells(i, 6) = Worksheets("Data").[$e$38] - Worksheets("Data").[$e$33]
      'Length 11-20 Passes = Max Length for 2 Harv. + 18 For. Passes 9*(96 feet/for trip)-
      'Max Length for 2 Harv. + 8 For. Passes 4*(96 feet/for trip)
      Cells(i, 7) = Cells(i, 3) - Worksheets("Data").[$e$38]
      'Length >20 Passes = Total Length - Max Length for 2 Harv. + 18 For. Passes 9*(96 feet/for
trip)
   ElseIf Trips >= 11 And Trips <= 20 Then
      Cells(i, 4) = Worksheets("Data").[$e$30]
      'Length 3-5 Passes = Max Length for 2 Harv. + 2 For. Passes 1*(96 feet/for trip)
      Cells(i, 5) = Worksheets("Data").[$e$33] - Worksheets("Data").[$e$30]
      'Length 6-10 Passes = Max Length for 2 Harv. + 8 For. Passes 4*(96 feet/for trip)-
      'Max Length for 2 Harv. + 2 For. Passes 1*(96 feet/for trip)
      Cells(i, 6) = Cells(i, 3) - Worksheets("Data").[$e$33]
     'Length 11-20 Passes = Total Length - Max Length for 2 Harv. + 8 For. Passes 4*(96 feet/for
trip)
      Cells(i, 7) = 0
      'Length >20 = 0
   ElseIf Trips >= 6 And Trips <= 10 Then
      Cells(i, 4) = Worksheets("Data").[$e$30]
      Cells(i, 5) = Cells(i, 3) - Worksheets("Data").[$e$30]
      Cells(i, 6) = 0
      Cells(i, 7) = 0
   Else
      Cells(i, 4) = Cells(i, 3)
      Cells(i, 5) = 0
      Cells(i, 6) = 0
      Cells(i, 7) = 0
      End If
Next i
End Sub
```

Unit 82 Segment Lengths and Traffic Intensities

Segment #	Total Segment Length (in)	Total Segment Length (ft)	Length in 3-5 Pass Category (ft)	Length in 6-10 Pass Category (ft)	Length in 11-20 Pass Category (ft)	Length in >20 Pass Category (ft)	Trips
1	1.7	561	65	195	302	0	19
2	1.5	495	65	195	236	0	17
3	1.0	330	65	195	71	0	12
4	0.6	198	65	133	0	0	8
5	0.3	99	99	0	0	0	5
6	0.3	99	99	0	0	0	5
7	0.3	99	99	0	0	0	5
8	0.2	66	66	0	0	0	4
9	0.2	66	66	0	0	0	4
10	0.2	66	66	0	0	0	4
11	0.3	99	99	0	0	0	5
12	0.3	99	99	0	0	0	5
13	0.5	165	65	100	0	0	7
14	0.4	132	65	67	0	0	6
15	0.5	165	65	100	0	0	7
16	3.2	1056	65	195	324	472	34
17	2.1	693	65	195	324	109	23
18	2.2	726	65	195	324	142	24
19	2.3	759	65	195	324	175	25
20	3.0	990	65	195	324	406	32
21	3.1	1023	65	195	324	439	33
22	2.6	858	65	195	324	274	28
23	5.7	1881	65	195	324	1297	60
24	3.3	1089	65	195	324	505	35
25	3.3	1089	65	195	324	505	35
26	3.2	1056	65	195	324	472	34
27	0.3	99	99	0	0	0	5
28	0.2	66	66	0	0	0	4
29	0.3	99	99	0	0	0	5
30	0.4	132	65	67	0	0	6
31	0.4	132	65	67	0	0	6
32	0.3	99	99	0	0	0	5
33	0.2	66	66	0	0	0	4
34	0.1	33	33	0	0	0	3
35	0.1	33	33	0	0	0	3
36	0.1	33	33	0	0	0	3
37	0.1	33	33	0	0	0	3
38	7.7	2541	65	195	324	1957	80
39	1.9	627	65	195	324	43	21
40	1.4	462	65	195	203	0	16
41	1.5	495	65	195	236	0	17
42	1.4	462	65	195	203	0	16

43	1.9	627	65	195	324	43	21
44	1.9	627	65	195	324	43	21
45	0.5	165	65	100	0	0	7
46	1.3	429	65	195	170	0	15
47	1.1	363	65	195	104	0	13
48	0.8	264	65	199	0	0	10
49	0.5	165	65	100	0	0	7
50	0.2	66	66	0	0	0	4
51	0.3	99	99	0	0	0	5
52	0.3	99	99	0	0	0	5
53	0.2	66	66	0	0	0	4
54	2.7	891	65	195	324	307	29
55	0.3	99	99	0	0	0	5
56	2.3	759	65	195	324	175	25
57	2.4	792	65	195	324	208	26
58	0.4	132	65	67	0	0	6
59	2.4	792	65	195	324	208	26
60	0.3	99	99	0	0	0	5
61	2.1	693	65	195	324	109	23
62	2.1	693	65	195	324	109	23
63	1.3	429	65	195	170	0	15
64	0.7	231	65	166	0	0	9
65	0.8	264	65	199	0	0	10
66	0.8	264	65	199	0	0	10
67	0.9	297	65	195	38	0	11
68	0.9	297	65	195	38	0	11
69	1.4	462	65	195	203	0	16
70	1.4	462	65	195	203	0	16
71	1.3	429	65	195	170	0	15
72	3.7	1221	65	195	324	637	39
73	1.1	363	65	195	104	0	13
74	1.0	330	65	195	71	0	12
75	1.1	363	65	195	104	0	13
76	1.0	330	65	195	71	0	12
77	1.2	396	65	195	137	0	14
78	1.1	363	65	195	104	0	13
79	1.0	330	65	195	71	0	12
80	0.9	297	65	195	38	0	11
81	0.7	231	65	166	0	0	9
82	0.7	231	65	166	0	0	9
83	3.3	1089	65	195	324	505	35
84	1.4	462	65	195	203	0	16
85	0.2	66	66	0	0	0	4
86	0.2	66	66	0	0	0	4
87	0.7	231	65	166	0	0	9
88	0.6	198	65	133	0	0	8
89	1.0	330	65	195	71	0	12
90	0.8	264	65	199	0	0	10
91	0.7	231	65	166	0	0	9

92	0.2	66	66	0	0	0	4
93	0.5	165	65	100	0	0	7
94	0.2	66	66	0	0	0	4
95	0.2	66	66	0	0	0	4
96	0.4	132	65	67	0	0	6
97	2.2	726	65	195	324	142	24
98	0.6	198	65	133	0	0	8
99	1.5	495	65	195	236	0	17
100	0.8	264	65	199	0	0	10
101	1.2	396	65	195	137	0	14
102	0.7	231	65	166	0	0	9
103	1.4	462	65	195	203	0	16
104	0.4	132	65	67	0	0	6
105	0.3	99	99	0	0	0	5
106	0.2	66	66	0	0	0	4
	Total (ft)		7207	13219	11668	9288	41382

Total Trips	Est Total Trips	Total Length	Est Total Length
1468	1432	41382	41580