Effects of Slash, Machine Passes, and Soil Moisture on Penetration Resistance in a Cut-to-length Harvesting

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ABSTRACT

Multiple entries into forest stands are often needed for fire hazard reduction and ecosystem restoration treatments in the Inland-Northwest U.S.A. region. However, soil compaction occurring from mechanized harvesting operations often remains for many years and may contribute to a decline in long-term site productivity. A controlled experiment on a silt loam soil was conducted to determine (a) the effectiveness of logging slash to buffer compaction, (b) the influence of the number of machine passes, and (c) the contribution of soil moisture to changes in penetration resistance during a cut-to-length harvest in northern Idaho. Penetration resistance was measured at three soil depths (10, 20, and 30 cm) for three different moisture contents (low, medium, and high) and slash amounts (none, light, and heavy) after each of 12 machine passes (one pass each with a harvester and an empty forwarder, and 10 passes with a fully-loaded forwarder). At all three soil depths the main effect of moisture content and machine passes on penetration resistance was significant, but slash amounts alone did not significantly affect penetration resistance. After 12 passes, we measured the greatest penetration resistance in the medium soil moisture treatment at 5 to15 cm of soil depth. When evaluated at similar moisture contents after harvesting, the soil that was driest during machine traffic (low moisture treatment) had the lowest penetration resistance. Slash was important for protecting the soil against compaction in the medium and high soil moisture treatments. Penetration resistance did not significantly increase after the second pass of a fully-loaded forwarder (31,752 kg) at any moisture content or slash level. Managing felling operations to take advantage of dry soil conditions or using slash when soils are moist may help reduce ruts and avoid long-term compaction impacts on this soil type.

Keywords: *soil compaction, site productivity, soil disturbance, mechanized harvesting.*

INTRODUCTION

With increased need for fire hazard reduction and ecosystem restoration treatments in the Inland-Northwest region of the U.S.A., multiple forest harvest entries are often considered to achieve desired management objectives. Further, compaction impacts on the surface soil may be cumulative if time between stand entries is not sufficient to allow for soil recovery [10, 13, 32]. The long-term effects on tree growth are not always consistent, but if detrimental compaction occurs tree growth may be impacted for decades [37]. Most soil compaction will occur in the first 10 passes of a harvesting machine [14], with the greatest increases occurring in the first few passes [10]. Soil compaction has been shown to reduce regeneration and growth of trees, but can also have little or no effect [9,16, 28]. When soils are compacted, root growth is often reduced because of mechanical impedance, limiting root access to water and nutrients, and reduced water movement creating anaerobic conditions [2]. However, determining the soil condition responsible for reduced productivity is difficult since texture, penetration resistance, and water content are interrelated [16, 30]. Plant response is more likely dependent on the extent of the soil-water changes than the absolute change in a physical property [16].

Cut-to-length (CTL) logging systems are often considered for fuel reduction and forest restoration treatments in the interior Northwest, USA. This logging system can efficiently produce sawlog material from high density stands filled with small-diameter trees while potentially leaving low impacts on soils [15, 19, 21]. A CTL system processes trees at the stump and leaves limbs and tree tops on the forwarding trails. Slash left on the trails can reduce soil compaction by providing a cushioning layer of slash [22, 23, 38], but the degree of the benefit varies with soil moisture [22], number of machine passes [22],

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terrain characteristics [38], slash type and density [22], and soil profile thickness [5, 20, 22, 26]. Logging slash can cover up to 70% of the skid trail area when using a CTL system [36].

Assessment of a soil's susceptibility to compaction is confounded by differences in initial conditions such as texture, moisture content, and air voids in the soil. Generally, with increasing soil moisture, the compaction (i.e. density increase) that results from a given compactive effort (e.g. repeated passes of a harvester and forwarder) increases to a point, 'the optimum water content', beyond which, compaction is limited by the inability of air to be driven from the soil (Figure 1) [6]. Greater compactive energy can cause density increases at even lower moisture contents. The result of compactive efforts at water contents above optimum water content is displacement and deformation of the soil rather than compaction. Trafficked soils below optimum moisture content will not reach as high a bulk density as when they are at the optimum moisture content [17]. Most compaction occurs when soil is near field capacity [1]. Up to and at the optimum moisture content, water facilitates the reorientation of soil particles. The texture of the soil, the level of moisture, and the degree of disturbance will determine the amount and effect of particle reorientation.

The ability to recognize the soil moisture conditions under which compaction may occur could improve a forest manager's ability to predict detrimental soil disturbance caused by mechanized harvest. Unfortunately, this information is not readily available for current logging technologies on a variety of soil textures. For engineering purposes, the Proctor test has been a standard for predicting the relationship between soil moisture and density [11,18]. However, the Proctor test can overestimate the bulk densities normally produced by newer harvesting equipment [11] and is not consistently reliable for predicting soil compaction from machines in the field [18]. Most predictions of compaction in the laboratory do not take into account machine pressure, the number of passes, the impact of turning (dynamic forces), and whether the machine is moving uphill or downhill [11, 35]. Therefore, it is often necessary to obtain site- and logging equipment-specific information from the field.

Because of the importance of soil moisture content at the time of harvesting and the lack of information on soil impacts from CTL harvesting systems, further investigation is needed where moisture-compaction relationships have not been well characterized. Such is the case for many locations in northern Idaho, including our study area. Our objective was to determine the effects of soil moisture content, the amount of slash, and number of CTL harvesting and forwarding passes on soil compaction in a north Idaho mixed conifer forest.

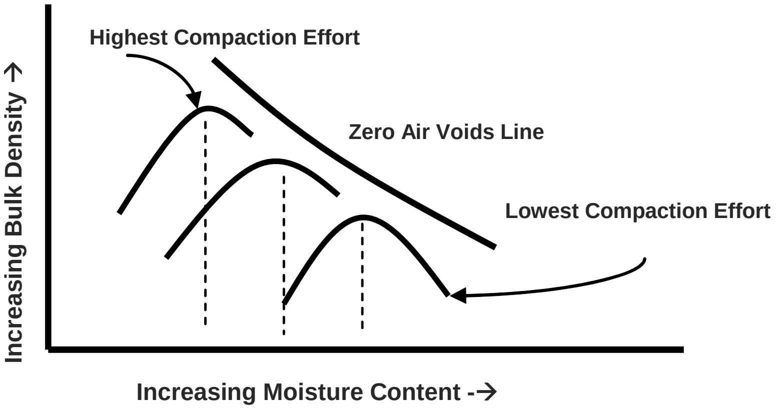


Figure 1: General relationships between moisture content, compaction effort and maximum bulk density [13].

STUDY METHOD

Study Area and Experimental Design

Research plots were established on the University of Idaho Experimental Forest in northern Idaho (46º50'50"N, 116º46'10"W), where the forest manager had previously selected sites for summer harvesting using a CTL logging system. Our study site was located on a relatively undisturbed area to avoid old landings and skid trails used in previous entries. Soils on this site are an Uvi series (fine-loamy, mixed, frigid Dystric Xerochrept) and are formed from loess and in residuum derived from granite. The texture changes from fine-loamy to loam at approximately 20 cm. Forest cover was predominantly Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) and western hemlock (*Tsuga heterophylla*) with sparse understory present.

The experimental design consisted of three identical strips of ground on a 10% slope, each 4 m x 50 m and separated by approximately 15 m, with each strip representing one of three levels of soil moisture: low, medium, and high (Figure 2). Each strip also had three randomly assigned replication blocks for slash treatments (none, light, and heavy). Slash blocks within moisture treatments were separated by a 2 m buffer.

A Freightliner FL 112 truck carrying 12,113 liters of water was used to apply water to only the medium and high moisture strips over an 8-hour period. An average of 8.9 cm of water was applied to the medium soil moisture strip with a standard garden hose and sprinklers spaced 3.8 m apart. A fire hose (3.81 cm diameter) was used to evenly spray water over the high soil moisture strip with an average of 12.7 cm of water. Care was taken to minimize soil impacts during the spray applications. The “low” soil moisture treatment was the existing, seasonally dry soil condition (July: <15% soil moisture content for the top 30 cm of soil). On the medium and high moisture treatments, applied water was allowed to infiltrate overnight and harvesting began the next day. Soil moisture content samples were collected in triplicate for each study strip at soil depths of 10, 20 and 30 cm before water treatment, after water treatment, and after the final machine pass. Collections were made with a small diameter core sampler (5 cm diameter and 7.5 cm length). Soil samples were sealed in plastic bags, brought back to the laboratory, weighed, dried for 24 hrs at 105° C, and reweighed for determination of moisture content.

Initial amounts of coarse woody material (>2.54 cm in diameter) on all three strips were measured using the line transect method [4]. Based on the coarse woody material survey, each study strip had a minimum of 65% bare ground

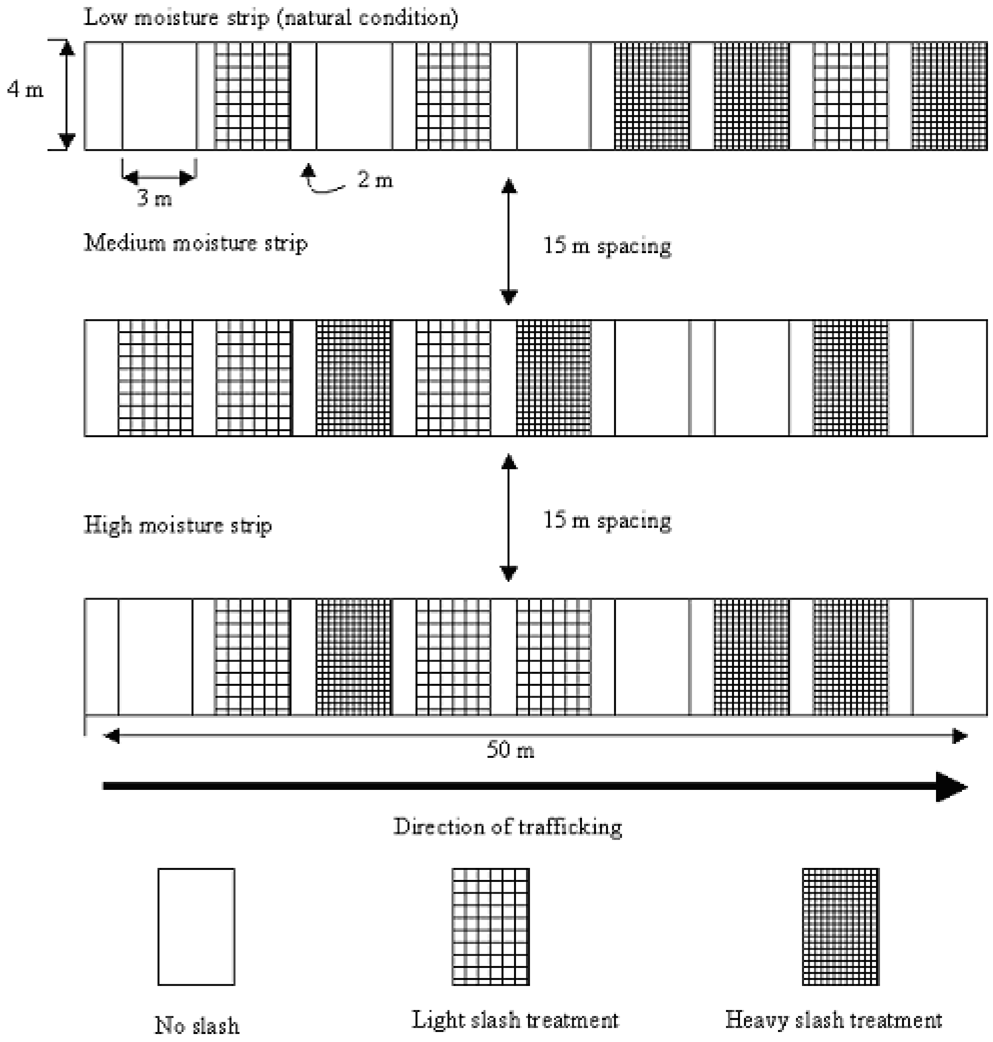


Figure 2. Controlled experiment design containing three different levels of soil moisture content and three replications of slash treatments in each soil moisture strip (not drawn to scale)

before the harvester moved into each strip. The harvester operator was instructed to fell and process trees as a "typical" thinning operation. After the harvester moved through each of the three strips, logging slash was reorganized by hand into the three different levels of slash:

- None: no slash
- Light: approximately 90 kg green weight of slash spread on 4 m x 3 m block (7.5 kg/m^2), over 75% of block covered with the materials (2.5 – 7.6 cm in diameter). The rest was smaller than 2.5 cm in diameter.
- Heavy: approximately 180 kg green weight slash spread on 4 m x 3 m block (15 kg/m^2), over 70% of block covered with the materials (>7.6 cm in diameter). The rest was smaller than 7.6 cm in diameter. The heavy slash treatment not only had a greater weight of slash, it also had greater proportion of larger diameter material.

Initial slash weight was taken by clearing slash on 4 m x 3 m blocks and weighing all the material. Diameter of slash material was measured by a ruler. A tally count was taken for the material in three categories: <2.5 cm, 2.5 - 7.6 cm and >7.6 cm in diameter. After weighing, slash was redistributed into the three slash treatments and placed perpendicular to the direction of machine travel.

The experiment was designed to mimic a common CTL thinning operation, using a harvester-forwarder pair to complete the thinning. The machine operators followed the researchers' instructions on their logging activities. Machine passes were tallied beginning with the harvester (H, 22600 kg mass). The harvester was a Valmet 500T equipped with the Caterpillar 325 undercarriage. Additional passes were made with an empty forwarder (EF, 18143 kg mass), and the same forwarder, loaded (F1-10, 31434 kg mass) for a total of 12 machine passes. The forwarder was an eight-wheel-drive Valmet 890.1 fitted with bogie wheel tracks. A bypass trail was used by the forwarder to move to the beginning of the strips for each pass so as not to compound the impacts of trafficking with turning.

Data Collection

An Agridry Rimik CP40 cone penetrometer was used to determine penetration resistance. Cone diameter, angle, and surface were 1.27 cm, 30^o and 1.27 cm^2, respectively. Penetration resistance data were collected after water application but before harvesting, as well as after the harvester pass, the empty forwarder pass, and each of 10 loaded forwarder passes. We assumed that an empty forwarder would not add additional impacts to the soil after one pass of a fully-loaded forwarder. At each sample point, three replicates of soil penetration resistance were taken after removing the slash. Penetration resistance was recorded in the center line (between wheel tracks), in the wheel track, and outside of the forwarding trail (undisturbed) (Figure 3).

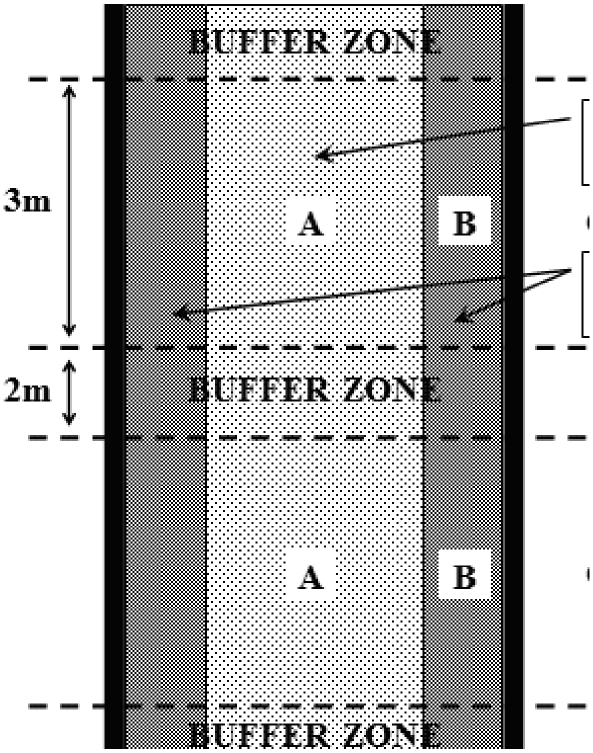


Figure 3. Diagram showing sample point location along the experiment strip.

To gauge how the soil's physical properties were responding to the machine traffic, soil cores were periodically collected during the harvesting operation. Undisturbed soil cores, meant to preserve the existing soil structure and pore distribution, were collected into plastic liners (7.5 cm O.D. x 38 cm) with a core sampler. Samples were collected in duplicate from the track in each moisture treatment and each slash treatment after 1 machine pass. Additional samples were collected from the low and high moisture treatments after 5 and 10 passes. Cores were capped, transported to the laboratory and frozen. Frozen cores were cut into 4 cm sections with midpoints corresponding to soil depths of 10, 20, and 30 cm. Soil sections were placed on ceramic plates and flooded with water. Saturated plates and samples were placed in pressure extractors to which 30 kPa (0.3 bar) of pressure was applied to simulate a matric suction defining field capacity. Soils were oven dried and water contents at field capacity were calculated on a dry-weight basis [7].

Because penetration resistance is greatly influenced by soil moisture conditions, in spring 2005, penetration resistance was remeasured in each strip when soil moisture content was uniform in all three strips. Penetration resistance and moisture content samples were collected as previously described. Although some penetration resistance recovery could have occurred from the wet/dry and freeze/thaw cycles between summer 2004 and spring 2005, this is a relatively small change when compared to the larger impacts of the harvest operations.

Rut depths were measured in the left and right wheel tracks for each moisture treatment and slash level after trafficking was complete (i.e. 10 passes of a fully-loaded forwarder). Ruts were measured in the mid-point of each treatment block (i.e. 1.5 m from the end of the treatment block). A horizontal reference was provided using a marker extending from the adjacent, undisturbed ground. A meter stick was used to measure rut depth, a distance between the ground surface and the horizontal marker at the center of the rut.

Statistical Analysis

This experiment was classified as a split-plot design with repeated measures of penetration resistance after each machine pass, and with three levels of soil moisture content and slash amount, each replicated three times. Treatment effects were tested using analysis of variance (ANOVA) with the number of machine passes, soil moisture, and slash level as the main effects; and *a posteriori* tests were conducted for pairwise comparisons of means [19]. Violations of homogeneity and normality for ANOVA analysis were found in penetration resistance data at soil depths of 20 and 30 cm. Data at these depths were logged transformed to meet the assumptions of normality and equal variance. Field capacity results were also analyzed with analysis of variance, using the least square means procedure. Residuals were plotted and the data set was found to meet the normality assumption. The amount of slash was not a critical factor in explaining differences in field capacity at any depth and was removed from the statistical model early in the analysis. For rut depth measurements, Levene's test was performed to evaluate homogeneity of variance before comparing mean rut depths between low, medium and high soil moisture and slash treatments. The effect of soil moisture and slash on rut depth was tested by ANOVA also.

RESULTS AND DISCUSSION

Effect of Soil Moisture

The initial mean moisture condition ranged from 11.2 – 14.6% for the entire profile before water was added (Low, Figure 4). Mean soil moisture was slightly higher in the upper soil layers and decreased with soil depth. Moisture content increased to 20.9 – 29.5% for the top 30 cm of soil in the medium and high soil moisture strips after the water treatment. Although we sprayed more water on the high moisture strip, both medium and high moisture content strips had similar moisture contents in 0 - 30 cm of mineral soil. After wetting the treatment sites, we measured a pre-harvest moisture content of approximately 30%, which was near the field capacity for this soil type (laboratory field capacity was measured as 31.7%). We did not measure soil organic matter content, however differences in

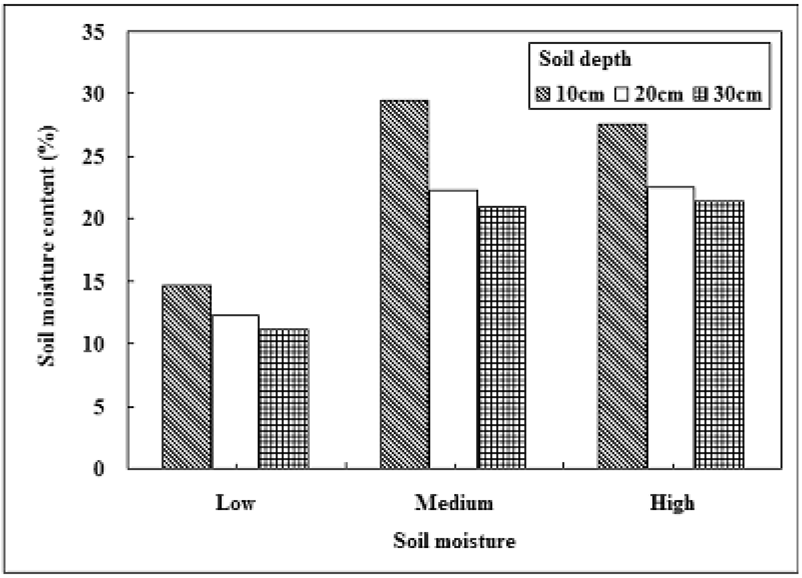


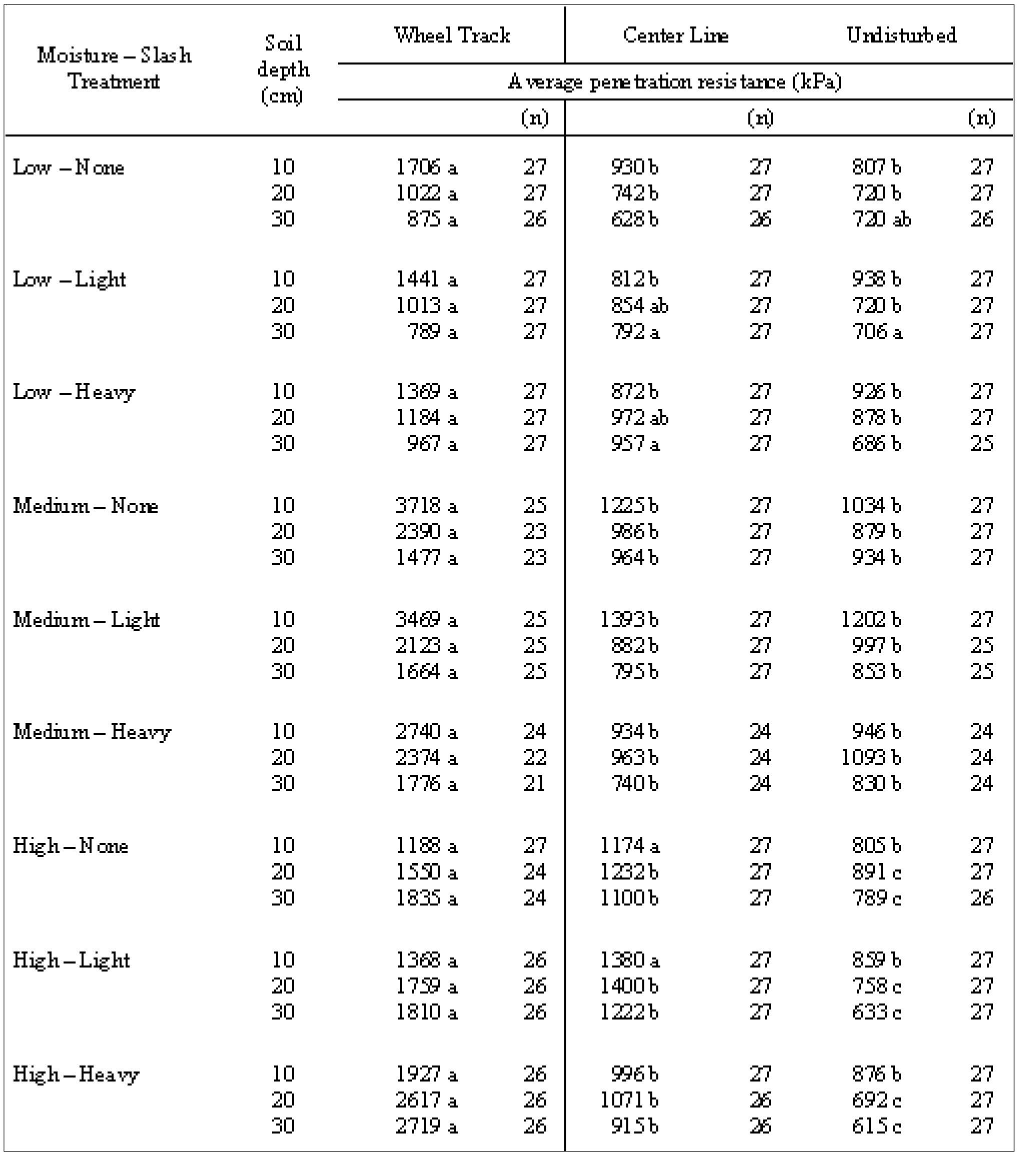
Figure 4. Soil moisture content after water treatment (before harvest) at three soil depths.

organic matter could account for treatment differences in compactability, rutting, and soil strength [39].

Penetration resistance data was difficult to collect in the seasonally dry strip because low soil moisture had created a hard-set condition in the soil. In the high moisture treatment, however, the soil penetrometer was easily pushed into the soil. This resulted in higher readings of penetration resistance in the low moisture strip and lower readings in the high moisture strip. Hence, comparison of penetration resistance data collected at the time of operation could not be appropriately made due to varying soil moisture conditions. Remeasurement of penetration resistance at similar moisture contents was completed in spring (April) 2005and allows for proper comparisons.

Soil conditions post-harvest (after 12 passes) at similar moisture contents revealed that penetration resistance readings in the wheel track were much higher than those in the center line (i.e. between wheel tracks) and the undisturbed areas for all the study strips (Table 1). Increased penetration resistance was also observed in the center (between wheel tracks) in the high moisture strip, but to a lesser degree in the low and medium moisture strips (Table 1). In the center line, higher penetration resistance readings were generally found at the 20 and 30 cm soil depths for all moisture and slash treatments. These re-

Table 1. Average penetration resistance for three locations; wheel track, center line and undisturbed. The mean values are data collected at similar soil moisture conditions (31-45%) in the year (2005) after the field experiment.



Moisture – Slash Treatment	Soil depth (cm)	Wheel Track		Center Line		Undisturbed	
		Average penetration resistance (kPa)					
			(n)		(n)		(n)
Low – None	10	1706 a	27	930 b	27	807 b	27
	20	1022 a	27	742 b	27	720 b	27
	30	875 a	26	628 b	26	720 ab	26
Low – Light	10	1441 a	27	812 b	27	938 b	27
	20	1013 a	27	854 ab	27	720 b	27
	30	789 a	27	792 a	27	706 a	27
Low – Heavy	10	1369 a	27	872 b	27	926 b	27
	20	1184 a	27	972 ab	27	878 b	27
	30	967 a	27	957 a	27	686 b	25
Medium – None	10	3718 a	25	1225 b	27	1034 b	27
	20	2390 a	23	986 b	27	879 b	27
	30	1477 a	23	964 b	27	934 b	27
Medium – Light	10	3469 a	25	1393 b	27	1202 b	27
	20	2123 a	25	882 b	27	997 b	25
	30	1664 a	25	795 b	27	853 b	25
Medium – Heavy	10	2740 a	24	934 b	24	946 b	24
	20	2374 a	22	963 b	24	1093 b	24
	30	1776 a	21	740 b	24	830 b	24
High – None	10	1188 a	27	1174 a	27	805 b	27
	20	1550 a	24	1232 b	27	891 c	27
	30	1835 a	24	1100 b	27	789 c	26
High – Light	10	1368 a	26	1380 a	27	859 b	27
	20	1759 a	26	1400 b	27	758 c	27
	30	1810 a	26	1222 b	27	633 c	27
High – Heavy	10	1927 a	26	996 b	27	876 b	27
	20	2617 a	26	1071 b	26	692 c	27
	30	2719 a	26	915 b	26	615 c	27

* Means in each row followed by the same letter are not significantly different based on one-way ANOVA test at the 0.05 level.

sults suggest that harvesting operations that occur when soils are dry can concentrate machine impacts in the wheel track. Harvesting on wetter soils extended the area of influence to greater width and depth.

Increases in penetration resistance under the wheel track after harvesting varied with soil moisture, slash treatment, and soil depth. The largest difference in penetration resistance in the wheel track was observed in the medium moisture strip where there was an increase of up to 260% (exceeding 3,000 kPa with no slash, at 10 cm of soil depth) after harvesting (Table 1 and Figures 5, 6, and 7). Past studies suggested that penetration resistance exceeding 2500 kPa would be sufficient to prevent penetration by root systems [17]. Penetration resistance increases were also noted at the 20 and 30 cm soil depths in the medium moisture strip but were not as large as those closer to the soil surface (Figure 6). Although the degree of soil compaction was reduced with slash, especially between low and medium moisture conditions (Table 2), the greatest compaction was still seen at soil depths of 5 to 15 cm (Figures 5 – 7). The ANOVA analysis of penetration resistance data confirmed that the effect of soil moisture on penetration resistance was significant at 10 and 20 cm soil depths, but was not able to be tested at 30 cm because it was confounded with moisture treatment effect. The moisture content at 30 cm soil depth was significantly different

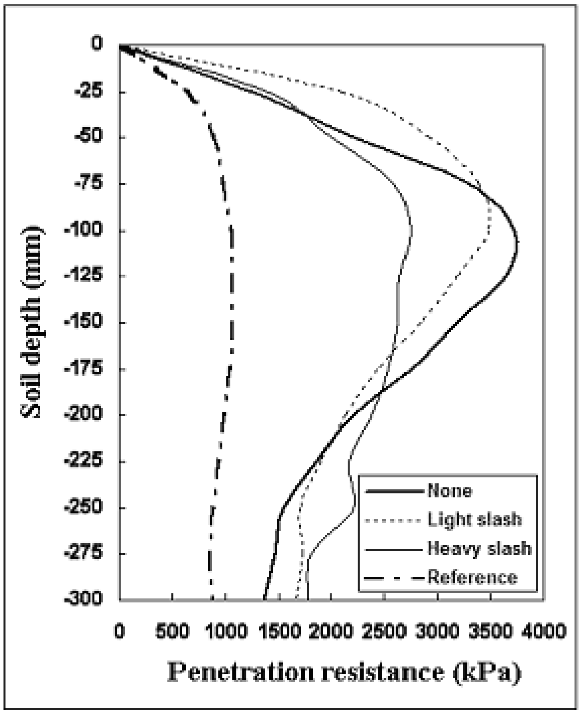


Figure 6. Penetration resistance changes in wheel tracks after harvest with varying slash levels and medium soil moisture. The graph is based on measurements taken in spring 2005.

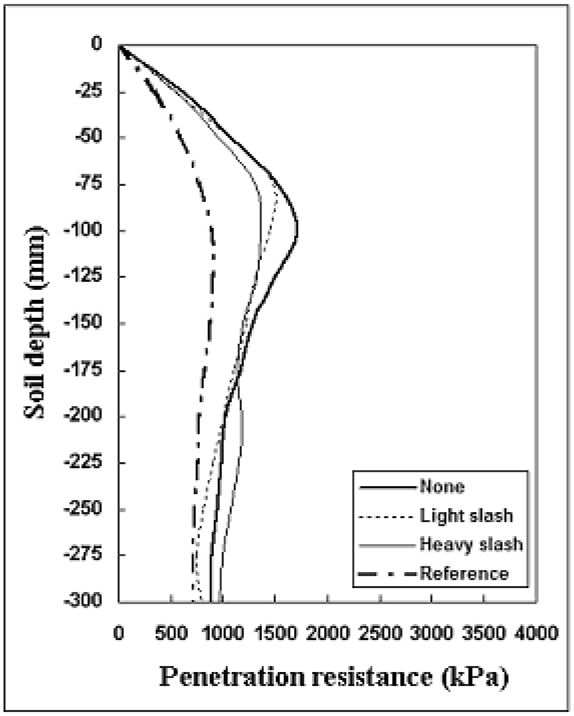


Figure 5. Penetration resistance changes in wheel tracks after harvest with varying slash levels and low soil moisture. The graph is based on measurements taken in spring 2005.

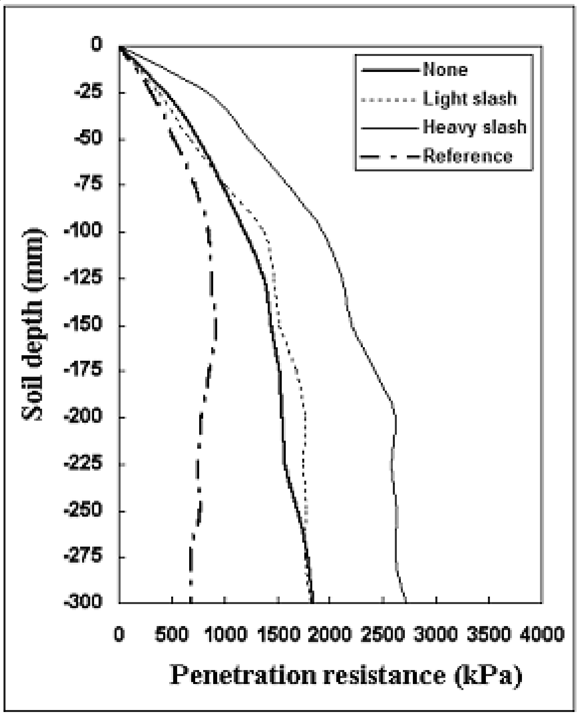


Figure 7. Penetration resistance changes in wheel tracks after harvest with varying slash levels and high soil moisture. The graph is based on measurements taken in spring 2005.

Table 2. Penetration resistance after harvest with various moisture levels. The mean values represent data collected in wheel tracks under a similar soil moisture condition.

Slash Treatment	Soil depth (cm)	Moisture Treatment Low	Moisture Treatment Medium	Moisture Treatment High
		------------------- (kPa)	------------------- (kPa)	------------------- (kPa)
None	10	1706 a	3718 b	1188 c
	20	1022 a	2390 b	1550 b
	30	875 a	1477 a	1835 b
Light	10	1441 a	3469 b	1368 a
	20	1013 a	2123 b	1759 b
	30	789 a	1664 b	1810 b
Heavy	10	1369 a	2740 b	1927 c
	20	1184 a	2374 b	2617 b
	30	967 a	1776 b	2719 c

* Means in each row followed by the same letter are not significantly different based on one-way ANOVA test at the 0.05 level.

between experiment strips (P<0.05). Pre-harvesting penetration resistance values between strips were significantly different at 30 cm soil depth (P<0.05).

After harvesting soils in the low moisture treatment showed slightly higher penetration resistance around the 10 cm soil depth (Table 1 and Figure 5). It was interesting to note that at 10 cm soil depth there was not much difference in penetration resistance between low and high moisture strips, but at the high soil moisture condition penetration resistance continued to increase with soil depth while penetration resistance decreased with soil depth under the driest soil condition (Figures 5 and 7). This suggests that dry, hard soil conditions effectively limited further soil effects from logging traffic to the surface soils (<20 cm) producing minimal soil compaction. In the high moisture treatment, excessive moisture in the soils did not provide support against the equipment's ground pressure and allowed the tires to penetrate into the deeper soil levels despite the presence of slash, causing greater strength differences in deeper soil levels (>30 cm) than at low and medium soil moisture (Figures 5, 6, and 7).

Soil moisture is a well established factor affecting the compactability of soils [26, 29]. Soil compressibility can decrease as soil dries when the effective stress increases as soil water potential decreases [3], and direct contact between soil particles increases as water films around soil particles become thinner [26]. Our data confirm the importance of soil moisture and the potential for compaction to occur under differing levels of soil moisture. When the experimental strips had similar moisture conditions in April 2005, the low soil moisture treatments, which were originally dry and hard-set, had the lowest penetration resistance and likely had less reorientation of soil particles and less of an impact on long-term soil productivity. Soils that were wet to very wet, and not showing large increases in penetration resistance during and immediately after trafficking, appeared to be more compacted when compared at a uniform moisture condition. As compaction energy increases, the optimum moisture content for compaction decreases [18]. However, the impact of optimum moisture can be confounded by soil texture. Davis [8] found that on a finer-textured sandy loam soil with a volcanic ash-cap influence, there was not a high sensitivity to soil moisture content. Our fine-loamy soil appeared to be very sensitive to increasing moisture content as deep ruts formed (Figure 8) during trafficking. In addition, as the slash mat was pushed into the soil by the forwarder, soil properties also were likely influenced. Needles, twigs, and branches altered the compactability of the soil with increasing numbers of trips [29].

Effect of Machine Passes

Our focus on the effect of machine passes was given to the medium moisture strip because its moisture condition was believed to be the closest to an optimum moisture content for compaction on this fine-textured soil. From pre-harvest levels (R = reference) penetration resistance increased up to the second pass of a fully-loaded forwarder (F2) (total of 4 passes) (Figures 9, 10, and 11); there was little increase in penetration resistance afterward. A single pass of the harvester on the slash mat did not increase penetration resistance, but forwarder traffic significantly increased penetration resistance at the 10 cm soil depth (Figure 9). At the 20 cm soil depth, however,

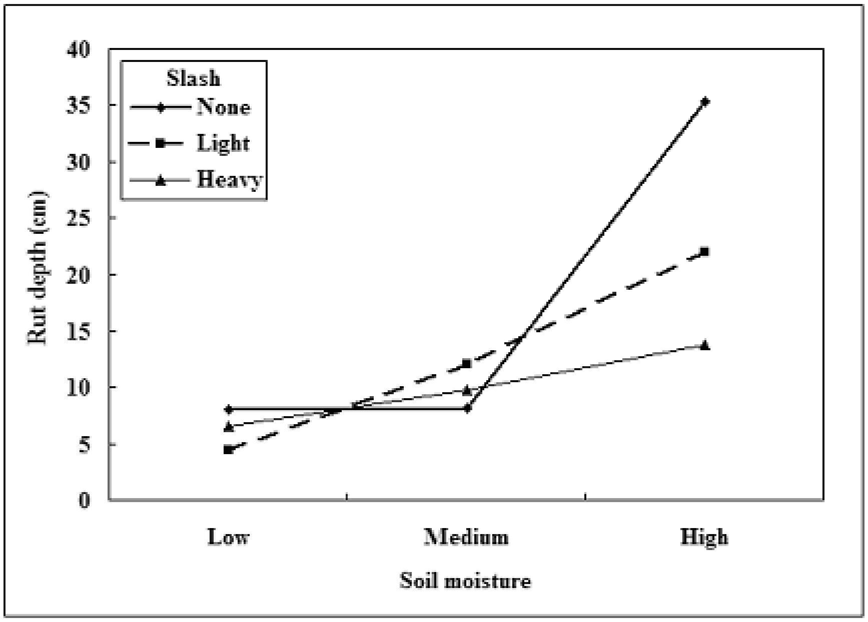


Figure 8. Average rut depth after a CTL harvesting at three different levels of soil moisture and slash.

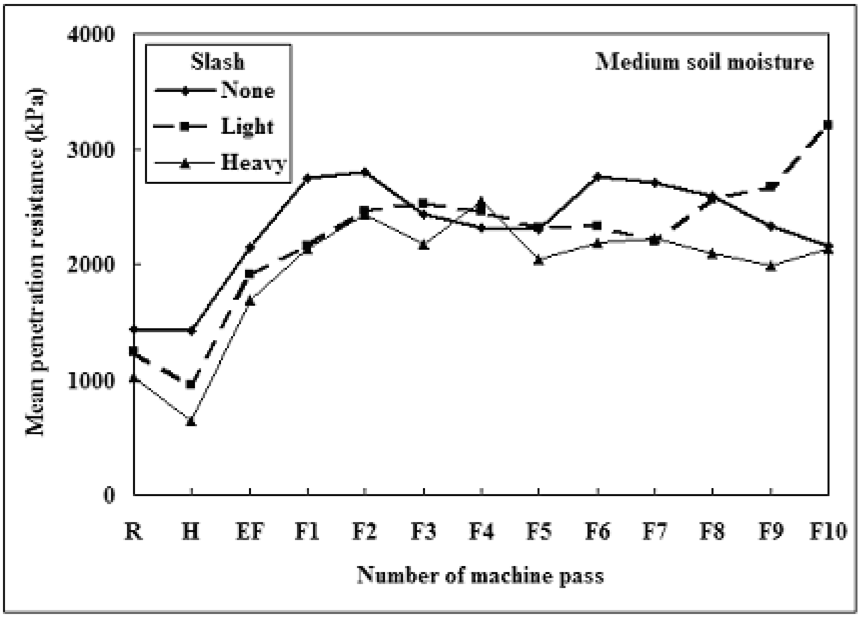


Figure 9. Penetration resistance <u>at 10 cm</u> depth with varying slash levels and machine passes.
R: reference, H: harvester, EF: empty forwarder, F: fully-loaded forwarder

both harvester and forwarder increased penetration resistance with their passes (Figure 10). At the 30 cm soil depth, increases in penetration resistance with machine traffic were not as noticeable (Figure 11). ANOVA analysis showed that for all soil depths, the main effect of machine passes significantly affected penetration resistance ($P<0.0001$). The largest increase of penetration resistance was observed at the first 10 cm soil depth, followed by the 20 cm soil depth, with the least increase of penetration resistance occurring at 30 cm soil depth. When CTL systems are used at a gravimetric water content near or greater than optimum moisture content for compaction, there can be a positive relationship with the number of traffic passes. McNabb et al. [25] found similar results on forest soils in Canada where compaction was present to a depth of at least 22 cm following harvesting operations on soils that were either at field capacity or wetter.

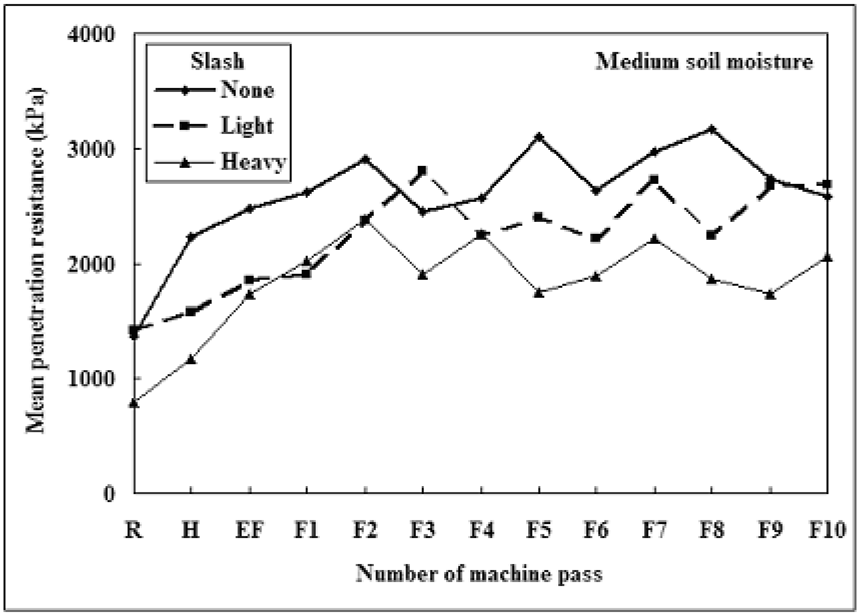


Figure 10. Penetration resistance <u>at 20 cm</u> depth with varying slash levels and machine passes.
R: reference, H: harvester, EF: empty forwarder, F: fully-loaded forwarder

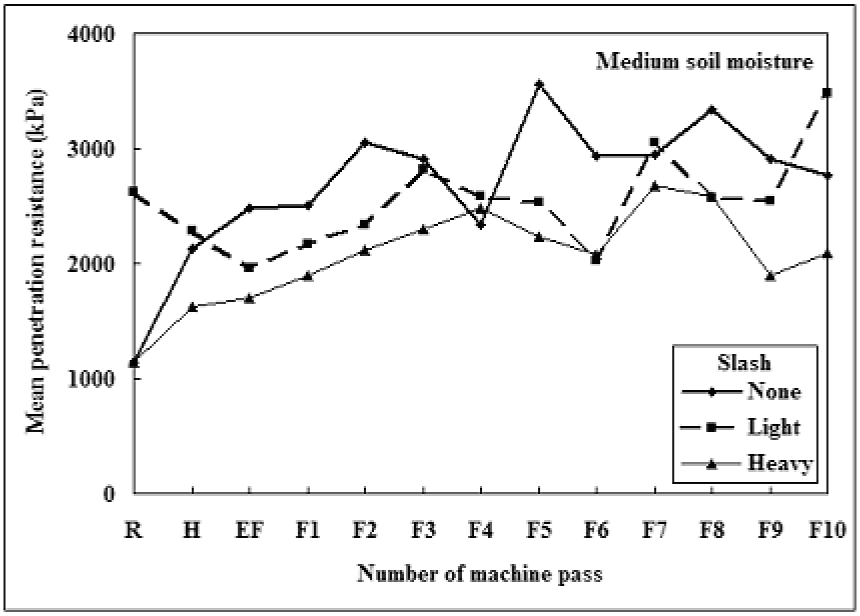


Figure 11. Penetration resistance <u>at 30 cm</u> depth with varying slash levels and machine passes.
R: reference, H: harvester, EF: empty forwarder, F: fully-loaded forwarder

Field capacity values were influenced by the number of machine passes. The surface soil (10 cm depth) showed a continued decrease in field capacity with increasing traffic (data not shown). Over all treatments, significantly less water was held in the soil of the wheel track after 5 and 10 passes of the machinery as compared to following the first pass ($P<0.0001$). The loss of larger water holding pores and the corresponding decrease in soil volume are reflected in penetration resistance which increases with number of passes. At 20 cm, field capacity values in each treatment were initially similar. However, differences were significant ($P<0.05$) at the 10 pass measurement in both the low and high moisture treatments. Field capacity values at 30 cm in the high moisture treatment did not change significantly after trafficking.

Effect of Slash

Amount of slash, soil moisture, and number of machine passes showed relationships with penetration resistance and rut depth on this site (Table 1 and 3, Figure 5 - 11). The combined effect of these factors resulted in variable penetration resistance at all soil depths, including an apparent interaction between slash and other factors (moisture and machine passes) (P>0.05). In soils with low moisture, bare ground (no slash) appeared to have higher penetration resistance at the 10 cm depth than in the treatments with various levels of slash, but no significant association between slash and penetration resistance was shown at any soil depth (P>0.05) (Table 3, Figure 5). However, we found that slash was significantly related to penetration resistance at 10 cm soil depth in the medium moisture condition (Table 3 and Figure 6) on the heavy slash treatment. This suggests that a small amount of slash does not provide enough cushioning to absorb the ground pressure and vibration in a CTL harvesting when these soils are wet. Small diameter slash tends to be crushed into pieces that can no longer distribute and absorb the machine's ground pressure and vibration in order to lessen its impact.

In the high moisture treatment, heavy slash resulted in highest penetration resistance after trafficking (Table 3, Figure 7), which is not unusual given the soil texture (loamy) and moisture conditions. We observed that slash was broken by heavy machine traffic at high soil moisture and did not provide trafficking support. Slash appeared effective in absorbing equipment ground pressure and vibration at the 10 cm and for medium moisture contents until the second pass of a fully loaded forwarder (Figure 9), but after that the slash effect was not obvious (Figure 9, 10, 11). There was no consistent association between slash and penetration resistance in the center line (between wheel tracks): penetration resistance differences in the center line might be influenced by other factors (e.g. soil moisture, vibrational compaction), rather than slash.

Interactions Between Moisture Content, Slash and Machine Passes

There were differences in the magnitude of penetration resistance which varied with soil moisture, slash amount and the number of machine passes. These results indicate an interaction between moisture content, slash and machine pass. Our ANOVA on the data collected both at the time of the experiment and, for penetration resistance, in the following year (at a similar soil moisture content) showed that slash alone did not significantly affect penetration resistance (P>0.05). Slash became important when combined with moisture condition or machine pass (P<0.05). The number of machine passes was significantly associated with penetration resistance levels for 10, 20 and 30 cm soil depths and also showed a strong association when combined with slash and moisture content. For example, slash treatment differences decreased with an increasing number of machine passes, especially after the second pass of a fully-loaded loader (Figures 9, 10, 11). Unlike the low soil moisture treatment, a greater amount of slash appeared beneficial on the moist soil. This was more pronounced at 10 and 20 cm soil depths: on bare ground, at 10 cm soil depth. Penetration resistance readings in the

Table 3. Penetration resistance after harvest with various slash levels. The mean values represent the data collected in wheel tracks under a similar soil moisture condition.

Moisture Treatment	Soil depth (cm)	Slash Treatment		
		None	Light	Heavy
		(kPa)		
Low	10	1706 a	1441 a	1369 a
	20	1022 a	1013 a	1184 a
	30	875 a	789 a	967 a
Medium	10	3718 a	3469 ab	2740 b
	20	2390 a	2123 a	2374 a
	30	1477 a	1664 a	1776 a
High	10	1188 a	1368 a	1927 b
	20	1550 a	1759 a	2617 b
	30	1835 a	1810 a	2719 b

* Means in each row followed by the same letter are not significantly different based on one-way ANOVA test at the 0.05 level.

medium moisture treatment were significantly different from those of the low and high moisture conditions ($P<0.05$). This was not shown in the heavy slash treatment ($P>0.05$).

Rut Depth

Rut depths were deeper for moist (medium and high moisture contents) than for drier soil moisture treatments. The high moisture strip developed ruts that were significantly (13.8 – 35.3 cm) deeper than the medium soil moisture strip (8.2 - 12.0 cm) or the low moisture strip (4.5 – 8.0 cm) (Table 4 and Figure 8). The main effect of soil moisture on rut depth was significant (Table 4). From the displacement of large volumes of surface soil and mixing of the surface layers in the high moisture strip, there is evidence that soil moisture exceeded the optimum moisture content for compaction in that strip.

Low moisture soils did not require heavy slash to minimize rut depth. Ruts that are produced during harvest operations will remain for many years, likely alter soil hydraulic flow, and, in combination with increased compaction, perhaps decrease site productivity. Ruts are often used in visual assessments of site productivity changes because they indicate changes in infiltration, erosion, water retention, and the water-air balance as an early indicator of altered productivity [33].

CONCLUSION AND MANAGEMENT IMPLICATIONS

It is important for forest managers to consider soil moisture, slash, and the amount of trafficking on each site to minimize soil compaction. Our results suggest that scheduling harvest operation during periods of dry soil conditions may effectively reduce soil compaction and related effects on fine loamy textural classes or other similar soils. Most compaction and rutting on such soils appear more likely when soils are at or above optimum moisture content for compaction (usually at or above field capacity). Field measurement of soil moisture may prove useful in determining when soils are more susceptible to compaction by CTL logging systems.

Results from this study support the use of designated or existing skid trails. Penetration resistance did not significantly increase after the second pass of a fully-loaded forwarder although there were some variations with slash and soil moisture conditions. To minimize impacts on soils from harvesting activities, conscious efforts should be made to reduce the area used for skid trails. Minimal skid trail areas with concentrated traffic (within designated skid trails) can be an effective strategy for reducing the aerial extent of compaction from harvesting. In addition, designated skid trails can be decompacted or ameliorated when appropriate.

One of the interesting findings was the association between slash and penetration resistance. Slash did not provide much benefit in minimizing traffic effects on dry soils: dry silt loam soils provide enough structural support to buffer the impacts of machine traffic regardless of the amount of slash. When soil is wet, there should be enough (i.e., heavy) slash to provide a cushion to absorb ground pressure; light slash or bare ground results in significant increases in penetration resistance (i.e., soil compaction). However the benefit of heavy slashing was limited to the top 10 cm of soil. Furthermore, slash appeared to be effective in minimizing the compactive energy of the forwarder for only the first 2 to 3 trips of a fully-loaded forwarder and after that the slash deteriorated and did not provide support.

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Table 4. ANOVA analysis on rut depth measurement.

Source	df[1]	Mean Square	F	*P*-value
Intercept	1	115.69	2252.08	<0.001
Slash	2	0.15	3.01	0.075
Moisture	2	1.57	30.60	<0.001
Slash * Moisture	4	0.16	3.16	0.039

[1] degrees of freedom

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