Soil compaction associated with cut-to-length and whole-tree harvesting of a coniferous forest

Sang-Kyun Han, Han-Sup Han, Deborah S. Page-Dumroese, and Leonard R. Johnson

Abstract: The degree and extent of soil compaction, which may reduce productivity of forest soils, is believed to vary by the type of harvesting system, and a field-based study was conducted to compare soil compaction from cut-to-length (CTL) and whole-tree (WT) harvesting operations. The CTL harvesting system used less area to transport logs to the landings than did the WT harvesting system (19%–20% vs. 24%–25%). At high soil moisture levels (25%–30%), both CTL and WT harvestings caused a significant increase of soil resistance to penetration (SRP) and bulk density (BD) in the track compared with the undisturbed area ($p < 0.05$). In the center of trails, however, only WT harvesting resulted in a significant increase of SRP and BD compared with the undisturbed area ($p < 0.05$). Slash covered 69% of the forwarding trail area in the CTL harvesting units; 37% was covered by heavy slash (40 $kg{\cdot}m^{-2}$) while 32% was covered by light slash (7.3 $kg{\cdot}m^{-2}$). Heavy slash was more effective in reducing soil compaction in the CTL units ($p < 0.05$). Prediction models were developed that can be used to estimate percent increases in SRP and BD over undisturbed areas for both CTL and WT harvesting systems.

Résumé : Le degré et l'étendue de la compaction du sol susceptibles de réduire la productivité des sols forestiers pourraient varier selon le type de système de récolte. Une étude sur le terrain a été réalisée dans le but de comparer la compaction du sol à la suite d'opérations de récolte de billes de longueur préétablie (LP) et par arbres entiers (AE). Le système LP utilise une moins grande superficie pour le transport des billes vers les jetées que le système AE (19–20% versus 24–25%). Avec une teneur en eau du sol élevée (25–30%), les deux systèmes de récolte ont causé une augmentation significative de la résistance du sol à la pénétration (RSP) et de la densité apparente (DA) dans les ornières comparativement à une zone non perturbée ($p < 0,05$). Au milieu des sentiers, cependant, seul le système AE a causé une augmentation significative de la RSP et de la DA comparativement à un zone non perturbée ($p < 0,05$). Les déchets de coupe couvraient 69% de la surface des sentiers de débardage dans les blocs récoltés avec le système LP; 37% étaient des déchets lourds (40 $kg{\cdot}m^{-2}$) tandis que 32% étaient des déchets légers (7,3 $kg{\cdot}m^{-2}$). Les déchets lourds étaient plus efficaces pour réduire la compaction du sol dans les blocs récoltés avec le système LP ($p < 0,05$). Nous avons développé des modèles de prédiction qui peuvent être utilisés pour estimer le pourcentage d'augmentation de la RSP et de la DA dans les zones non perturbées pour les systèmes de récolte LP et AE.

[Traduit par la Rédaction]

Introduction

With an increasing demand for fire hazard reduction and ecosystem restoration treatments in the Inland Northwest, USA, multiple entries of heavy equipment into forest stands are often required to achieve forest management objectives (Han et al. 2006). Managers faced with choosing between different harvesting equipment options and methods in diverse soil conditions require information on expected soil impacts in order to minimize the impact on soil physical properties (Wronski and Murphy 1994). Soil compaction occurs as a result of applied loads, vibration, and pressure from equipment that is used during harvesting and site preparation activities (Adams and Froehlich 1984). Soil compaction can be characterized as a breakdown of surface aggregates, which leads to decreased macropore space in the soil and a subsequent increase in the volume of soil relative to air space, leading to an increase in bulk density (BD) and soil resistance to penetration (SRP) (Adams and Froehlich 1984; Pritchett and Fisher 1987; Gomez et al. 2002). A decrease in soil macroporosity can impede root penetration, water infiltration, and gas and nutrient exchange (Quesnel and Curran 2000), and these changes can result in a reduction, increase, or no change in tree regeneration and growth.

In the Inland Northwest, whole-tree (WT) and cut-to-length (CTL) harvesting systems are commonly used in mechanized harvesting operations. CTL harvesting is becoming increasingly popular, but about 65% of the current infrastructure continues to be based on WT harvesting

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(Ponsse 2005). Debate over the relative merits of each system has recently been renewed in relation to fuel reduction treatments and small wood harvesting. CTL harvesting has the potential to significantly reduce site-related problems such as soil compaction and loss of nutrients that can occur with WT harvesting. The CTL harvesting process creates a slash mat in front of the machine with tree limbs removed during tree processing at the stump. This slash mat distributes the weight of the harvester or forwarder over a larger area and reduces direct contact between the machine tire and the soil surface. In addition, CTL harvesting can minimize ruts by using slash to reinforce skid trails and protect against compaction (Eliasson and Wästerlund 2007). The WT harvesting system uses a skidder to drag the entire tree to the landing for processing after felling. The use of WT harvesting is popular among fuel reduction proponents because fire hazard is effectively reduced by removing whole trees from high-density stands. WT harvesting, however, has high potential for soil compaction and disturbance because skidder travel tends to sweep duff and litter from trails, exposing bare mineral soil (Hartsough et al. 1997).

Overall, soil impacts are a function of both the degree of soil impact (percent change in soil condition) and the extent of soil impact (percentage of area affected). The degree of soil compaction is related to soil texture (Page-Dumroese et al. 2006), soil moisture, harvesting system (Adams and Froehlich 1984), amount of logging slash (Wronski 1980; McMahon and Evanson 1994), and number of machine passes (Soane 1986; McDonald and Seixas 1997). Williamson and Neilsen (2000) indicated that soils in dry forests or those formed on coarser gravelly parent material resisted compaction more than soils in wet forests or those formed from finer-grained materials. Soil moisture at the time of machine traffic also has a major influence on the reduction and redistribution of pore space as soils are compacted (Adams and Froehlich 1984). Dry soils are more resistant to changes in pore size and distribution but this resistance is reduced as soil moisture increases (McDonald and Seixas 1997; Han et al. 2006). One of the critical factors affecting the degree of soil compaction is the number of machine passes in a ground-based system. Maximum soil compaction normally occurs within the first 10 passes of a harvesting machine (Gent and Ballard 1984), with the greatest impact occurring in the first few passes (Froehlich et al. 1980; Han et al. 2006).

The extent of soil impact is also influenced by the harvesting equipment and system used. For example, a single logging operation using crawler tractors or rubber-tired skidders typically produces compacted soils on 20% to 35% of the area harvested (Adams 1990). Steinbrenner and Gessel (1955) found that skid roads comprised 26% of a tractor-logged site. Lanford and Stokes (1995) compared skidder systems with forwarder systems and found that skidder systems disturbed a greater area and compacted more soil than forwarder systems. McNeel and Ballard (1992) found that in units using CTL harvesting, trails occupied less than 20% of the harvested area, and more than 13% of the area experienced only light disturbance. Bettinger et al. (1994) observed that logging trails occupied 23% of the total harvested area in a CTL unit.

Our field-based study was performed to broaden existing knowledge of the degree and extent of impacts of CTL and WT harvesting systems on fine-textured soils in northern Idaho. The specific objectives were to (1) quantify the extent of trail area used for primary wood transport, (2) measure the degree of soil compaction caused by harvesting activities, (3) assess the potential of a slash mat to reduce soil compaction on CTL harvesting fields, and (4) develop prediction models to estimate the percent increase in soil compaction from baseline data after CTL or WT harvesting.

Methods

Site description

The study site was established on a Potlatch Company forest stand about 4 miles northwest of Deary in northern Idaho (46°50′27″N, 116°40′42″W), USA. The forest stand was composed of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), lodgepole pine (*Pinus contorta* Dougl. ex Loud.), and Western larch (*Larix occidentalis* Nutt.). The study site was 19.5 ha with an average tree diameter at breast height (DBH) of 27 cm, an average tree height of 20 m, and a ground slope ranging from 2% to 32%.

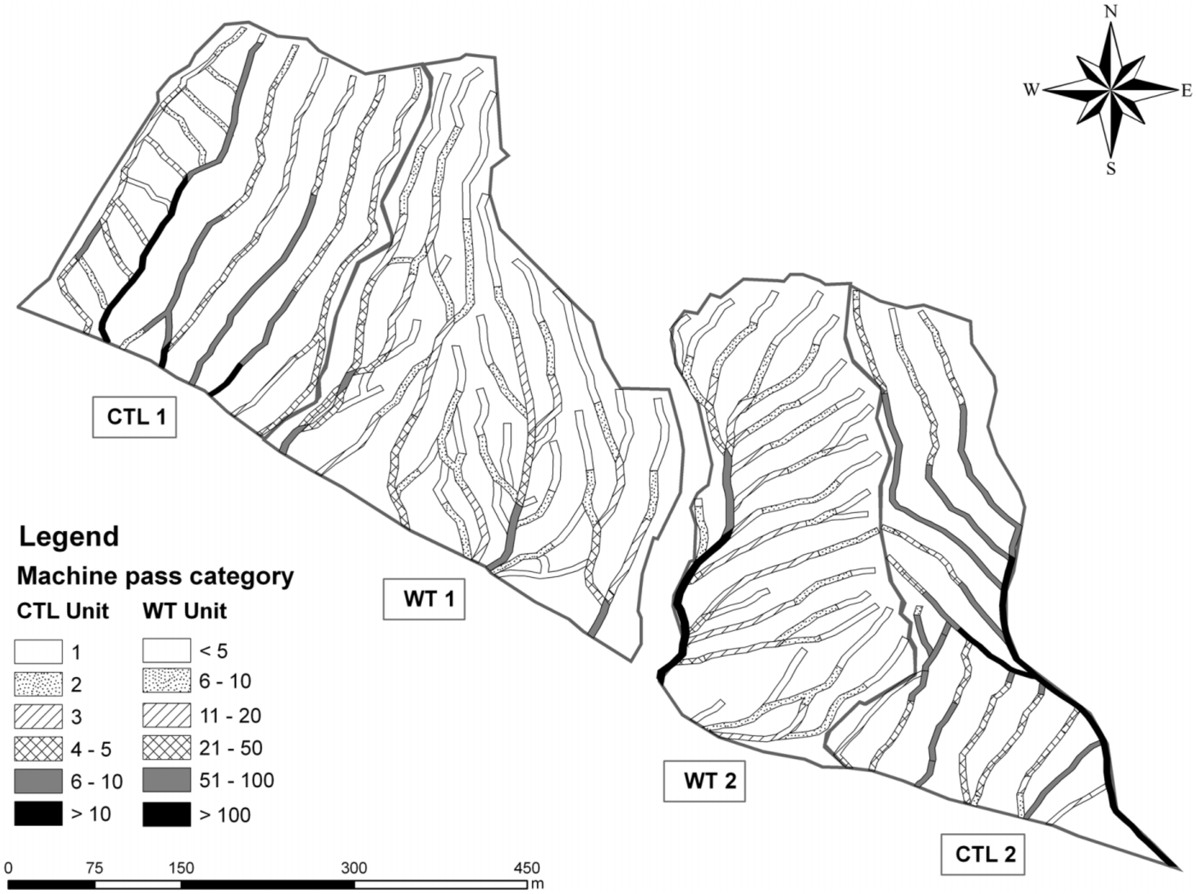
Study area soils were Andosols in the WRB (FAO) classification and consisted of the Helmer series (ashy over loamy, amorphic over mixed superactive, firigid, Alfic Undivitrand) or the Vassar series (ashy over loamy, amorphic over isotic, Typic Vitricryand) (Soil Survey Staff 1999). Helmer soils are located at toeslopes and footslopes and are moderately well drained with a shallow fragipan on slopes >25%. Vassar soils, formed in loess and volcanic ash overlying material weathered from granite, gneiss, or schist, were usually found on slopes <15%. The bedrock in the study stands was situated at 130–140 cm. The study site had a mean annual precipitation of 750 mm and an average annual air temperature of 6 °C. This area was first harvested in 1943 using manual felling and tractor skidding.

Study design and harvesting operations

Two units within the study area were selected. Each unit was divided into two subunits for the two different harvesting systems (Fig. 1). CTL and WT harvesting systems were randomly assigned within each unit (CTL 1 and WT 1; CTL 2 and WT 2). Harvest units and subunits were selected to have similar slope, aspect, soil, and stand composition.

The harvest prescription for the study area was clearcutting. Harvesting took place between May and June 2005 using either CTL or WT harvesting. CTL harvesting operations used a Valmet 500T harvester (machine mass 21 800 kg) and a Valmet 890 forwarder (machine mass 16 800 kg, maximum permissible load 18 000 kg). For the WT harvesting operations, a Timbco T435 feller-buncher (machine mass 26 000 kg), a CAT D-518 track-based skidder (machine mass 12 600 kg), a PC 220 Komatsu processor (machine mass 23 400 kg), and a PC 200 Komatsu loader (machine mass 21 400 kg) were used. General harvesting trails were laid out by harvester and feller-buncher operators before harvesting based on topography and landing locations along the hauling road. Because of changes in technology since the last harvesting operation, only two of the old skid trails could be effectively used for this op-

Fig. 1. Map of the study site and the trails used by cut-to-length (CTL) and whole-tree (WT) harvesting systems.



eration; other old trails were not readily useable with the newer CTL and WT harvesting systems. Farbo (1996) provides a detailed chronological and geographical record of 185 Potlatch logging camps from 1903 to 1986, but this record does not contain detailed information on old skid trails.

Data collection and analysis

After harvester and feller-buncher operations, all trails installed by harvesting equipment (feller-buncher and harvester) were sketched on the map to count the number of machine passes on each trail. Trails were divided into intervals of 15 to 30 m prior to skidding and forwarding activities. The lengths of the intervals were marked on nearby landmarks such as stumps, logs, and residual trees and were also marked on the trail map. We followed the forwarder and skidder at a safe distance and counted the number of passes over each section of the trail. In this study, movements of the harvester and feller-buncher were not included in the number of machine passes, since one pass of a tracked machine does not significantly impact this soil type (Han et al. 2006). A machine pass was defined as one round trip (one round trip = one trip empty + one trip loaded) regardless of whether the forwarder or skidder was fully or partially loaded with wood.

After harvesting, GPS data were collected with a Trimble Geo XT unit at every 15 m along the centerline of the trails to create a post-harvest trail map. The width of each trail was measured every 15 m to determine the average width. In the CTL block, width of the trail center and width of the wheel track were also measured, since the forwarder tended to repeatedly travel the same track. The skidder tracks of the WT subunits were more diffuse and not easily delineated, but there were good indications (i.e., ruts) of the wheel track and center area within the trails. The GPS and trail width data were used to calculate trail area used for primary wood transport in each harvest unit. From GPS data and the sketched map including number of passes, a trail map by machine pass category was created using ArcGIS 9.1 (ESRI Inc. 1999; Fig. 1).

A Rimik CP40 recording cone penetrometer (Agridry, Toowoomba, Australia) with a base cone area of 113 mm^2 was used to measure SRP. Readings in kilopascals (kPa) were automatically recorded at 25 mm increments as the penetrometer was manually inserted to a depth of 300 mm. Transects were installed across the center on all skid trails every 30 m. On each transect, we measured SRP at the trail center, in both tracks, and in reference sampling points (off-trail area). Three replicates of SRP were taken at each point. A total of 2907 SRP measurements were collected in all subunits (Table 1). Davidson (1965) reported that SRP can be measured correctly only when the cone penetrometer is used at or near soil field capacity. Our SRP measurements were collected when soil moisture conditions (25%–30% at 7.5 cm soil depth) were close to field capacity.

Soil bulk density was sampled along the same transects as

Table 1. Description of data collection from cut-to-length (CTL) and whole-tree (WT) harvest units.

Treatment	Sampling locations	Soil depths	Sampling points	Measurements per sampling point	Total measurements
Soil resistance to penetration					
Unit 1					
CTL 1	3	3	82	3	738
WT 1	3	3	100	3	900
Unit 2					
CTL 2	3	3	61	3	549
WT 2	3	3	80	3	720
Bulk density					
Unit 1					
CTL 1	3	3	27	3	243
WT 1	3	3	33	3	297
Unit 2					
CTL 2	3	3	20	3	180
WT 2	3	3	26	3	234

Note: The three sampling locations were reference, center, and track. The three soil depths were 7.5 cm, 15.0 cm, and 22.5 cm.

Table 2. Mean soil resistance to penetration and bulk density in the reference areas.

	Unit 1			Unit 2			
Soil depth (cm)	*n*	Mean	SD	*n*	Mean	SD	*p* value*
Soil resistance to penetration (kPa)							
7.5	182	980	441	141	1132	390	<0.001
15.0	182	1204	466	141	1440	568	<0.001
22.5	182	1320	576	141	1570	666	0.004
Bulk density (Mg·m^{-3})							
7.5	60	0.87	0.12	46	0.90	0.12	0.278
15.0	60	1.06	0.16	46	1.17	0.17	<0.001
22.5	60	1.16	0.16	46	1.27	0.20	0.004

Note: *n*, sample size; SD, standard deviation.
*Wilcoxon rank-sum test, $p < 0.05$.

SRP, but transects were located at every 90 m across the centerline. On each transect, BD samples were collected at the center, from one of the tracks (left or right), and from the reference area (off-trail area). We assumed that the reference area had not been driven on by harvesting machines because the forest floor was intact and there was no indication of soil compression. A core sampler (147 cm^3) was used to collect BD samples at depths of 7.5 cm, 15 cm, and 22.5 cm. Soil cores were placed in plastic bags for transport from the field. In the laboratory, soil samples were weighed, oven-dried at 105 °C for 24 h, and reweighed. Net wet and dry masses were recorded to the nearest 0.01 g. BD was calculated with the gross soil dry mass and volume of the tube and was reported in megagrams per cubic metre. Soil moisture contents were calculated from each BD sample and additional soil cores were taken to monitor soil moisture during harvesting operations. A total of 954 soil BD samples were collected (Table 1).

During harvesting operations and data collection, soil moisture contents were relatively constant, ranging from 25% to 30% at 7.5 cm soil depth. However, soil moisture contents in CTL subunits were slightly lower than those in WT subunits (23%–25% vs. 29%–30%). In all subunits, average soil moisture contents were highest in the upper soil layers and decreased with increasing soil depth. There was intermittent light rain for 4 days during the harvesting operation, but it did not cause significant changes in soil moisture at any soil depth.

Logging slash was also surveyed along the same transects as the BD samples and SRP data. Slash was classified into three different levels: bare (no slash), light (<7.3 kg·m^{-2}), and heavy (<40.0 kg·m^{-2}). Slash mass was calculated using the downed woody debris survey method outlined by Brown (1974).

Data analysis was performed using Statistical Analysis System (SAS) (SAS Institute Inc. 2001) and Statistical Package for the Social Sciences (SPSS) (SPSS Inc. 1998). Data analysis was performed separately for units 1 and 2, since the reference values of the two units were clearly different (Table 2). Data were evaluated for normality before running the analyses. The Wilcoxon rank-sum test was used to compare the degree of soil compaction between the two different harvesting systems. The Kruskal–Wallis and multiple comparison tests were performed to test for differences among

Table 3. Mean values (±standard deviation) for soil resistance to penetration (kPa) collected from the reference, trail center, and track areas.

Soil depth (cm)	CTL					WT				
	n	Reference	Center	Track	*p* value*	*n*	Reference	Center	Track	*p* value*
Unit 1										
7.5	82	913±434a	981±617a	1877±609b	<0.001	100	1035±385a	1281±651b	1898±729c	<0.001
15.0	82	1130±465a	1319±745a	2261±805b	<0.001	100	1266±462a	1627±666b	2294±756c	<0.001
22.5	82	1220±526a	1421±798a	2355±834b	<0.001	100	1402±606a	1778±830b	2324±796c	<0.001
Unit 2										
7.5	61	1055±470a	1176±513a	2182±622b	<0.001	80	1191±305a	1404±654b	1793±534c	<0.001
15.0	61	1559±695a	1545±592a	2620±621b	<0.001	80	1350±432a	1739±617b	2166±698c	<0.001
22.5	61	1764±819a	1960±864a	2779±658b	<0.001	80	1424±477a	1761±621b	2279±760c	<0.001

Note: Means in the same row with the same letter are not significantly different ($p > 0.05$).
*Kruskal–Wallis test, $p < 0.05$.

the three sampling regions (track, center, and reference). These tests were performed separately for each harvesting system (CTL and WT) and at each soil depth (7.5 cm, 15 cm, and 22.5 cm). The effect of slash was tested using a one-way analysis of variance (ANOVA), and regression analysis was used to develop the models that estimate the percent increase of SRP or BD. In prediction models, the forward selection method was used to search a suitable subset of explanatory variables. The significance level was set to 5% ($\alpha = 0.05$).

Results and discussion

Degree of soil compaction in the trails

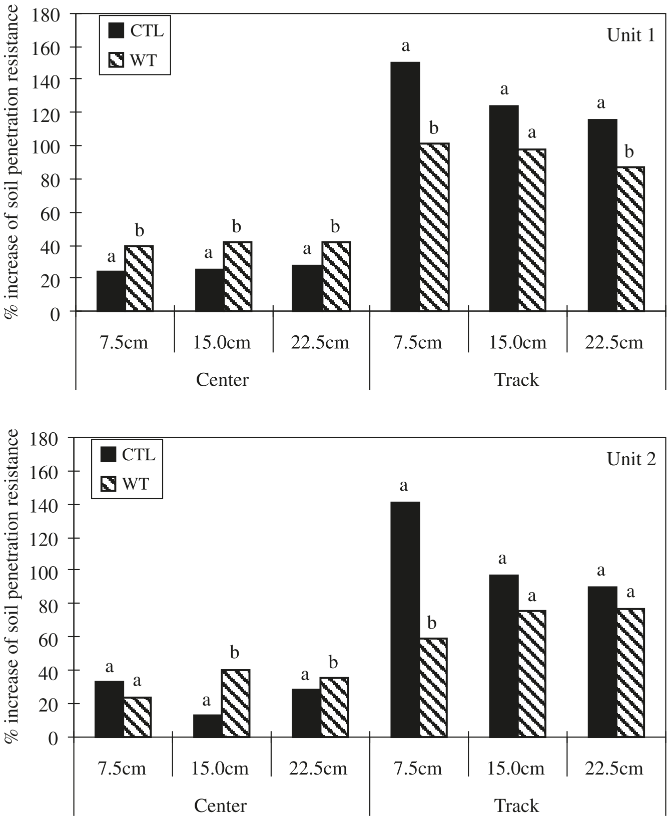
Soil resistance to penetration (SRP)

In the reference areas, SRP readings ranged from 913 to 1191 kPa at 7.5 cm soil depth and increased with increasing soil depth in both units (Table 3). At all soil depths, there was a significant difference in SRP readings between units 1 and 2 (Tables 2 and 3) although both units had the same forest stand and soil texture (ashy silt loam). However, within each unit, CTL and WT subunits had similar SRP readings at all soil depths except for 7.5 cm. At this depth, SRP in the WT subunits was significantly higher than that in the CTL subunits ($p < 0.05$). Because of this initial difference between CTL and WT subunits at 7.5 cm soil depth, we used the percent increase of SRP resulting from harvesting activities to compare SRP readings between CTL and WT subunits.

In both units and with both types of harvesting, we noted an increase of SRP in the center and track of the trails compared with the reference area (Table 3 and Fig. 2). WT harvesting resulted in a significant increase of SRP in both the center and the track areas as compared with the reference area ($p < 0.05$). In the CTL subunits, however, only the SRP readings in the track area were significantly higher than those in the reference area at all soil depths ($p < 0.05$).

In the center of the trail, WT subunits had higher SRP values than CTL subunits at all soil depths except for 7.5 cm in unit 2 (Fig. 2). In unit 1, SRP in the CTL subunit increased 24%–28% at all soil depths, compared with the reference area. In the WT subunit, SRP increases ranged from 39% to 42% for all soil depths (Fig. 2). In unit 2, we found similar percent increases of SRP but the values were lower than those for unit 1, where initial SRP readings were lower than those in unit 2. This result indicated that initial soil compaction level strongly affected the degree of soil compaction following harvesting operations. In both units, WT harvesting caused more soil compaction at the center of trails than CTL harvesting, particularly below 15 cm soil depth. In harvesting operations, the forwarder in the CTL blocks remained in the wheel tracks created during previous trips and did not drive on the center of the trails. These results are consistent with those of other studies (Allbrook 1986; Han et al. 2006; Page-Dumroese et al. 2006). Han et al. (2006) found similar results on other fine-textured soils in the Inland Northwest, USA, where CTL harvesting did not create significant soil compaction in the center of the trail compared with the reference areas. However, the skidder used in WT harvesting did not use the same tracks and

Fig. 2. Percent increase of soil resistance to penetration after harvesting using CTL and WT systems. Means with the same letter are not significantly different ($p > 0.05$)



caused a high degree of soil disturbance across the entire skid trail. Allbrook (1986) also found that WT harvesting on a sandy loam soil at high soil moisture contents caused a significant increase of SRP in the center of the trails.

In the wheel track, percent increases of SRP were higher in CTL blocks than in WT blocks ($p < 0.05$; Fig. 2). In both units, the CTL subunit had an SRP increase of 90%–150%, while the increase in SRP in the WT subunit was 59%–101%. Additionally, increases of SRP were larger in the top soil layer (within 7.5 cm of the soil surface) and smaller in deeper soil layers (Fig. 2). Other studies have reported the percent change of SRP following CTL and WT harvesting. Han et al. (2006) reported that in fine-loamy soils with 21%–30% soil moisture, SRP readings increased up to 260% in the track after CTL harvesting. Allbrook (1986) found that on a sandy loam soil with a moisture content of 38%, WT harvesting resulted in a 157% increase of SRP in the track. Williamson and Neilsen (2000) reported that SRP after WT harvesting increased by 167% under wet conditions on a sandy loam soil. Compared with past studies, this study found a smaller increase of SRP. Although soil moisture conditions were comparable between this study and past studies, this study was performed on a silt loam soil while past studies were conducted mostly on sandy loam soils. Sandy loam, loam, and sandy clay loam soils are more easily compacted than silt loam, silty clay loam, or clay soils under similar soil moisture conditions (USDA 1996).

In this study, SRP readings in the track of the trail ranged from 1877 to 2779 kPa in the CTL subunits and from 1793 to 2324 kPa in the WT subunits. High SRP readings such as those found in our study may be close to the limiting level for root and seedling growth. For example, seedling growth is restricted at SRP values of 2500 kPa in dry soil conditions (Greacen and Sands 1980). Sands and Bowen (1978) reported that a critical soil resistance of 3000 kPa in sandy soils was sufficient to prevent radiata pine root growth. Based on our results, root and seedling growth could be restricted in the wheel tracks of both harvesting systems, particularly when the soil is dry.

Soil bulk density (BD)

Average BD values for the trail center, wheel track, and reference area are summarized in Table 4. In the reference area, BD values were similar between CTL and WT subunits at all three soil depths ($p > 0.05$). In both units, the top soil layer had the lowest BD value, ranging from 0.86 to 0.91 $Mg \cdot m^{-3}$, and the values increased steadily with increasing soil depth, up to 1.27 $Mg \cdot m^{-3}$ at 22.5 cm (Table 4).

In CTL subunits there were no significant differences in BD between the center of the trail and the reference area at any soil depth (Table 4). In the wheel tracks, however, both harvesting systems caused significant increases of BD compared with the reference area. The largest increase in BD was observed at the 7.5 cm soil depth: 34%–39% in the WT subunits and 27%–28% in the CTL subunits (Fig. 3). In wheel tracks in both units, WT harvesting resulted in a greater increase in soil compaction at all soil depths than CTL harvesting, but differences between CTL and WT harvesting were not significant ($p > 0.05$). The different trends of SRP and BD could be explained by slight differences in soil moisture content between CTL and WT subunits. Although SRP and BD were measured at CTL and WT subunits during the same periods, the CTL subunits had lower moisture contents than the WT subunits. Lower moisture contents in the CTL subunits could contribute to higher SRP owing to higher frictional forces. The percent increase of BD in this study was comparable to those reported in past studies (McNeel and Ballard 1992; Williamson and Neilsen 2000). In CTL harvesting, McNeel and Ballard (1992) reported that the average wheel track BD increased up to 20% more than the measurement from the adjacent control sites on a sandy loam soil. Williamson and Neilsen (2000) reported that after WT harvesting, BD increased by 40% in wet soil conditions. However, other studies (Allbrook 1986; McNeel and Ballard 1992; Lanford and Stokes 1995) observed a slightly lower percent increase in BD than this study. Allbrook (1986) found that WT harvesting on soil with 38% moisture resulted in a 23% increase in soil BD in the wheel track of trails. The differences from past studies may have been caused by a combined effect of soil moisture, soil texture, harvesting system, and initial soil properties (i.e., initial BD) (Froese 2004). Han et al. (2006) investigated the effect of soil moisture on soil compaction by running CTL harvesting machines at three different levels of soil moisture. They reported that soil moisture was a major factor affecting the compactability of soils.

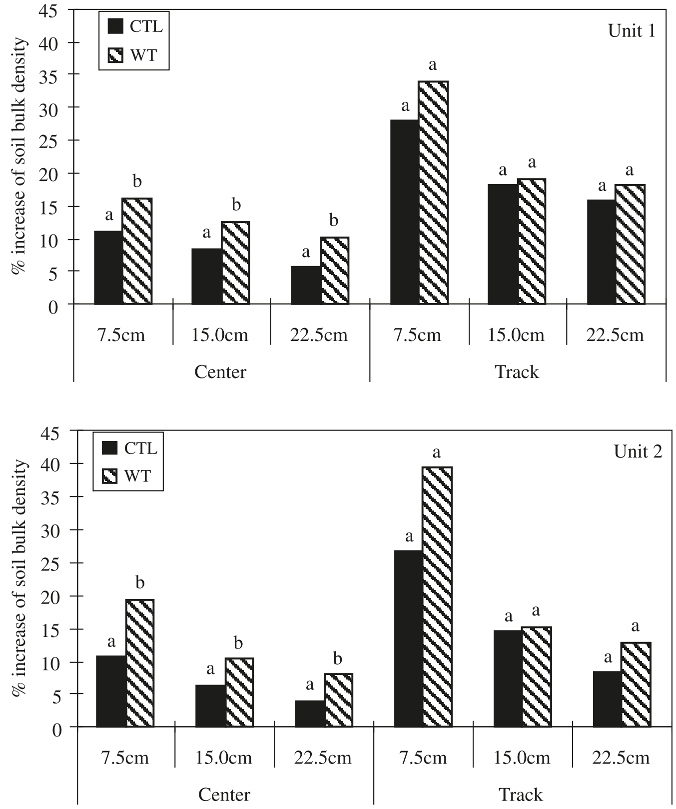
Heavy harvesting equipment may decrease soil macroporosity, leading to poor water infiltration and gas exchange and thus negatively affecting soil biological activity and root

Table 4. Mean values (±standard deviation) for bulk density ($Mg \cdot m^{-3}$) collected from the reference, trail center, and track areas.

	CTL					WT				
Soil depth (cm)	*n*	Reference	Center	Track	*p* value	*n*	Reference	Center	Track	*p* value
Unit 1										
7.5	27	0.89±0.13a	0.97±0.18a	1.11±0.16b	<0.001	33	0.86±0.12a	0.98±0.16b	1.13±0.13c	<0.001
15.0	27	1.08±0.16a	1.16±0.18ab	1.27±0.19b	0.003	33	1.05±0.16a	1.17±0.16b	1.24±0.16b	<0.001
22.5	27	1.19±0.17a	1.25±0.19ab	1.36±0.20b	0.026	33	1.13±0.15a	1.24±0.16b	1.32±0.22b	<0.001
Unit 2										
7.5	20	0.88±0.13a	0.96±0.17a	1.10±0.16b	<0.001	26	0.91±0.11a	1.08±0.18b	1.26±0.19c	<0.001
15.0	20	1.13±0.21a	1.20±0.21a	1.28±0.17a	0.089	26	1.20±0.13a	1.32±0.15b	1.38±0.16b	<0.001
22.5	20	1.26±0.26a	1.30±0.24a	1.35±0.21a	0.586	26	1.27±0.14a	1.36±0.15b	1.43±0.15b	<0.001

Note: Means in the same row with the same letter are not significantly different (Kruskal–Wallis test, $p > 0.05$).

Fig. 3. Percent increase of soil bulk density after harvesting using CTL and WT systems. Means with the same letter are not significantly different ($p > 0.05$).



growth. Lacey and Ryan (2000) reported that if bulk density is increased more than 15%, soil compaction may restrict root growth. Bulk density values that may limit root growth appear to vary with soil texture, tree species, and experimental conditions (Miller et al. 2004). Forristal and Gessel (1955) estimated that 1.25 $Mg \cdot m^{-3}$ was the upper limit of BD for root growth in sandy loam soils, whereas Heilman (1981) suggested that root-limiting BD was closer to 1.7–1.8 $Mg \cdot m^{-3}$ in sandy loam to loam-textured soils. Cullen et al. (1991) observed no root penetration at BD over 1.9 $Mg \cdot m^{-3}$. In this study, BD measurements in the wheel track after harvesting ranged from 1.10 to 1.36 $Mg \cdot m^{-3}$ in the CTL subunits and from 1.13 to 1.43 $Mg \cdot m^{-3}$ in the WT subunits, indicating that new trees growing in the track area of the skidding and forwarding trails may have difficulty achieving root penetration in the compacted soils.

The relationship between soil resistance to penetration (SRP) and bulk density (BD)

For this study, soil resistance to penetration and bulk density were measured to estimate the degree of soil compaction in each harvesting unit. Although the two different methods were applied at the same sampling points, results from SRP readings in the wheel tracks were not consistent with those from our BD cores. In several past studies, the relationship between SRP and BD was reported for several soil texture classes (Allbrook 1986; Clayton 1990; Vazquez et al. 1991; Froese 2004; Ampoorter et al. 2007). Allbrook (1986) and Clayton (1990) stated that SRP was related pos-

Fig. 4. Correlation between soil resistance to penetration and bulk density.

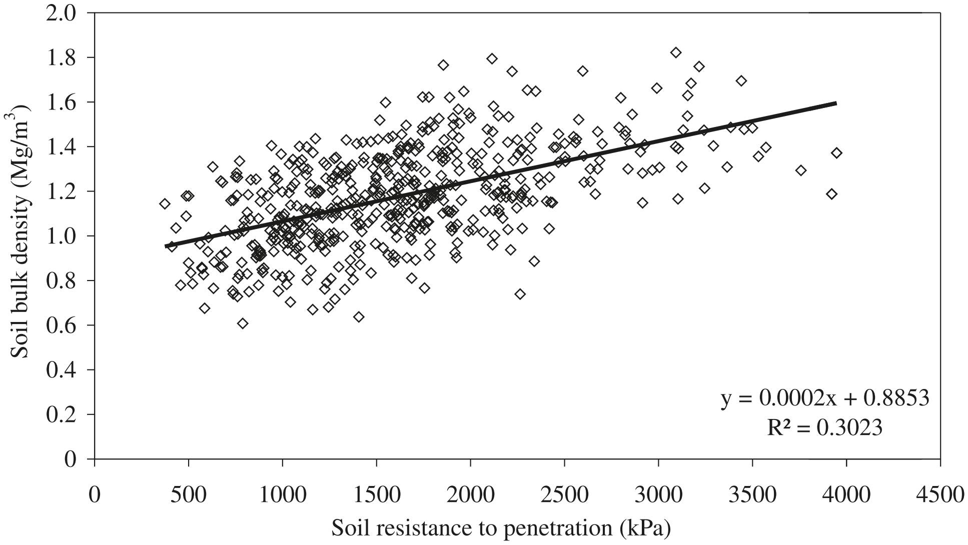


Fig. 5. Percent increase of soil resistance to penetration in the track with different levels of slash in the CTL harvesting units. Means with the same letter are not significantly different ($p > 0.05$).

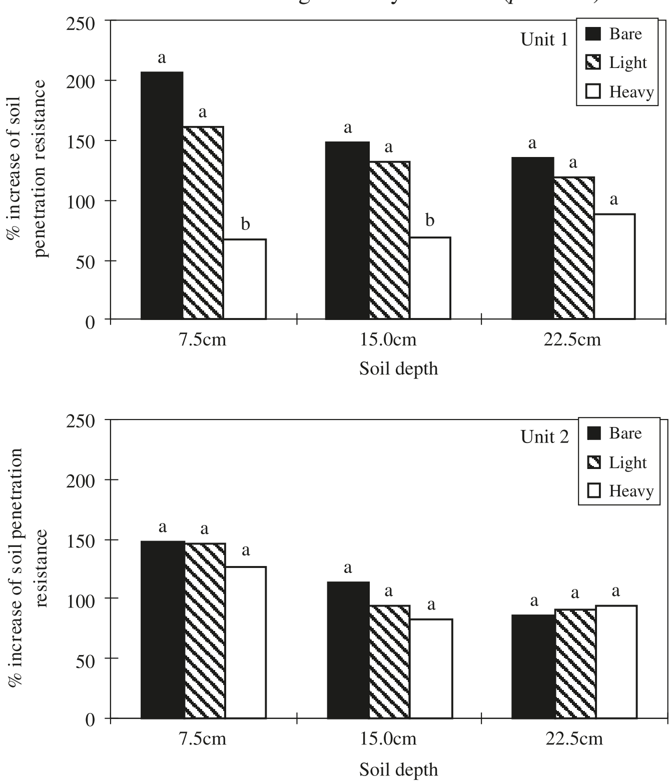
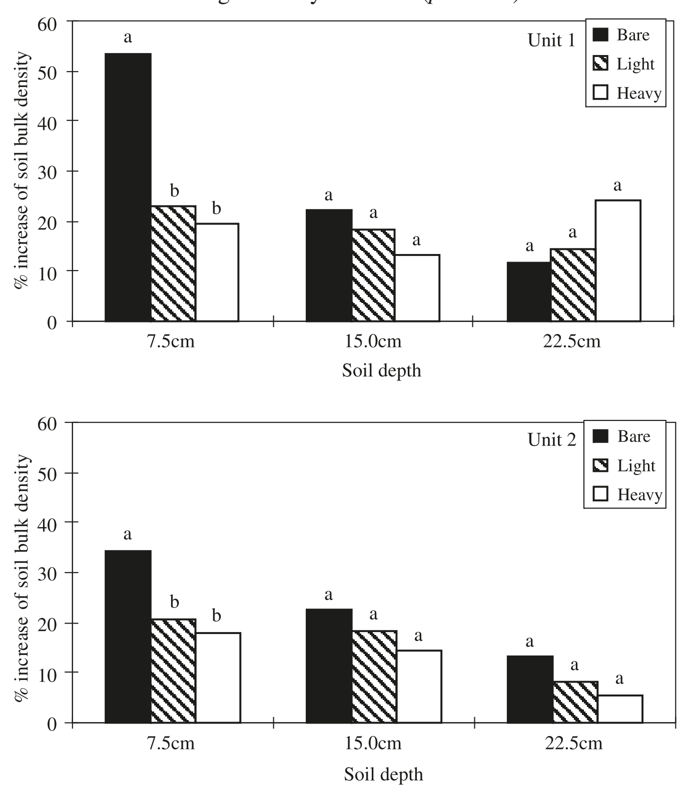


Fig. 6. Percent increase of soil bulk density in the track with different levels of slash in the CTL harvesting units. Means with the same letter are not significantly different ($p > 0.05$).



itively to BD. They also found that compacted soils exhibited high increases in SRP, yet only small increases in BD. In our study, we found trends similar to those of past studies, but BD was not strongly correlated with SRP ($r^2 = 0.30$; Fig. 4). The poor correlation between SRP and BD could be explained by soil moisture, organic matter content, rock fragments, and field variability. Vazquez et al. (1991) suggested that strong correlations between SRP and BD are limited to homogeneous soils under controlled conditions. Soil resistance to penetration is measured as the friction between the cone and soil particles when a cone penetrometer is pushed into the soil. Therefore, the most important factor affecting soil resistance to penetration is soil moisture (Bennie and Burger 1988). In our study, the low correlation could be attributed to slight differences in soil moisture content between CTL and WT subunits.

The poor correlation between SRP and BD could also be explained by high spatial variability. In our study, measured

Table 5. Average trail width, track width, and area of trails in cut-to-length (CTL) and whole-tree (WT) harvesting units.

Harvesting system	Block	Area (ha)	Trail width *n*	Trail width Mean (m)	Mean track width (m)	Trail length (m·ha^{-1})	Trail area in harvesting block ha	Trail area in harvesting block %
CTL	1	4.88	75	3.63	1.80	532	0.95	19
	2	6.01	78	3.61	1.78	561	1.21	20
WT	1	4.00	117	4.47	—	553	1.04	26
	2	4.55	82	4.63	—	534	1.09	24

Note: The trail width includes tracks and the center area between tracks of the skid trails. The track width of the WT units was often not obvious, since trees being skidded erased any previous tracks.

SRP and BD had large standard deviations within each subunit despite three subsamples per sampling point and about 1000 samplings (Tables 1, 3, and 4). Although three replications for SRP were performed at the same sampling point, values of SRP among three replications varied without an apparent cause at some sampling points. Silva et al. (1989) suggested that field analyses of soil data are difficult because of spatial variability. For example, organic matter content and its distribution in a soil would affect soil physical properties including compactability (Zhang et al. 1997).

Importance of slash to mitigate compaction

CTL harvesting and the creation of a slash mat could be an effective way to minimize soil compaction (McMahon and Evanson 1994; McDonald and Seixas 1997; Han et al. 2006). However, the trail area that is not covered by slash may be more severely impacted owing to direct contact between the machine track and the soil surface. In our study, slash covered 69% of the forwarding trail area in the CTL harvesting subunits, with 37% of the trail area covered by heavy slash (<40.0 kg·m^{-2}) and 32% of the trail area covered by light slash (<7.3 kg·m^{-2}).

In measurements of SRP, the buffering effect of slash on mineral soil compaction was found when heavy or light slash was added to the equipment track in unit 1, but slash was not effective in unit 2 (Fig. 5). In unit 1, heavy slash reduced the impacts of ground traffic by 210% at 7.5 cm and 113% at 15 cm as compared with bare ground (no slash). In terms of BD, only heavy slash helped to reduce the machine-caused impacts at up to 15 cm soil depth in the track of forwarding trails (Fig. 6). In both units, light slash appeared to be effective in minimizing soil surface impacts from harvesting activities, but this result was not significant ($p > 0.05$; Figs. 5 and 6). A small amount of slash did not provide enough cushioning in wet soil to absorb the ground pressure and vibration of the harvesting equipment. Light slash tended to be crushed into pieces and could no longer distribute and absorb the impact of the machine. Han et al. (2006) reported similar results when a light slash mat (<7.5 kg·m^{-2}) was left in a CTL harvesting on wet soil. Jakobsen and Moore (1981) reported that the critical amount of slash required to protect soil is 18 kg·m^{-2}. It appears that slash levels will likely have to be adjusted for each soil texture class and moisture level (Han et al. 2006). Other studies have shown that the effectiveness of slash is an interaction of the amount of slash and the number of machine passes (McDonald and Seixas 1997; Han et al. 2006). Initially, slash mats provide an adequate soil buffer, but with increasing machine passes the slash mat breaks down and becomes less effective at minimizing soil impacts from machine traffic. In our study, no significant effect of slash on SRP readings was shown in the center of forwarding trails ($p > 0.05$).

Spatial extent of skid and forwarding trails

Knowledge of the area used for skidding or forwarding trails is important in assessing damage to the soil from harvesting operations. The trail area usually varies with terrain, tree size and volume, harvesting methods, moisture conditions at harvesting, equipment type, and harvesting system (Bettinger et al. 1994; Landsberg et al. 2003; Miller et al. 2004).

In this study, only the trail areas used for primary wood transport (i.e., skidding or forwarding) were used to quantify the extent of trails and soil compaction (Fig. 1). Although the two different harvesting systems were applied in similar terrain, tree density, and moisture conditions, CTL harvesting created less trail area for primary wood transport (19%–20% of total harvest block) than did WT harvesting (24%–26% of total harvest block) in both units ($p < 0.05$). The primary difference in trail area between the two harvesting systems is due to the post-harvest trail width. In both units trail length was not significantly different between CTL (532–561 m·ha^{-1}) and WT (534–553 m·ha^{-1}) harvesting, but the average trail width in the WT subunits (4.47–4.63 m) was greater than that in the CTL subunits (3.61–3.63 m) ($p < 0.05$; Table 5).

In the CTL blocks, track width was easily discernable, since the forwarder repeatedly traversed the same area within the trail and did not cross the center area. It was difficult to delineate the track area from the rest of the skid trail area in the WT harvesting units because when the trees were skidded the previous track was erased. The average width of the center area between tracks in the forwarding trails was 1.78–1.80 m.

When past studies evaluated compacted areas at a CTL harvesting site, they generally included the entire trail, not distinguishing between the center and the track of the trail (McNeel and Ballard 1992; Gingras 1994; Lanford and Stokes 1995). However, this study found that the center of the trail and the undisturbed area were not significantly different in terms of SRP and BD (Tables 3 and 4). Therefore, although the whole forwarding trail after CTL harvesting occupied a large area of the unit, when only the impacted track

Table 6. Prediction model to estimate percent increase of soil resistance to penetration when soil moisture content is 25%–30%.

Harvesting system	Soil depth (cm)	Prediction model	F value	p value	C_p	r^2	n
CTL	7.5	% increase = 1819.74 + 32.64 ln M – 20.23 ln D – 233.16 ln I – 84.62(S1) – 43.35(S2)	38.89	<0.001	6.00	0.59	144
	15.0	% increase = 1221.59 + 46.38 ln M – 16.30 ln D – 151.04 ln I – 55.03(S1) – 34.56(S2)	49.92	<0.001	6.00	0.65	144
	22.5	% increase = 1260.51 + 50.83 ln M – 20.96 ln D – 155.62 ln I – 25.97(S1) – 17.98(S2)	55.14	<0.001	6.08	0.67	144
WT	7.5	% increase = 1156.59 + 13.19 ln M – 17.69 ln D – 145.92 ln I	65.81	<0.001	4.00	0.53	180
	15.0	% increase = 1272.28 + 23.01 ln M – 16.41 ln D – 161.66 ln I	66.45	<0.001	4.00	0.53	180
	22.5	% increase = 1213.78 + 19.64 ln M – 20.85 ln D – 148.86 ln I	69.14	<0.001	4.00	0.54	180

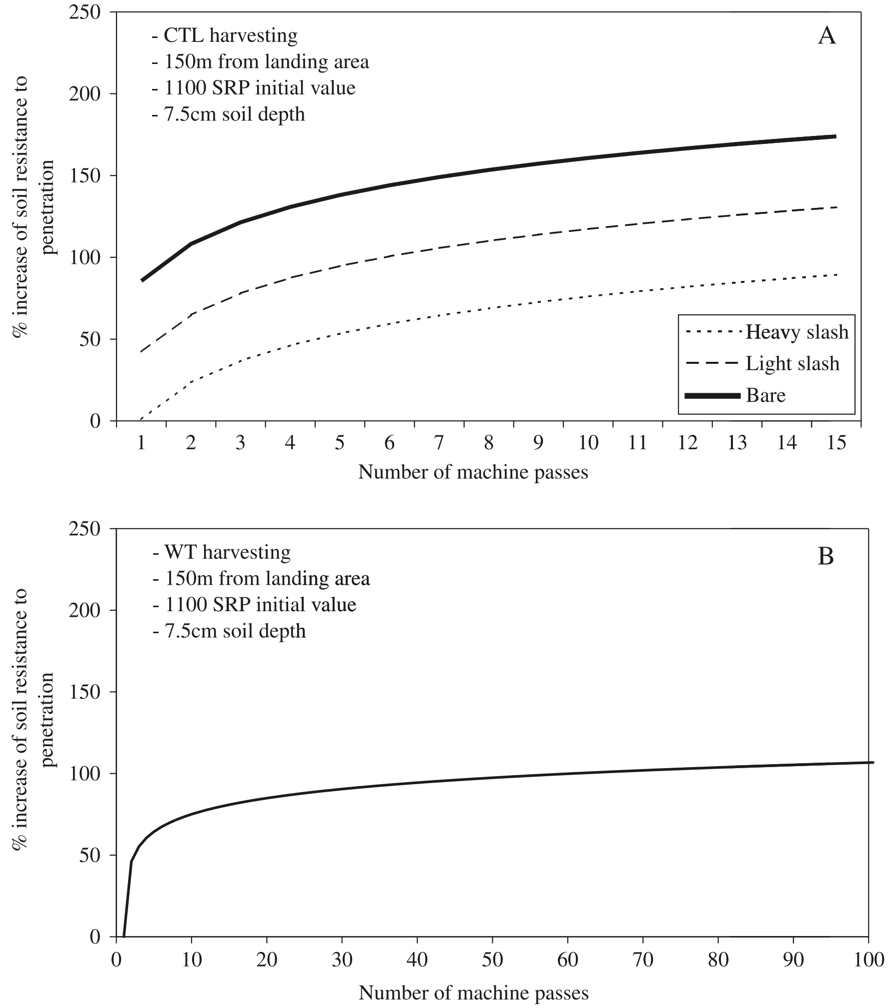
Note: M, number of machine passes; D, distance (m) from landing area; S1, heavy slash = 1 and others (light slash or bare ground) = 0; S2, light slash = 1 and others (heavy slash or bare ground) = 0; and I, initial values for soil resistance to penetration (kPa). C_p, Mallows' C_p statistic (Mallows 1964, 1973).

Table 7. Prediction model to estimate percent increase of soil bulk density when soil moisture is 25%–30%.

Harvesting system	Soil depth (cm)	Prediction model	F value	p value	C_p	r^2	n
CTL	7.5	% increase = 68.28 + 0.11 ln M – 9.35 ln D – 104.63 ln I – 13.63(S1) – 12.62(S2)	12.61	<0.001	4.00	0.55	47
	15.0	% increase = 32.67 + 3.63 ln M – 2.78 ln D – 51.93 ln I – 8.49(S1) – 3.02 ln S2	10.60	<0.001	4.40	0.37	47
	22.5	% increase = 48.50 – 4.86 ln D – 65.98 ln I	14.28	<0.001	2.27	0.40	47
WT	7.5	% increase = 16.24 + 5.72 ln M – 1.14 ln D – 106.50 ln I	16.14	<0.001	4.00	0.47	59
	15.0	% increase = 49.35 + 3.57 ln M – 6.82 ln D – 47.96 ln I	17.30	<0.001	4.00	0.49	59
	22.5	% increase = 52.91 +3.73 ln M – 7.61 ln D – 41.65 ln I	10.33	<0.001	4.00	0.36	59

Note: M, number of machine passes; D, distance (m) from landing area; S1, heavy slash = 1 and others (light slash or bare ground) = 0; S2, light slash = 1 and others (heavy slash or bare ground) = 0; and I, initial values for soil bulk density ($Mg{\cdot}m^{-3}$). C_p, Mallows' C_p statistic (Mallows 1964, 1973).

Fig. 7. Percent increase in soil resistance to penetration (SRP) as a function of the number of machine passes in CTL (A) and WT (B) harvesting based on prediction models.



area was considered, the spatial extent of the compacted area was only 10% of the harvested area.

In both units, GIS analysis allowed us to determine the percentage of trail area in each of the number of machine pass categories (Fig. 1). The collection of machine pass data is difficult, but provides a visual representation of heavily trafficked areas and the extent of the most severe soil compaction. It also provides a database representing historic use of the site for managers. This information may be used to select harvesting systems and trails in future logging operations, and can also assist in establishing plans for tree regeneration in the harvested area. In this study, the highest percentage of trail area in the CTL subunits fell in the 4 to 5 pass category (32%), while the "less than 5" pass category was highest (34%) in the WT subunits. The combined 0 to 20 pass categories accounted for about 85% of the total trail area in the WT subunits. In the CTL subunits, the combined 3 to 10 pass categories accounted for 75% of the total trail area (Fig. 1). In both harvesting units, about 70% of the total trail area was defined as severely compacted because most soil compaction occurred after a few passes of a laden logging machine; approximately 80% of soil compaction was in the top soil layer.

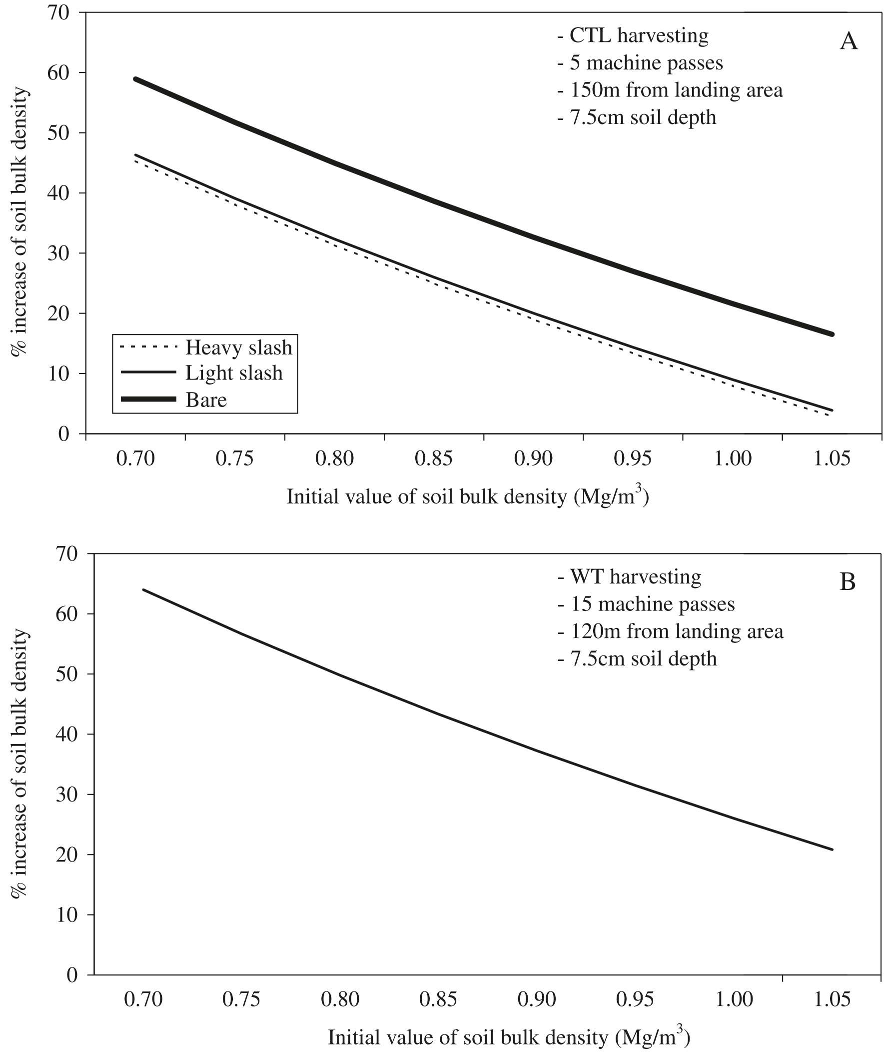
Prediction models to estimate potential soil impacts

For both harvesting systems, we developed prediction models to estimate the percent increase of SRP and BD based on the number of machine passes, distance from landing area, initial SRP or BD, and slash added to the trail (Tables 6 and 7). This information is useful when forest managers develop strategies to prevent unacceptable levels of soil damage that may degrade soil productivity.

In both harvesting units, our models for SRP (r^2 = 0.53 to 0.67) provided better fits to the data than those for BD (r^2 = 0.36 to 0.55) (Tables 6 and 7). The percent increase of SRP and BD increased with an increase in the number of machine passes. However, the distance from the landing area and initial SRP showed a negative relationship with the percent increase of SRP, meaning the percent change was less pronounced as distance from the landing increased.

For all three soil depths, our models indicate that the number of machine passes is highly correlated with increases in SRP in both CTL and WT harvesting systems (Fig. 7). However, this is not the case for BD: in the wheel track, most soil compaction occurred after a few passes of a laden logging machine, and 70% of soil compaction in the top soil sampling level was achieved after only five machine

Fig. 8. Percent increase in soil bulk density as a function of initial soil bulk density in CTL (A) and WT (B) harvesting based on prediction models.



passes in the CTL block (Fig. 7). In the WT block, 80% of soil compaction in the top 7.5 cm of soil occurred after only 10 machine passes (Fig. 7). Soil compaction continued to increase with additional passes in both harvesting units, but there was a lower level of increase or no further increase after five passes in the CTL harvesting sites and 10 passes in the WT harvesting sites. Rollerson (1990) reported similar results (most soil compaction occurred during the first 10–20 passes) after WT harvesting, whereas Williamson and Neilsen (2000) found that 62% of final soil compaction occurred after only one pass on skid trails. Han et al. (2006) also found that there was a rapid increase in SRP up to the second pass of a fully loaded forwarder during CTL harvesting.

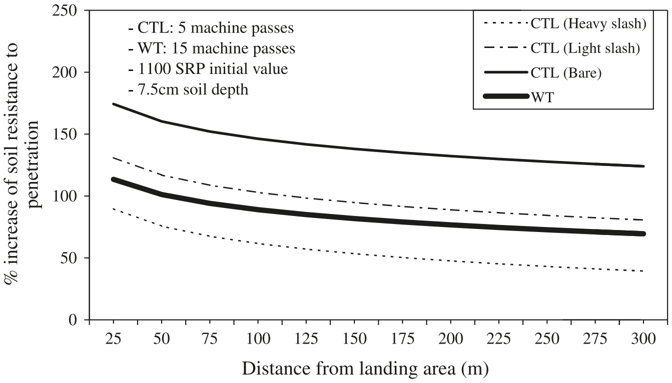
The initial values of SRP and BD were highly negatively correlated with their respective percent increases in the prediction models (Fig. 8). Percent increases were greater in soils with lower initial SRP and BD. Page-Dumroese et al. (2006) also reported that as initial BD increased, the level of change decreased. These results can be useful in determining the limitations on harvesting as a function of soil moisture content and initial soil BD or SRP readings. High initial SRP and BD values under dry-season conditions may result in less soil compaction after operations (Page-Dumroese et al. 2006). Similar results were observed by Williamson and Neilsen (2000) and Han et al. (2006). They also suggested that scheduling harvesting operations during drier conditions could minimize soil impacts.

The prediction model we developed shows that the percent increases in SRP and BD are negatively correlated with the distance from the landing area (Fig. 9). Trails close to the landing area receive higher density machine traffic, which results in greater compaction, than areas farther from the landing area.

Conclusion and management implications

Soil compaction is a common consequence of mechanized forest harvesting operations, especially when soil moisture is high (around 30%). This study was conducted to compare the degree and extent of soil compaction between CTL and WT harvesting systems in northern Idaho, USA. At high moisture levels, both CTL and WT harvesting caused a high degree of soil compaction in the track of the trails. CTL harvesting caused less soil compaction in the trail center and

Fig. 9. Percent increase in soil resistance to penetration (SRP) as a function of the distance from the landing area in CTL and WT harvesting based on prediction models.



used less area for primary wood transport compared with WT harvesting. Therefore, WT harvesting may require more careful planning and layout than CTL harvesting when forest managers design a harvesting plan using a ground-based harvesting system. Slash in the CTL harvesting unit appears to be effective in minimizing soil compaction, but only 37% of the CTL forwarding trails were covered by heavy slash (<40.0 kg·m^{-2}). Therefore, careful planning of the slash mat and ensuring its continuity on the skid or forwarding trails is critical to limiting the severity of compaction.

Although harvesting technology changes, this study supports the use of designated and historic skid trails. Soils with high initial BD were compacted less than those with low initial BD. Since most soil compaction occurred after the first few passes of machines used for skidding or forwarding, restriction of traffic to designated skid trails would be an effective strategy to minimize soil compaction on ash-cap or fine-textured soils that have low initial BD. Therefore, designing harvesting operations with due consideration to strategies such as slash treatments could help limit soil compaction in areas close to log landings.

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