Influence of Two Ground-Based Skidding Systems on Soil Compaction Under Different Slope and Gradient Conditions

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ABSTRACT

Forest soils are sensitive to compaction by forest machinery. Forest operations such as harvesting and skidding have a high potential for soil compaction. This study was carried out in the Hyrcanian hardwood forests of Iran to measure the changes in bulk density (ρ_b) in the top 10 cm of soil following machine and animal skidding. The density change or compaction was induced by (i) a rubber-tired skidder in three skid trails: flat skid trail (STF), skid trail with transversal slope (STTS), and skid trail with longitudinal gradient (STLG) and (ii) a mule in two animal trails: flat animal trail (ATF) and animal trail with transversal slope (ATTS). Soil cores were collected pre- and post-skidding at random locations along the upslope and downslope tracks of each skid trail to determine bulk density and moisture content of the soil.

Average soil bulk density in the tracks of machine skid trails was significantly greater than the soil density outside the tracks, but the increase in bulk density was not significant on the animal trails. An increase in soil density was considered significant if $p < 0.05$.

A highly significant increase in soil bulk density ($p < 0.01$) occurred with machine skidding after the first 12 skidding cycles on the STF before stabilizing. In comparison, on STLG and STTS the increase of bulk density was greatest after the first six skidding cycles. Additional cycles did not cause a significant increase in soil density. While the number of skidding cycles to reach the steady compaction state varied between flat trails and those with a slope, the severity of compaction was the same between them. Concentrating machine operations will minimize the areal extent of compaction and the use of mules could further reduce the impact of the extraction of short logs.

Keywords: *soil compaction, ground-based skidding, soil bulk density, animal trail, skid trail, Iran*

Introduction

A unique aspect of forest soils is their low bulk density, high macroporosity, and high rate of infiltration (Froehlich and McNabb 1984, Froehlich et al. 1985, Huang et al. 1996, Horn et al. 2004). Soil compaction from ground skidding is a common consequence of soil disturbance (Senyk and Craigdallie 1997). Forest soils easily compact from the use of logging machinery, such as skidding machines, which carry heavy loads in off-road conditions. The unprotected forest soil acts as a weak receptor against static and dynamic forces created by skidding and forwarding machines especially on skid trails and landings where high frequencies of machine movement exists (Heninger et al. 2002).

The extent and degree of soil compaction is dependent on several factors including:

1. soil properties: texture, soil moisture content at the time of trafficking (Senyk and Craigdallie 1997, Brais and Camire 1998, Kozlowski 1999, Rab 1999), soil organic matter, slash, and twigs content (Froehlich and McNabb 1984, Wasterlund 1985, Kozlowski 1999), soil structure (Froehlich and McNabb 1984), parent materials (Brais and Camire 1998), and pore size distribution (Froehlich and McNabb 1984, Wasterlund 1985);
2. the magnitude and nature of compressive forces: vehicle mass (Froehlich 1978, Herbauts et al. 1996, Rab 1996, Senyk and Craigdallie 1997), machine size (Greacen and Sands 1980, Herbauts et al. 1996), machine type, number of skidding cycles (Froehlich and McNabb 1984, Rab 1996, Brais and Camire 1998), and duration of loading (Froehlich and McNabb 1984);
3. skid trail conditions: grade of skid trail (Greacen and Sands 1980, Senyk and Craigdallie 1997, Rab 1999), direction of skidding (Froehlich and McNabb 1984, Brais and Camire 1998), and extraction pattern (Brais and Camire 1998);
4. forest stand characteristics: stand structure and density and species composition and life traits (Senyk and Craigdallie 1997, Harvey and Brais 2002);
5. harvesting system (Carter et al. 1997, Rab 1999, Harvey and Brais 2002); and

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6. training, experience, and expertise of equipment operators (Greacen and Sands 1980, Harvey and Brais 2002).

The effects of skidder traffic on soil compaction are well documented in the literature. For example, Dickerson (1976) assessed the compaction resulting from tree-length skidding on loamy sand to a silty clay loam soil in the Oxford area of northern Mississippi. After 20 cycles with a rubber-tired skidder, the bulk density of wheel-rutted soils increased by 20 percent on average to 1.55 Mg/m^3. With increasing vehicle traffic, soil bulk density increased, but most of the compaction occurred on the very first traffic cycle of a skidder. Consequently, additional traffic caused a progressively smaller decrease in soil volume (Froehlich 1978, McDonald et al. 1998, Brais and Camire 1998, McNabb et al. 2001).

One of the objectives of scientific harvesting operations is to identify equipment and practices that foster sustainable forest management. In mountainous and steep areas, terrain slope is an important factor affecting operational efficiency, costs, and erosion. It may also affect soil compaction and as such identification and consideration of terrain slope in planning forest operations and aligning skid trails, in particular, may be an important consideration for protecting soil resources. Unfortunately, few studies have investigated the effects of trail gradient and side slope on compaction in skid trails.

As an alternative to skidding machinery, animals are used regionally for skidding small log sizes over short distances in flat terrain. Relatively few studies have quantified the effects of animal skidding on soil compaction (Wang 1997, 1999; Horn et al. 2004). More information is needed for assessing conventional forest harvesting operations involving animal skidding.

The primary objective of this study was:

i. to assess changes in soil bulk density for skid trails with machine traffic and different longitudinal gradients and side (transversal) slopes and
ii. to quantify the threshold levels of skidding frequency beyond which significant compaction would occur.

The secondary objective was to compare the effects of animal and machine skidding on soil bulk density.

Materials and Methods

Study Area

Two study sites were selected in mature stands at the southern coast of the Caspian Sea (Mazandaran Province, Iran, **Fig. 1**). Here, forest harvesting and silviculture operations are most common in the summer and autumn. **Tables 1 and 2** summarize relevant climate and soil information about the study sites.

The natural vegetation of the sites consists of mixed deciduous species: hornbeam (*Carpinus betulus* L.), oak (*Quercus castaneifolia* C.A. Mey.), beech (*Fagus orientalis* Lipsky), maple (*Acer velutinum* Boiss.), and alder (*Alnus subcordata*). The average depth of soil to the bedrock ranged from 60 cm in the Pahnekola district to 70 cm in the Aghamashad district. Particle size distribution of the soils was classified according to the Unified Soil Classification System (**Table 2**). Soil texture ranged from a fine-grained clay loam (in Pahnekola) to a coarse-grained loamy sand (in Aghamashad). These areas are susceptible to erosion due to their steep mountainous conditions, heavy rainfall, and marl and limey sandstone sediments. Marls, due to their special constitution (35% lime and 65% clay), have low infiltration capacity in particular and thus are susceptible to intense run-off and erosion. Soil protection and productivity are problematic on such sites.

Harvesting operation at the study sites were performed by hand-felling and processing followed by transportation to roadside by either a rubber-tired skidder or a mule. Hand-felling, by chainsaw and axes (especially in thinning operations), is the most common harvesting technique in Iran. Highly mechanized systems, such as harvesters and feller-bunchers, are not used because most of the forests are located on mountainous sites with steep slopes or in lowlands on clay soils sensitive to disturbance by machine loads. Furthermore, the stands are dominated by mature hardwood trees which further limits the potential use of mechanized systems. Rubber-tired skidders are used to extract logs 3 to 4 m long on drivable terrain of up to 35 percent slope. Mules are used to transport short wood (1 m in length) from the felling site to the nearest forest road in flat terrain or on low favorable slopes.

Table 1. ~ *General characteristics of the two study sites.*

District	Location	Mean annual precipitation	Climate	Sampling time
Aghamashad	53° 05′ 56″ E 36° 21′ 18″ N	784 mm	moist with cool winter	Sep. 2004
Pahnekola	53° 05′ 05″ E 36° 25′ 07″ N	848 mm	moist with semi-cool winter	Oct. 2004

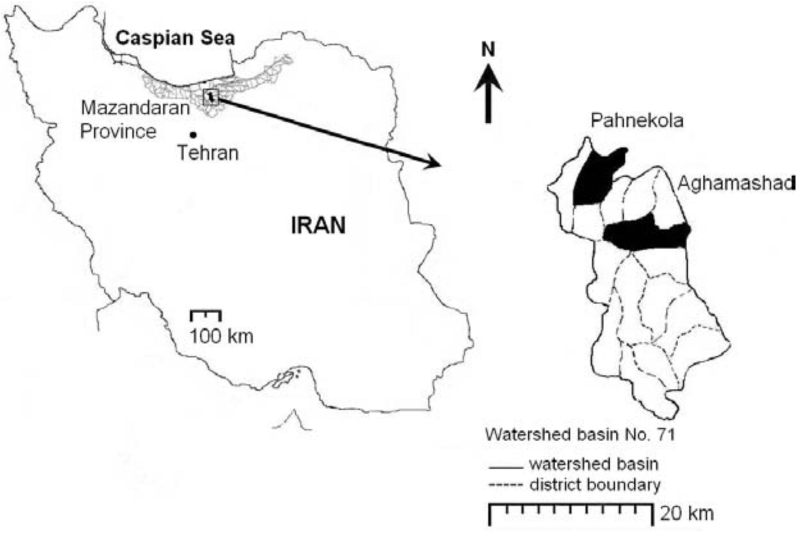

Figure 1. ~ *Location of site study.*

Study Design

A rubber-tired skidder (Timberjack 450C) and a mule (0.650 t weight) were used to extract felled timber. The inflation pressure of the tires (1.1 m width) was 220 kPa, and the contact area of each mule hoof was 94 cm^2. To assess the relationship between the number of skidding cycles (each cycle encompasses one loaded and one unloaded pass) and the changes in soil bulk density for two contrasting extraction systems and three slope/gradient positions, two sites were incorporated in the experimental design.

For the trail setup, longitudinal gradient was used to describe the grade of the trail, and transversal slope was used to express the lateral or side slope of the trail.

At the Aghamashad study site, the treatments consisted of two machine trails: a flat skid trail (STF) and the skid trail with transversal slope (STTS). The STF had a gradient of 0 to 5 percent and a sideslope of less than 5 percent. The STTS had a gradient of 6 percent and a sideslope of 20 percent (**Fig. 2**). In addition, two animal trails were included at this study site. The flat animal trail (ATF) and the animal trail with transversal slope (ATTS) were aligned parallel to and 5 m upslope of the STF and the STTS. They had similar gradients and sideslopes as the STF and STTS.

A second study site at Pahnekola included one machine trail: a skid trail with a 30 to 35 percent longitudinal gradient (STLG) and a sideslope of 4 to 7 percent. This trail was used for downslope skidding. In summary, the skidder operated on three trails and the mule operated on two skid trails with different longitudinal gradients or transversal slopes (**Table 3**).

Each machine and animal trail was oriented perpendicular to the main axis of the connecting haul road. The 30-m-long testing segments in each trail began 15 m from the edge of the road in the adjacent forest. Immediately after skidding, soil samples were taken at random locations within the animal trails and in upslope and downslope tracks of the machine trails. The upslope and downslope tracks were named according to their location on the uphill or downhill side of a skid trail.

The soil samples were collected from the top 10-cm layer of the mineral soil using steel tubes (10 cm long and 5 cm inside diameter), which were inserted into the soil by a hammer-driven device. The thickness of the tube walls ranged from 1.4 to 3.3 mm. After extracting the steel tube from the soil with minimal disturbance to the contents, the soil core was trimmed flush with the tube end and extruded into a plastic bag for transportation to the laboratory. The soil samples were weighed and ovendried at 105°C to constant mass to determine their bulk density and moisture content (MC). The pre- and post-skid-

Figure 2. ~ *A general layout of STTS (top) and STF (bottom).*

Table 2. ~ *Particle size distribution (g/100 g), moisture content (%), and pH of 0 to 10 cm soil depth at the experimental sites.*

Sampling site	Soil texture	Sand (g/100 g) 2.0 to 0.075 mm	Silt (g/100 g) 0.075 to 0.002 mm	Clay (g/100 g) <0.002 mm	Mean moisture content (%)[a]	pH
Aghamashad	Loamy sand	62	23	15	30	7.4
Pahnekola	Clay loam	26	40	34	35	7.5

[a] At the time of traffic.

Table 3. ~ *Description of treatments and treatment codes used in this study.*

Treatment code	Location	Skidding device	Longitudinal gradient of trails	Transversal slope of trails	Total load	Load per cycle
			- - - - - - (%) - - - - - -		- - - - - - (m^3) - - - - - -	
STF	Aghamashad	Timberjack 450C	0 to 5	< 5	262.1	3.6
STTS	Aghamashad	Timberjack 450C	6	20	262.1	3.6
STLG	Pahnekola	Timberjack 450C	30 to 35	4 to 7	137.8	3.3
ATF	Aghamashad	mule	0 to 4	< 5	15.3	0.16
ATTS	Aghamashad	mule	0	20	15.3	0.16

ding samples were taken at the same depth in the wheel-track section of the machine trails and in the animal trail. For each of the varying skidding frequencies, two to six soil samples were collected from each trail section.

Soil samples were taken in the STF and STTS machine trails after 6, 12, 24, 36, 54, and 72 cycles and after 6, 12, 21, 33, and 42 cycles in the STLG. In the mule trails (ATF and ATTS) sampling was done after 6, 12, 24, 36, 54, 75, and 93 cycles. These skidding frequencies were studied during regular skidding operations of cut-to-length and shortwood operations.

The width of soil disturbance along the machine and animal trails was measured in 1-m intervals perpendicular to the axis of the 30-m trail sections. Soil disturbance was identified by exposed mineral soil or mineral soil mixed with organic matter (Alcazer et al. 2002).

Statistical Analysis

Using SPSS (2003), the validity of the data was confirmed with multiple tests. Data distribution was tested for normality using the Kolmogorov-Smirnov test. To determine the threshold level of soil compaction, a one-way analysis of variance (ANOVA) (completely randomized design) was used, testing the significance of the differences in induced soil compaction between skidding cycle treatments and control readings on each trail. This was done for all of the data for the animal trails and the upslope and downslope tracks of the machine trails. Duncan's multiple comparisons test (Zar 1984) was used to isolate statistically significant groups. Because of the difference in soil texture between the two study sites, bulk density values of the related skid trails were analyzed separately. Soil density before and after skidding operations was compared using independent samples t-test. A paired t-test was performed to identify differences between bulk density values of upslope and downslope tracks of skid trails. To compare the disturbance width of trails in different slope positions, the Kruskal-Wallis test (Zar 1984) was used followed by the Mann-Whitney U test (Zar 1984). Results of the statistical analyses were considered significant if $p < 0.05$.

Results

Soil Bulk Density in Machine Trails

The independent samples t-test (**Table 4**) indicated that skidding had a statistically significant effect on the bulk density of machine trails in comparison with their early undisturbed status. Mean values for bulk density were slightly higher on the trail with longitudinal gradient (STLG) than on the trails with and without transversal slopes (STTS and STF). Maximum mean values of bulk density of compacted soils were in the order of STLG > STTS > STF. The mean bulk density on the three trails before and after skidding increased by 0.42 to 0.43 Mg.m^{-3} or 45 to 48 percent (**Table 4**).

Soil Bulk Density in Upslope and Downslope Tracks of Machine Trails

One-way ANOVA was used to test bulk density differences on the upslope and downslope tracks of three machine trails for different skidding frequencies. The results are summarized in **Table 5**. Generally, the soil density of each track of the machine trails increased significantly as skidding frequency increased, whereas the soil bulk density in the animal trail did not change significantly with skidding frequency. The changes in bulk density post-skidding are illustrated in **Figure 3**. The flat machine trail (STF) showed the highest increase of bulk density at upslope and downslope tracks after the first 12 skidding cycles (Duncan's). Related bulk density values of STF on the upslope

Table 4. ~ *Summary of the bulk density (ρ_b) in Mg.m^{-3} (average of samples of all cycles) and its relative changes before (zero traffic) and after skidding operations in each of the skid and animal trails by independent samples t-test.*

	STF	STTS	STLG	ATF	ATTS
Mean (standard deviation)					
Before skidding	0.89 (0.14)	0.9 (0.12)	0.94 (0.11)	0.91 (0.07)	0.89 (0.09)
After skidding	1.31 (0.08)	1.33 (0.11)	1.36 (0.06)	0.98 (0.08)	0.99 (0.08)
Change of ρ_b (%)	+47	+48	+45	+8	+11
p-value	0.00	0.00	0.00	0.223	0.119
|T|-value	10.96[a]	9.45[a]	9.64[a]	1.34[b]	1.78[b]

[a] Significant at the 0.01 probability level.
[b] Not significant.

Table 5. ~ *Summary of the effect of skidding traffic on soil bulk density (ρ_b) at upslope and downslope tracks of machine and animal trails by significant compaction in one-way ANOVA tests.*

	STF		STTS		STLG			
	Upslope track	Downslope track	Upslope track	Downslope track	Upslope track	Downslope track	ATF	ATTS
F-value	12.802[a]	17.597[a]	13.558[a]	13.447[a]	7.453[a]	6.158[a]	0.457[b]	1.152[b]
p-value	0.000	0.000	0.000	0.000	0.003	0.006	0.856	0.364

[a] Significant at the 0.01 probability level.
[b] Not significant.

and downslope tracks were 1.27 Mg/m^3 and 1.18 Mg/m^3 and 58.7 percent and 36.5 percent higher than the control values (zero cycle), respectively (**Fig. 3**). Beyond 12 cycles, very little increase in bulk density was noted. In the upslope and downslope tracks of the machine trail with transversal slope (STTS), bulk density increased by 78.1 percent and 71.9 percent of control value during the course of the first six cycles (Duncan's). Up to 66 cycles of additional traffic did not significantly increase bulk density any further (**Fig. 3**). The soil samples from the machine trail with longitudinal gradient (STLG) indicate similar behavior: bulk density values of the top 10-cm layer of upslope and downslope tracks achieved their maximum level after the first six cycles. This means that the bulk density increased by approximately 53.6 percent and 65.4 percent, respectively, compared to the control value (zero cycle, **Fig. 3**). The average soil MC at the time of the skidding was 30 percent for STF and STTS and 35 percent for STLG.

Comparing soil density values in upslope and downslope tracks of the different machine trails (**Fig. 5**) shows that the transversal sloped trail (STTS) had statistically significant differences ($p = 0.035$) between the bulk density of the tracks, whereas the flat trail (STF) and the trail with longitudinal gradient (STLG) showed no such difference between the tracks ($p = 0.245$ and 0.986, respectively, paired t-test).

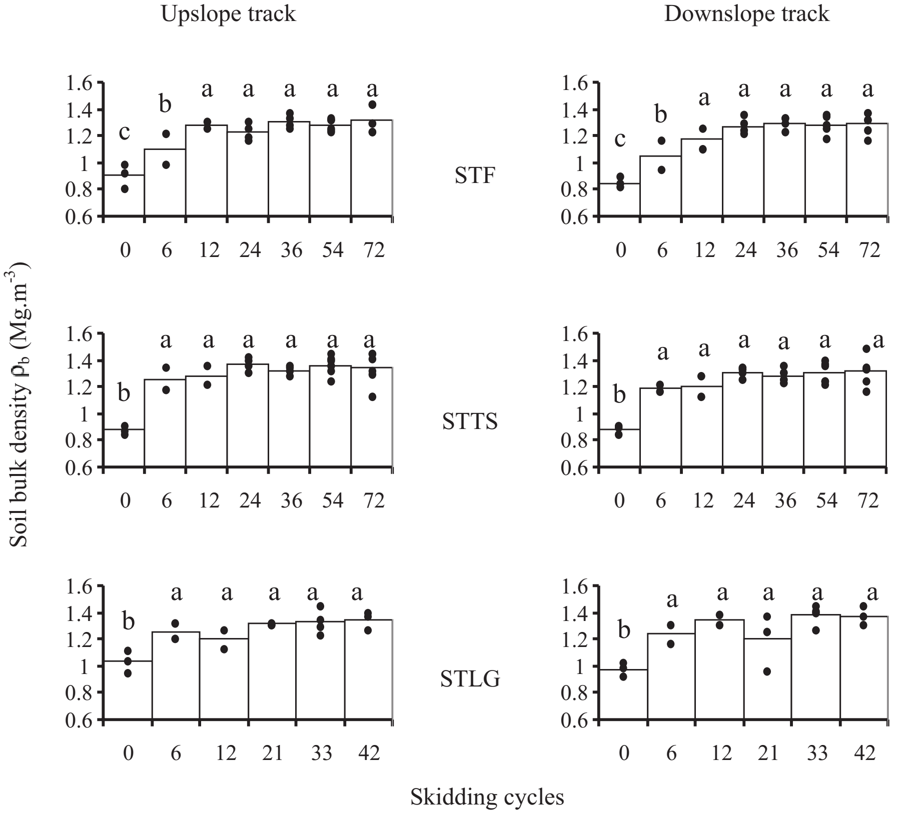

Figure 3. ~ *Mean bulk density (along with dotted raw data) of upslope and downslope tracks of machine trails after different skidding frequencies (cycles). Mean values followed by the same letter are not statistically different by Duncan's test.*

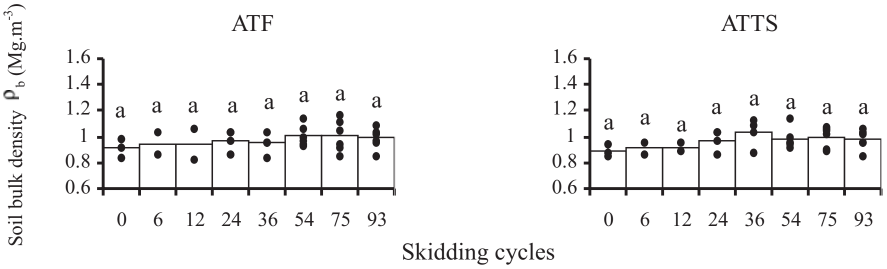

Figure 4. ~ *Mean bulk density (along with raw data) of animal trails after different skidding frequencies. Mean values followed by the same letter are not statistically different by Duncan's test.*

Soil Bulk Density in Animal Trails

ANOVA showed that mule skidding at different slope positions of the trail had no statistically significant effect on soil compaction (**Table 5, Fig. 4**). There was a slightly greater numeric mean of bulk density (**Table 4**), however, on the transversal sloped animal trail (ATTS,) than on the flat trail (ATF).

Width of Machine and Animal Trail

The width of disturbed soil along the trails was significantly different between machine and animal trails ($x^2 = 133.56$, $p = 0.000$). Generally, the disturbed area along the machine trails was substantially wider than along the animal trails (**Table 6**). The maximum and minimum widths of disturbed soil were found on STTS (6.85 m) and on ATTS (1.44 m), respectively. Between the flat skid trail and the trail with longitudinal gradient (STF and STLG), the width of the disturbed area was not significantly different. Average values of disturbance width were in the order STTS > STLG > STF > ATF > ATTS (**Table 6**).

Discussion

Changes of Bulk Density in Machine Trails

In this study, machine-based skidding significantly increased the soil bulk density (ρ_b) in the tracks of skid trails (**Table 4**). Soil samples taken from the skid trails after different skidding frequencies showed on average an increased bulk density of 45 to 48 percent compared to the samples taken before skidding; the maximum increase in soil density of single samples ranged

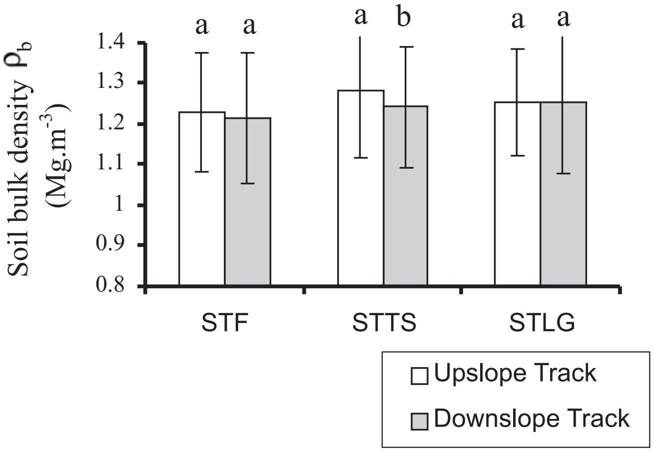

Figure 5. ~ *Mean bulk density (± SD) post skidding for upslope and downslope tracks of skid trails (averaged for all skidding frequencies). Mean values followed by the same letter are not statistically different by paired t-test ($\alpha = 0.05$).*

from 35 to 74 percent. This was obviously caused by soil volume reductions (rutting) during machine movement when soil particles and aggregates (Greacen and Sands 1980, Carter et al. 1999) gained closer proximity, in particular, by lessening the number of coarse pores (Startsev and McNabb 2001). Similar results were found by Dickerson (1976), Froehlich (1978), Alban et al. (1994), McDonald et al. (1998), Brais and Camire (1998), and McNabb et al. (2001).

Changes of Bulk Density in Machine Trails with Different Gradients/Slopes

There was no detectable difference in compaction between machine skidding on flat trails and trails with longitudinal gradient or transversal slope. This was surprising. We expected skidding along flat trails to have the lowest compaction, the trails with transversal slope to have intermediate compaction, and the trails with longitudinal gradient to have the highest compaction. This assumption was based on the uneven load distribution between the downhill and uphill tires of the skidder on the trail with a transversal slope or between the front and rear axles of the skidder on the trail with a longitudinal gradient which would result in higher dynamic peak loads being exerted on the ground. What we found as a result of these dynamic high peak loads, instead, was a reduced rate of skidding cycles at which maximum compaction level was reached. The different site conditions, however, may have affected the impacts of the different gradients/slopes. In addition, the effect of the skidding frequencies on the change of bulk density may have overridden the comparatively smaller effects of different gradient/slopes.

Changes of Bulk Density with Skidding Frequency

The results of this study demonstrate that the increase in bulk density on skid trails with up to 35 percent longitudinal gradient or 20 percent transversal slope was highest after the first few cycles. In detail, the results showed that the soil density increased significantly in both the upslope and downslope tracks of the STTS and STLG trails after six skidding cycles. Beyond six cycles, there was no detectable increase in bulk density. The reason for this was probably an increase in the soil's bearing capacity inside the tracks through higher shear strength after compaction by the first six skidding cycles. These results are consistent with findings from others (Froehlich 1978, Froehlich and McNabb 1984, McNeel and Ballard 1992, McDonald et al. 1998, Brais and Camire 1998, McNabb et al. 2001).

On the STF, both upslope and downslope tracks showed a significant increase in bulk density after 12 skidding cycles, with no significant changes caused in additional cycles.

The upslope and downslope tracks of the trail with transversal slope (STTS) both were heavily compacted following the skidding activities. But, samples of the upslope track showed a more significant increase of bulk density than samples of the downslope track. The opposite was expected since the downslope wheels of a skidder on a lateral slope are more loaded. Interestingly, Senyk and Craigdallie (1997) found that soil bulk density was greatest on the upslope track of a haul road compared to the soil density of the downslope track and between the tracks. It is not clear why this should be the case. A possible explanation for this could be "lateral wheel-slip" of the skidder, resulting in the accumulation of displaced topsoil from upslope tracks and between tracks onto the downslope track of the trail, exposing deeper soil layers with higher bulk density on the upslope track. Another reason for lower bulk density at the downslope track might be the dragging of the logs on or close to this track. Dragged behind the skidder, the logs and especially the log heads might have ripped and loosened up the surface of the highly compacted downslope wheel track (**Fig. 2, top**).

The upslope and downslope tracks of the STF and STLG had no significant difference in terms of soil compaction. This is related to the rather homogeneous weight distribution of the skidder on the skid trails. In these cases, the logs were dragged

Table 6. ~ *Soil disturbance widths (m) of skid and animal trails after skidding activities. The mean values followed by the same letter are not statistically different from the result by Mann-Whitney U.*

Statistics	STF	STTS	STLG	ATF	ATTS
Mean ± standard deviation	4.47 ± 0.96 b	6.85 ± 0.68 a	4.75 ± 0.33 b	2.19 ± 0.46 c	1.44 ± 0.4 d
Minimum	4	6	4.15	1.45	0.9
Maximum	5.6	8.6	5.35	3.2	2.35
%CV	21.4%	9.87%	7.01%	21.09%	27.61%
n	30	30	30	30	30

between the tracks. Unfortunately, only a few studies have investigated the effect of skidding operations under different slope positions on soil compaction.

Change of Bulk Density in Animal Trails

Results from this study indicate that mule skidding did not cause any significant difference in the bulk density of the soil, neither on ATF nor on ATTS. Overall, the marginal change of soil density on the animal trails suggests that animal skidding caused much lower soil compaction than machine-based skidding. A number of studies (Wasterlund 1994; Ficklin et al. 1997; Wang 1997, 1999) have examined the extent of soil disturbance created by animal skidding. Horn et al. (2004) used a multi-step compression device to assess the effects of several skidding methods on soil compaction. They found that in natural conditions, the impact of horse skidding on the soil was zero and, therefore, had the least effect of all skidding methods compared (skidding with steel-tracked and rubber-tired skidders, forwarder, and harvester).

Width of Machine and Animal Trail

This study showed that the width of soil disturbance along skid trails related directly to the transversal slope of the terrain. STTS showed the maximum disturbance width caused by “bias movement of log” during skidding activities: logs or log heads run either on the downslope track or disturbed the adjacent downhill soil, thus widening the disturbed area. Both skid trails with low and high longitudinal gradient (STF and STLG), but low transversal slope, showed much narrower areas of soil disturbance because the logs were dragged between the tracks. The study also confirms that animal trails have a much lower area of disturbance than skid trails. But, better maneuverability and free running of the mules led to increased widths on the flat trails compared to the animal trails with transversal slope (**Table 6**).

Conclusion

In conclusion, the results of this study showed that skidding frequency was an important factor in soil compaction of skid trails and that compaction by machines occured at a faster rate on trails with longitudinal gradients or transversal slope than on flat trails. In comparison, the degree of compaction on the animal trails was not related to the frequency of animal traffic. The effects of mule skidding on soil disturbance seemed to be marginal. In view of this, use of mules to complement machine-based skidding on highly sensitive areas may be appropriate. Considering the maximum occurrence of compaction in the very first skidding cycles, concentrating skidder off-road traffic to a limited area of pre-planned skid trails will also help to avoid soil compaction throughout forest stands, thus fostering sustainable forest management.

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