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Assessment of ground-based skidding impacts on the horizontally rate and extent of soil disturbance along the margin of the skid trail

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Abstract

· **_Key message_** **Skidding operations significantly influenced soil physical properties up to a 2-m distance from the wheel ruts in a forest ecosystem. The most significant changes in soil properties were identified within a 0.5 m to 1 m transitional zone**.

· **_Aims_** The main purpose of this investigation was to determine how far into a forest stand changes in soil physical properties were evident due to skidding operations.

· **_Methods_** Treatment plots with three replications included combinations of four distance zones at 0.5 m intervals (0 to 2 m in distance) on both sides of skid trail edges to the forest, three slope gradient levels were applied (gentle <10 %,

moderate 10–20 %, steep >20 %) and two levels of traffic intensities 20 and 40 passes (with a rubber-tyred skidder, model HSM 904). A total of 576 soil samples were used in this study.

· **_Results_** Results showed that the physical properties of soil were significantly changed by each traffic intensity in the first distance zone, where the slope was >20 % compared to soil changes at a slope of <20 %. The largest changes in soil properties were identified at 0.5 m transitional distance zones for a slope gradient >20 % after 20 and 40 skidding cycles.

· **_Discussion_** Dry bulk density values reached its maximum levels in the first 0.5 m from the skid trail on slopes >20 % after 40 skidding cycles.

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Contribution of the co-authors Ahmad Solgi: collecting data
Akbar Najafi: designing the experiment, writing the paper, supervising the work, coordinating the research project
Sattar Ezatti: collecting data in the field and running the data analysis
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1 Introduction

Timber harvesting operations increase almost constantly in terms of their size and in the power and load capacity of logging machines (Ampoorter et al. 2007). This may lead to soil degradation in forest ecosystems, especially in mountain terrains and result in modification to the structural characteristics of the soil (Ezzati and Najafi 2010). The small contact area where the wheels of logging vehicles impact on the ground results in low traction efficiency and high ground pressures (Bygdén et al. 2004). Additionally, uneven axle loads are known to be an unsuitable option for steep slope terrains. Historically, soil disturbance on skidded areas had been relatively high, since skid roads (excavated and bladed trails) often accounted for over 20 % of a clear-cut on a steep slope (Dykstra and Curran 2000). Soil disturbance from compaction can vary in intensity and spatial variability within a specific

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profile, both horizontally and vertically. Its intensity and extent are a function of the ground pressure and total load (ground pressure × contact area of the tyre or track) and soil characteristics (texture and its structure) (Håkansson and Lipiec 2000), skidding directions (Arya et al. 2014), slope of the skid trail and traffic intensity (McNabb et al. 2001; Najafi et al. 2010).

Extending soil disturbance refers to the degree of soil disturbance caused by ground skidding along the edges of the skid trail and extending into the adjoining soil. The distribution of disturbance can occur in the form of small and evenly distributed areas or, alternatively, in large areas in one or a few locations at an increasing distance from the wheel ruts. Greacen and Sands (1980) noted that a feature of compaction in the field is spatial variability, both vertically and horizontally. The pressure that a machine exerts not only influences the area located directly under its tyres; this pressure can also be horizontally distributed on the soil in the surrounding area (Horn et al. 2007). Wert and Thomas (1981) found that the transitional zones (within a 3-m band on both sides of the skid road) carried only 75 % of tree volume of the undisturbed areas 32 years after logging. No detailed bulk density or chemical data were reported.

In contrast, Pennington et al. (2004) found increases in estimated standing volume in the transitional zones (within a 5-m band both sides of the snig track) in three forest stands 17–23 years after logging. Helms and Hipkin (1986) also reported 18 % increases in soil dry bulk density on the areas adjacent to snig tracks compared to areas of the lowest bulk density.

Application of large shear stress due to heavy mechanized operations (Vomocil et al. 1958) in forest areas to a soil in equilibrium with an applied static load may also cause a considerable further decrease in void ratio. Raper et al. (1995) discussed that for the compaction induced by the tyres, the biggest impact in the soil was the vertical transmission of forces. Arvidsson (2003) observed that heavy axle loads during sugar beet harvesting in southern Sweden could often cause subsoil compaction, including increased penetration resistance and reduced hydraulic conductivity, which can be a long-term threat to soil productivity.

This variability tends to be common in agriculture, where mechanized operations are systematically spread across an area. However, this variability is more random within forest operations, particularly in unevenly aged stands, where mechanized forest operations are less evenly spread throughout the area. Therefore, these effects may decline with increasing distance from the wheel ruts into forests. According to Wronski (1984), side compaction caused by vehicle traffic could be attributed to the lateral movement of soil beneath the zone of maximum compression. The rotation of the tyres results in shear forces that tend to loosen the soil (Vossbrink and Horn, 2004). In soil compaction, not only pure static stress, but also dynamic forces play a role, caused by vibration of the engine, the attached implements and by wheel slip (Yavuzcan et al. 2005).

Skidding that causes soil disturbance is a challenge faced by foresters, especially in mountain forest regions. Numerous studies in the literature to date have addressed the detrimental impact of soil disturbance from a range of traffic intensity and the slope of the skid trail, both in forestry and in agriculture (McNabb 1994; Arvidsson 2003; Hamza and Anderson 2005; Ezzati and Najafi 2010; Cambi et al. 2015). However, the distribution of compaction on the margins of skid trails has, to date, received little attention. The paucity of such information has caused problems in determining the threshold spread of compaction on both sides of the skid trail. Thus, the aim of the current research is to study the horizontal impacts of skidding operations on the rate, extent and profile of soil compaction on the skid trail margins layer (up to 10 cm depth of soil profile) and compare it to an undisturbed area. The focus of the present study is (i) to analyse how far into the forest stands timber skidding operations have influenced soil compaction and (ii) assess these changes under varying conditions of slope and traffic intensity.

2 Method and materials

2.1 Study site

The study was conducted in a northern forest in Iran, located at 36° 13′ N latitude and 36° 15′ N, and 53° 10′ E and 53° 15′ E longitude. The study area receives 860 mm of precipitation annually in the form of rain at lower elevations and snow from mid-September through to May as elevation increases. The forest is composed of deciduous trees dominated by oriental beech (*Fagus orientalis* Lipsky) and hornbeam (*Carpinus betulus*). The estimated canopy cover, mean diameter (DBH) and mean height are 0.8, 29.7 cm and 22.94 m, respectively. Soil texture was identified in the soil laboratory to be clay loam across the trail.

2.2 Experimental set-up

A skid trail of 0.9 km in length by four metres in width, which ran downhill and roughly parallel to the slope, was selected as the study area. All timbers were transported by a rubber-tyred skidder, model HSM904; the main technical characteristics of the skidder are provided in Table 1. An effort was made to choose a skid trail with a range of different longitudinal slope classes and any cross fall. Minimum and maximum slope gradients were 0 to 33 % along the trail, respectively. A random complete block design (RCBD) was utilized to collect data about the skid trail. Twenty-four treatments were imposed on the skid trail, where the experimental variables included traffic

Table 1 Skidding machine technical specifications

Technical specifications	HSM 904
Product group power	Wheel skidder 177 HP
Weight (Mg)	8.7
Number of wheels	4
Tyre dimension (mm)	600/6–30.5

intensity for 20 and 40 skidder passes (half empty and half loaded passes), a slope in the form of gentle (<10 %), moderate (10–20 %) and steep (>20 %), as well as distance zones (four, all of which were 0.5 m in distance) along the same track. A schematic design of sample plot locations is shown in Fig. 1 and descriptions of each block characteristics is presented in Table 2.

Five sample lines were delineated perpendicular to the trail in each block, 10 m long by 4 m wide, with a 2-m buffer zone between lines to avoid interactions. Three of the five lines were then selected randomly to measure the soil physical properties. Soil samples were collected at 13 locations: between tracks (BT), left wheel (LT), right wheel (RT) and undisturbed area (control samples) at both sides; the extent of compaction was studied using eight locations at four equal distance locations (0.5 m intervals) on both margins (edge of skid trail) into the forest after 20 and 40 skidding cycles. Soil samples were taken by using 100 mm steel cylinders, 50 mm in diameter, following a perpendicular line to the axis of the skid trail (Fig. 1). A total of 36 (6 plots × 3 lines × 2 sample) control samples, corresponding to sampling on each sampling line at both sides, were taken in the undisturbed area, where there was no skidding impact; this sample was taken at least 30 m

away from the skid trail and at least one tree length from the skid road's edge in order to reduce side effects (Ezzati et al. 2011). To characterize the state of compactness of a soil layer, dry bulk density (DB), total porosity (TP), macroporosity (MP), microporosity (MIP) and void ratio (VR) were measured and compared to the undisturbed areas.

Samples from the research area were shipped to the laboratory double sealed in plastic, where they were promptly weighed and then dried in an oven at 105 °C and reweighed to calculate dry bulk density. Soil response to applied stress was quantified according to the changes brought about in pore space. Due to variability of the size, shape and continuity of the soil samples, porosity could be a good indicator to explain changes in soil structure that one influenced by soil compaction. In this paper, total porosity was calculated based on Eq. 1 as follows:

$$TP = 1 - \left(\frac{DB}{2.65}\right) \times 100 \qquad (1)$$

Where TP is total porosity (%), DB is dry soil bulk density (g cm^{-3}), 2.65 (g cm^{-3}) is the assumed particle density according to the ASTM D854-00 2000 standard.

Macroporosity was determined using the water description method (Danielson and Sutherland 1986). In this method, soil samples were saturated in plastic tubes over a period of 5 days, the water level was slowly raised to prevent air entrapment, and weighed. The samples were then drained for 3 h and weighed again (Rivenshield and Bassuk 2007; Ezzati et al. 2012). We calculated the macroporosity based on Eq. 2

$$MP = \frac{w_s - w_{dr}}{v} \times 100 \qquad (2)$$

Fig. 1 Illustration of sample line locations on the given block and sample point positions on the lines. Three of the five established lines were selected randomly with at least 2 m distance to avoid interaction
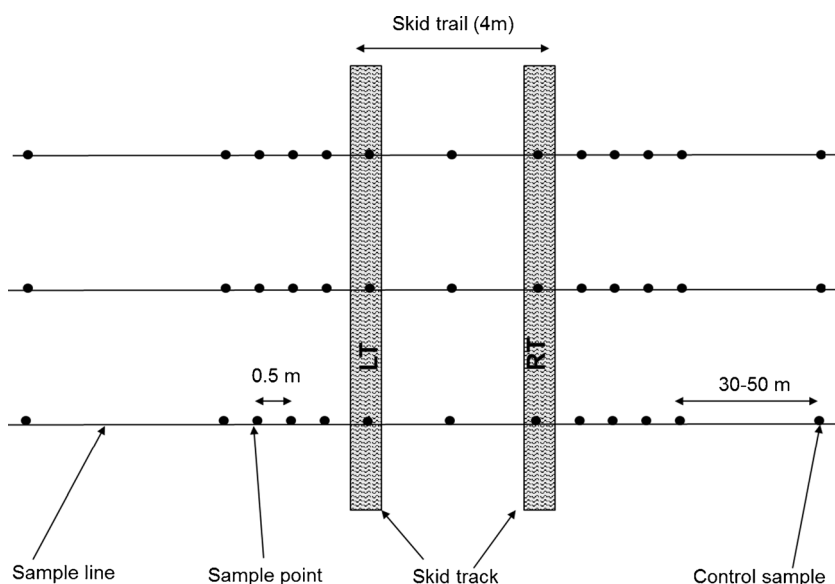
Skid trail (4m)

LT   RT

0.5 m

30-50 m

Sample line   Sample point   Skid track   Control sample

Table 2 Characteristic of sampling plot locations

Block no.	Gradient (%) of block	Block order	Traffic (passes)	Length of block (m)	Elevation (m)
1	19.0	2	40	20.0	878.0
2	6.0	1	40	18.0	886.0
3	29.0	3	40	28.6	906.8
4	16.0	2	20	34.8	915.7
5	27.0	3	20	26.2	947.0
6	9.0	1	20	17.8	971.3

The plots were located at different levels of traffic and slopes on the skid trail. Three slope gradients were present for each traffic intensity segment of each skid trail: gentle slopes in which the slope gradient of the skid trail was between 0 and 10 %, moderate slope was between 10 and 20 % and steep slopes in which the gradient exceeded 20 %

Where MP is macroporosity (%), w_s represents saturated weight (g), w_{dr} specifies the drained weight (g) and v refers to the volume (cm^3). Microporosity was also calculated based on Eq. 3 as follows:

$$MIP = \frac{w_{dr} - w_d}{v} \times 100 \qquad (3)$$

where w_{dr} is drained weight (g), w_d is dry weight (g) and v refers to the volume (cm^3). Void ratio is the volume of voids associated with the unit of the solid and calculated according to Eq. 4 as follows:

$$e = \frac{\rho_s}{DB} - 1 \qquad (4)$$

where e is void ratio, ρ_s is the particle density of the soil (g cm^{-3}) grains and DB is the measured dry bulk density (g cm^{-3}), calculated according to Richard et al. (2001).

2.3 Statistical analysis

To assess the impact of traffic intensity and slope gradient levels on the horizontal compaction rate and extent of soil disturbance along the margin of the skid trail, a series of statistical analyses were made using the SPSS 11.5 statistical package (Zar 1999).

One-way and three-way ANOVA was used to assess the significance of observed differences in average bulk density, total porosity, macroporosity, microporosity and void ratio under different traffic levels, trail slopes, and extent of soil disturbance along the margin of the skid trail and to assess the significance of interaction effects. Duncan's multiple range test (significance test criterion $P \leq 0.05$) was used to determine the significance of differences between average bulk density, total porosity, macroporosity, microporosity and void ratio for different treatments.

3 Results

3.1 Dry bulk density

Following the removal of timber from the experimental plots, assessments were made to understand the impact of load results from timber skidding activities on the topsoil layer at the margin of the skid trail. The average changes in values of DB are shown in Table 3 for the soil's top 10 cm at the different transitional distance zones for both margins of the skid trail for two slope gradients after the 20th and 40th skidding cycles.

The DB values ranged from 0.92 to 0.76 g cm^{-3} at 0.5 and 2-m interval zones, respectively, for slopes greater than 20 % after the 20th skidding cycle. With increases in both skidding pass and slope of skid trail, values of DB were increased; however, with increasing distance from the wheel ruts, these values decreased. The greatest value of DB was found in first 0.5 m interval zone, after 40 skidding passes on slope class >20 %, and reached to 0.99 g cm^{-3} (Table. 3). Table 3 shows that the different load distribution patterns on the soil profile were not homogeneous with increasing distance from the wheel ruts to the adjacent forest. In general, DB values did not show any significant increase with increased distances over 0.5 m for gentle slope classes with two levels of traffic intensity. The results of data analyses confirmed that, regardless of the number of skidding cycles, lowest compaction occurred on the slope gradient treatments <10 % among all distance zones. The increase in DB values in the slope class >20 % for all distance zones ranged from 8.5 to 31.5 % and 30 to 41.4 % after 20th and 40th skidding cycles, respectively, compared to the undisturbed area (Table. 4a, b).

In Fig. 2a, b, DB values are plotted against distance zones following 20 and 40 traffic passes. In the wheel ruts, DB reached a maximum level of 1.2 g cm^{-3} at the soil surface; further into the forest, DB decreased sharply and tended to gradually change in comparison with what occurred in undisturbed areas. These effects were noted for both gentle and medium slope gradient classes within

Table 3 Effect of traffic (20 and 40 passes) and slope (0–10, 10–20 and >20 %) on mean values of bulk density at various distances from skid trail edge

Passage Distance zone (m)	Slope (%)					
	0–10		10–20		>20	
	20	40	20	40	20	40
0.5	0.78aA	0.84aA	0.92bA	0.96bA	0.92bA	0.99bA
1.00	0.71aA	0.79aAB	0.85bB	0.91bA	0.95cA	0.97bA
1.50	0.71aA	0.77aAB	0.82bB	0.89bA	0.89bA	0.94bA
2.00	0.70aA	0.72aB	0.71aC	0.78aB	0.76aB	0.91bA

Dry bulk density was measured as 0.704 g cm^{-3} at the control areas, values are mean and different letters within each treatment shows significant differences ($P < 0.05$)

Capital case letters refer to the comparison made among four distance zones for each skidding cycle and slope class separately (column)

Lower case letters refer to the comparison made among three slope categories at each skidding cycle for the various distance zones (row)

both skidding cycles (Fig. 2a, b). Soil compaction becomes harmful if the bulk density rises more than 15 % compared with the control area. The portion of treatment sites showing more than 15 % increase in bulk density rose dramatically with increasing slope and/or number of skidding passes.

3.2 Total porosity

Total porosity (TP) decreased significantly with an increase in skidding traffic and the slope of the skid trail; the largest decrease occurred after 40 cycles on steep slope treatments (Table 5). The analysis of variance for total porosity produced

similar levels of significance for other sources of variation and interactions, as for the analysis of DB values (Table 5). The analyses of data with increasing distance from the wheel ruts to the margins showed that TP values increased considerably at all distance zones within both skidding cycles (Table 5). Decreases in TP values were significant up to the 1 m interval zone after 20 skidding cycles, while significant declines were found in these values up to the 2 m interval zones, compared with the undisturbed areas, after 40 skidding cycles at all slope gradient classes. Decreases in TP values after 20 and 40 skidding cycles ranged from 0.5 to 11.7 % and 4.2 to 18.7 %, respectively, for slope gradients >20 % at all distance zones, compared to the undisturbed area

Table 4 Average changes in soil physical properties (%) compared to undisturbed area following 20 (a) and 40 (b) skidding passes for various distance from edge of skid trail and slopes categories

(a)

Slope (%)

Distance zone (m)	0–10					10–20					>20				
	DB	TP	MP	MIP	VR	DB	TP	MP	MIP	VR	DB	TP	MP	MIP	VR
0.5	11.4	−4.2	−19.1	12.6	−12.7	31.4	−7.6	−28.7	16.4	−22.1	31.4	−11.8	−41.8	22.3	−31.9
1.00	1.4	−0.9	−3.6	2.0	−1. 5	21.4	−5. 5	−14.4	5.7	−14.5	35.7	−5.0	−14.0	5.2	−23.6
1.50	1.4	−0.7	−2.3	1.1	−0.7	17.1	−3.9	−11.0	4.27	−11.6	26.1	−2.8	−7.7	2.8	−19.9
2.00	0.0	−0.5	−1.6	0.6	0.0	1.4	−1.1	−1.0	−1.4	−2.2	8.5	−0.8	−2.1	0.7	−1.5

(b)

Slope (%)

Distance (m)	0–10					10–20					>20				
	DB	TP	MP	MIP	VR	DB	TP	MP	MIP	VR	DB	TP	MP	MIP	VR
0.5	20.0	−13.4	−58.6	38.1	−35.9	37.1	−17.0	−68.7	40.5	−32.3	41.4	−18.7	−76.7	50.2	−39.5
1.00	12.9	−11.3	−47.1	29.7	−31.2	30.0	−8.9	−44.1	31.2	−35.1	38.6	−15.4	−62.3	38.1	−37.7
1.50	10.0	−5.9	−20.2	10.4	−28.3	27.1	−7.1	−17.6	4.9	−27.9	34.3	−14.5	−54.8	30.6	−34.1
2.00	2.9	−4.2	−14.3	7.1	−12.7	11.4	−5.4	−11.8	1.7	−10.5	30.0	−11.5	−43.0	24.4	−30.4

Fig 2 **a** Mean ± Std.Error of bulk
density in skid trails for different
slope gradient classes with
different distance zones from
wheel rut into the forest following
20 skidding passes. Different
letters indicate statistically
significant differences among
different zones for each slope
gradient class. **b** Mean ± Std.Error
of bulk density in skid trails for
different slope gradient classes
with different distance zones from
wheel rut into the forest following
40 skidding passes. Different
letters indicate statistically
significant differences among
different zones for each slop
gradient class separately
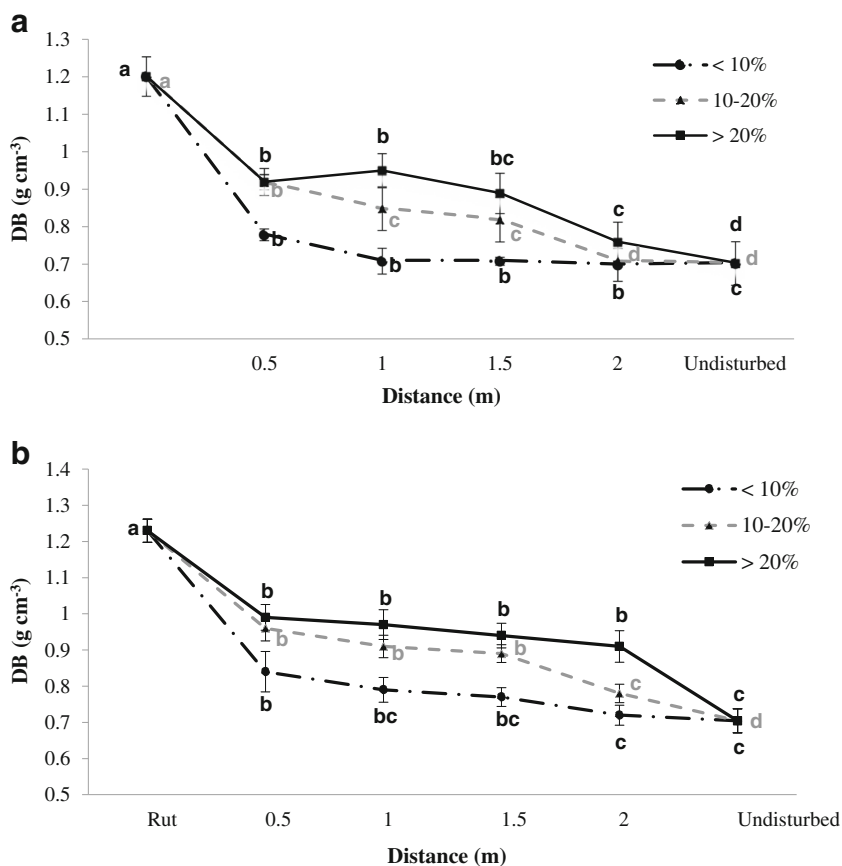
(Table 4). The differences in TP values were less than for
bulk density, which most likely indicates that macroporosity
was less variable than bulk density (Table 4).

3.3 Macroporosity

The relative quantity of coarse pores (>50 μm) was signifi-
cantly decreased by traffic intensity and slope gradient

(Table 6). In general, the control area had the highest amount
of coarse pores. The largest effect of skidding activities on MP
values occurred within the first 0.5 m interval to the wheel rut
after 40 passes, where the slope gradient was greater than
20 %. The means of MP value increased with an increase in
distance from the wheel ruts to the transitional zones in the
uppermost layer after being subjected to traffic (Table 6).
Table 4 summarizes the percentage differences in MP values

Table 5 Mean values of total
porosity as influenced by traffic
(20 and 40 passes) and slope (0–
10, 10–20 and >20 %) at different
distances from skid trail edge

Passage Distance zone (m)	Slope (%)					
	0–10		10–20		>20	
	20	40	20	40	20	40
0.5	70.70aB	68.20aC	65.15bC	63.92bC	61.26cC	60.00cC
1.00	73.11aA	70.11aB	70.12bB	65.50bB	67.28cB	62.50cB
1.50	73.29aA	71.00aB	71.74abAB	69.51aA	68.63bAB	63.11bB
2.00	73.44aA	73.01aA	73.22aA	70.74bA	69.85bA	65.32cA

Total porosity was measured as 73.84 % for the control area, values are mean and different letters within each
treatment shows significant differences ($P < 0.05$)

Capital case letters refer to the comparison made among four distance zones for each skidding cycle and slope
class separately (column)

Lower case letters refer to the comparison made among three slope categories at each skidding cycle for the
various distance zones (row)

Table 6 Effect of traffic (20 and 40 passes) and slope (0–10, 10–20 and >20 %) on soil disturbance estimated by mean values of macroporosity at various different distances

Passage	Slope (%)					
	0–10		10–20		>20	
Distance zone (m)	20	40	20	40	20	40
0.5	31.80aB	28.05aC	22.90bD	16.27bD	12.30cD	9.15cD
1.00	37.90aA	33.65aB	33.80bC	20.79bC	22.00cC	14.83cC
1.50	38.40aA	34.99aB	36.30abB	31.38bB	32.40bB	18.02cB
2.00	38.70aA	38.91aA	38.50aA	33.70bA	34.70bA	22.40cA

Macroporosity was measured as 39.32 % for the control area. Values are mean. Different letters within each treatment shows significant differences ($P < 0.05$)

Capital case letters refer to the comparison made among four distance zones for each skidding cycle and slope class separately (column)

Lower case letters refer to the comparison made among three slope categories at each skidding cycle for the various distance zones (row)

among the distance treatments compared to the undisturbed state. Macroporosity was very low throughout the study area, especially on medium and steep slope gradients for the first distance interval. The MP in the first zone on a steep slope treatment following 40 skidding cycles was measured as 9.1 % in the topsoil layer, which is commonly regarded as a critical level for soil aeration. Table 6 shows that a significant decrease in MP values continued up to a 2-m distance zone for a slope gradient >20 % for both skidding cycles intensities.

3.4 Microporosity

Changes in microporosity (MIP) values as the result of an increase in compaction were relatively minor for slope treatments <10 % from the wheel ruts into the transitional zones (Table 7). However, the biggest changes in MIP values were present for slope gradients >20 % at all distance zones following 40 skidding cycles. According to the results, when DB

increased, the rate of MP significantly decreased and parallel to this, MIP volumes significantly increased (Table 4). These results were significant for slopes with a gradient >20 % and up to 1 and 2 m distance zones from the wheel ruts, after the 20th and 40th skidding cycles, respectively. The percentage changes in MIP values among the distance treatments compared to the undisturbed area is presented in Table 4. The most significant changes in MIP values were by about 22.3 and 50.2 %, which was related to the first 0.5 m interval for slopes where the gradient was greater than 20 % and measured for the two traffic intensities, respectively (Table 4).

3.5 Void ratio

Changes in the mean values of void ratio (VR) were measured as significant with an increase in traffic intensity and slope gradient on the margins of the skid trail (Table 8). The greatest reduction in mean values for VR value occurred in the first

Table 7 Mean values of microporosity influenced by traffic (20 and 40 passes) and slope (0–10, 10–20 and >20 %) at various distances

Passage	Slope (%)					
	0–10		10–20		>20	
Distance zone (m)	20	40	20	40	20	40
0.5	38.86cA	40.19cA	42.22bA	47.67bA	48.51aA	51.85aA
1.00	35.21bB	36.48cB	36.33bB	44.76bB	45.28aB	47.68aB
1.50	34.90aB	35.97cB	35.48aBC	38.11bC	36.22aC	45.09aC
2.00	34.72aB	34.05cC	34.7aC	36.97bC	35.11aC	42.94aD

Microporosity was measured as 34.52 % for the control area. Values are mean. Different letters within each treatment shows significant differences ($P < 0.05$)

Capital case letters refer to the comparison made among four distance zones for each skidding cycle and slope class separately (column)

Lower case letters refer to the comparison made between two slope categories at each skidding cycle for the various distance zones (row)

0.5 m interval for a slope gradient >20 % following 40 skidding cycles (Table 8). Table 8 shows that the greatest reduction in VR was concentrated on steep slopes, rather than the gentle slopes, so that these values were significantly different up to 1.5 and 2 m interval zones for a slope gradient >20 % after 20 and 40 skidding passes, respectively. The lowest value of VR values was recorded in medium and steep slope gradients after 40 skidding passes (Table 4).

4 Discussion

4.1 Dry bulk density

The spatial patterns of variable traffic intensities and slope gradients were closely reflected by changes in the soil physical properties in the margin of the skid trail shortly following harvest operations. The study of the area of contact between the soil and the skidder tyres revealed that traffic intensity and slope gradient considerably influenced soil characteristics up to a distance of 2 m from the wheel ruts in both transitional zones.

Results showed that maximum compaction expressed as DB occurred within 1 m from the wheel ruts and declined with increasing distance as the total pressure was spread out over the area, compared to results from the undisturbed areas (Fig. 2a, b). This supports results published by Williamson and Neilsen (2000), Defossez and Richard (2002) and Ampoorter et al. (2007). A decrease in compaction with increasing distance from the machine footprint area can be characterized in terms of two parameters: cohesiveness, the bonding of soil particles and the angle of internal friction, which is the resistance of movement between soil particles (Greacen and Sand 1980, cited by Wood et al. 2003).

An increase in slope gradient and traffic intensity caused increased compaction up to 1.5 m intervals from the wheel ruts after 20 skidding cycles. This was most pronounced for slopes greater than 20 %, up to 2 m into the forest, following 40 skidding cycles. The DB values increased in terms of percentage in three slope gradients measured as gentle, medium and steep by about 11.4, 31.4 and 31.4 %, respectively, following 20 skidding cycles, whereas these values were 20, 37.1 and 41.4 %, respectively, for the first 0.5 m interval following 40 skidding cycles, when compared to the undisturbed areas (Table 4). The data suggested that disturbances increased in extent with an increase in slope gradient. As can be seen in Table 3, soil compaction in steep slope areas was between about two and three times greater than in the gentle slope area following 20 and 40 skidding cycles for the first 0.5 m interval, compared with the undisturbed areas. These findings are in accordance with the results of Najafi et al. (2010), who reported skid trail disturbance twice as high on steep slopes (>20 %) than on more gentle slopes (<20 %).

4.2 Porosity

The increments in DB values were translated as a decrease in soil porosity. It is likely that the increase in density took place at the expense of the macroporosity volume. One explanation for this happening with increasing soil compaction, specifically in the top layer of soil is because soil particles are rearranged and the continuity of pore spaces of both micro- and macro-pores may collapse. Decreases in macroporosity (MP) can cause poor aeration, reduce permeability to water and inhibit gaseous exchange between soil and air (Greacen and Sands 1980, Rab 1994; Ezzati et al. 2012). Additionally, an increase in DB is restricted by the MP remaining in the soil matrix at the nearest zone to the machine's footprint area after being subjected to traffic (Table 6). Under these conditions, further decreases in soil volume as a result of remaining in a steady state of compaction are not possible. This might be ascribed to residual soil air in micro-voids (Williamson and Neilsen 2000). Soil compaction

Table. 8 Mean values of void ratio in different distance zone from the edge of skid trail. Void ratio were measured following 20 and 40 passes on the plots where were established at three different slope classes.

Passage Distance zone (m)	Slope (%)					
	0-10		10-20		>20	
	20	40	20	40	20	40
0.5	2.41cA	2.15cA	1.88bA	1.77bA	1.87aA	1.67aA
1.00	2.72cB	2.36cB	2.11bB	1.90bB	1.79aB	1.72aB
1.50	2.74cC	2.44cC	2.21bC	1.98bC	1.99aC	1.82aC
2.00	2.76cC	2.70cC	2.72bC	2.41bC	2.47aC	1.92aC

Note; void ratio was measured 2.76 for the control area. Values are mean. Different letters within each treatment shows significant differences (P < 0.05)

Capital case letters refer to the comparison made among four distance zones for each skidding cycle and slope class separately (column)

Lower case letters refer to the comparison made between two slope categories at each skidding cycle for the various distance zones (row)

produced by forest vehicles significantly reduced the soil's total porosity and aeration porosity, while increasing its microporosity; this result was found for all of our treatments involving an increase in compaction stress (Tables 4 and 7). These findings are in line with the results of Startsev and McNabb (2001), who reported that during compaction, micropores may be unaffected and soil porosity changes could be confined to the mesopore space. In general, it can be noted that porosity is inversely related to bulk density and the decrease in mean porosity is likely to be a result of the increase in mean bulk density following the harvest (Rab 2004; Williamson and Neilsen 2000).

A macroporosity of at least 10 % is a critical level. Any changes from normal state to a state approaching 10 % is likely to have some impact on root proliferation and saturation hydraulic conductivity and in turn forest regrowth. Table 6 infers that, except for the slope >20 % within the first 0.5 m interval after 40 skidding cycles, all values of MP were above the critical level; thus, root proliferation and saturated hydraulic conductivity may not have been affected (Rab 2004).

The changes in MP values are only significant up to 1.5 m distance from wheel rut for slope gradients >20 % after 20 and 40 skidding passes. Changes in the margin soil's physical properties are to be expected in response to heavy machine traffic, due to reductions in soil volume and the closer proximity of soil particles. The net result of the closely packed soil particles and aggregates will be a loss of large-diameter soil pores, which are essential in the transmission of air and water; however, an increase will occur in small diameter capillary pores, which are necessary for water storage (Kooistra 1994). This change in porosity, reflected by increasing DB values and decreasing TP, MP and VR, is commonly observed in studies of traffic impact and soil compaction. During the passage of wheeled machines, existing voids are reduced in size and changed in shape and may become deformed, disrupted, closed or disappear completely (Kooistra 1994).

5 Conclusion

Although soil disturbance resulting from logging operations in different traffic intensity and slope gradient classes has been extensively studied in the last three decades, the horizontal and vertical distribution of disturbance has received less concern so far, especially in mountainous forested ecosystems. The extent and distribution of soil disturbance after skidding operations shows that pressure of harvesting vehicles can be distributed horizontally at the soil surface at least 2 m distance from the wheel ruts although, the current experimental design (limit of 2 m) does not fully explore the extent of the impacts along the margins. Soil bulk density and macroporosity reached their maximum levels on a slope greater than 20 %

after 40 skidding passes. However, after the first 0.5 m interval zone, changes in soil properties significantly declined with an increase in distance, compared with the undisturbed areas. The information obtained in this study may be useful for managers attempting to carry out timber harvesting in an efficient manner, while still meeting environmental standards. The research can be improved by future studies on the vertical distribution of soil disturbance (subsoil) and impact of these processes on rooting of vegetation and microbial activities of soil fauna at different slope gradients, traffic intensities and skid trail directions after completing timber harvest operations in steep-slope terrains. The adverse effects of soil disturbance and in some instances the degree of disturbance can be controlled by imposing management constraints, such as limiting operations on steeply sloped areas with greater than 20 % gradients, reducing tyre pressure to the minimum allowable weight, installing larger diameter tyres to increase the length of the machine footprint, and increasing the number of axles, and decreasing the number of equipment passes.

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