Combined Effects of Skidding Direction, Skid Trail Slope and Traffic Frequency on Soil Disturbance in North Mountainous Forest of Iran

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Abstract

Harvest traffic with heavy equipment causes damage to forest soils. Whereas increased soil damage has been reported with increasing harvest equipment traffic and on increasing slope gradients, it is unclear how much soil damage is caused by different directions of skidding. We examined the effects of traffic frequency, skid trail slope and skidding direction on the dry bulk density and total porosity of skidding trail soil in an Iranian temperate forest. The studied treatments included combinations of three different traffic frequencies (3, 7, and 12 passes of a rubber-tired skidder), three levels of slope (<10%, 10–20% and >20%) and two skidding directions (uphill and downhill). The impact on soil properties was greatest during the skidder initial passes. On steep slopes, only three skidder passes were required to cause substantial increases in soil bulk density relative to control plots, regardless of skidding direction. Independently of the traffic frequency and trail slope, uphill skidding caused substantially greater increases in dry bulk density and greater decreases in soil porosity than did downhill skidding. Total porosity was significantly lower on steep slopes than on gentle slopes regardless of traffic intensity and skidding direction. In general, fewer uphill skidder passes were required to achieve substantial soil disturbance than was the case for downhill skidding, possibly because skidders move more slowly when travelling upwards and uphill skidding places greater loads on the skidder rear axle.

Keywords: bulk density, downhill skidding, soil compaction, total porosity, uphill skidding

1. Introduction

Forest operations involving heavy machinery and animals may have negative effects on the remaining stand (Jourgholami and Majnounian 2013, Wang 1997). Some of the most common adverse impacts relate to the degradation of soil properties. Forest soils are susceptible to compaction because they are loose with a high organic matter content and are generally low in bulk density, high in porosity, and low in strength (Froehlich et al. 1985, Solgi et al. 2015a). Increased soil compaction and decreased soil porosity can reduce site productivity (McMahon 1995, Najafi and Solgi 2010). Consequently, soil compaction caused by logging activities can adversely affect the future regeneration and growth of trees (Sakai et al. 2008).

The degree of soil compaction is influenced by several factors including site and soil characteristics (Ampoorter et al. 2007), soil moisture (Greacen and Sands 1980, Jakobsen and Greacen 1985, Naghdi and Solgi 2014), harvesting system (Han et al. 2009, Jamshidi et al. 2008, Warkotsch et al. 1994) and type of equipment used (Greacen and Sands 1980), amount of slash (Gerasimov and Katarov 2010, McDonald and Seixas 1997), number of machine passes (Naghdi et al. 2007), properties of tires used on forest machines and harvesting vehicles (Sakai et al. 2008), and pressure applied to the soil (Eliasson 2005). It is, therefore, important for forest managers to understand how these factors interact, so that they can organize their operations in a way that will minimize soil disturbance (Demir et al. 2007, Sakai et al. 2008, Naghdi and Solgi 2014, Solgi and Najafi 2014).

Soil compaction is an unavoidable consequence of skidding operations, and can vary in intensity and distribution (Solgi et al. 2015b). Most of the physical soil disturbance caused during forest management activities is directly attributable to the movement of heavy equipment. Consequently, the impact of machine traffic on soil compaction has been studied in some detail. Traffic intensity plays an important role in soil compaction because deformations can increase with the number of passes, which may lead to excessive soil disturbance (Naghdi et al. 2007, Solgi et al. 2015a). In addition, slope steepness reportedly has a strong effect on soil disturbance during timber harvesting (Krag et al. 1986). During skidding on a terrain trail, a vehicle's weight (and that of its load) will be distributed unevenly across its axles, with the rear axle typically being most heavily weighted. Najafi et al. (2009) reported that both the magnitude (extent) and depth of soil disturbance increased with the slope of the trail because of this effect. Finally, the direction of machine traffic (i.e. uphill vs. downhill) can modify the impact of vehicle traffic on the soil. Jourgholami et al. (2014a) concluded that the direction of forwarding had an effect on soil compaction. However, the effects of skidding direction on soil disturbance have received less attention than other aspects of machine traffic.

A goal of forest managers is to minimize the negative impacts of vehicular passes during harvesting, especially because the effects of disturbance can persist for decades (Rab 2004). Estimation of the extent of disturbance from different direction of skidding is critical for selecting the best direction to minimize the negative impacts, especially in developing countries, where limited financial capacity prohibits the purchase of more modern and sophisticated equipment (Nikooy et al. 2013).

The aim of this study is to fill this need by examining the impact of skidding direction (i.e. uphill vs. downhill) on soil physical properties on the skid trail in a mountainous beech stand of Iran. Our working hypothesis was that soil disturbance would increase with changing skidding direction from downhill to uphill skidding.

Table 1 Soil texture classes at a depth of 0–10 cm for skid trails. The range of particle size was <0.002, 0.002–0.05 and 0.05–2 mm for clay, silt, and sand, respectively

Soil particle size distributions, g 100 g^{-1}			Soil texture
Clay	Silt	Sand	
28	39	33	Clay loam

2. Materials and Methods

2.1. Site description

The research was conducted during August 2014 in Shenrood forest, Guilan province, northern Iran between 36°13′N and 36°15′N and 53°10′E and 53°15′E (Fig. 1). The area is predominantly covered by oriental beech (*Fagus orientalis* Lipsky) stand. The canopy cover, mean diameter, mean height and stand density were 80%, 29.72 cm, 22.94 m and 170 trees ha^{-1}, respectively. The soil class of our study area was classified as Cambisol according to the World Reference Base (WRB). The texture of the soil along the studied skid trail was classified as clay-loam on the basis of a particle size analysis using the Bouyoucos hydrometer method (Kalra and Maynard 1991). The description of the soil size distribution in skid trail is presented in Table 1. The average depth of soil to the bedrock was 70 cm. 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 capacities and thus are susceptible to intense run-off and erosion. The study area has an elevation of approximately 800 m above sea level and a northerly aspect. The average annual rainfall recorded at the closest national weather station, located 20 km from the research area, was 860 mm. The maximum mean monthly rainfall of 120 mm usually occurs in October, while the minimum rainfall of 25 mm occurs in August. The mean annual temperature is 15 °C, with the lowest values occurring in February. At the time of skidding, the weather conditions were dry and warm, and the average gravimetric soil moisture content was 21%. The soil had not been driven on before the study began.

2.2. Forest operations and machine specifications

At the study site, a combination of group selection and single tree selection silvicultural treatments were performed. In the Hyrcanian forests, harvesting and silvicultural operations are most common in autumn and winter, while log extraction is usually completed during the spring and summer period. Harvesting operations were carried out motor-manually, using chainsaw and axes (especially in thinning operations) for the tree-felling and processing. The logs were later transported from the forest stand to the roadside by means of a 4WD Timberjack 450C rubber-tired skidder which has an unloaded weight of 10.3 tons with 55% of the axle weight on the front axle and 45% on the rear axle. This model is the most common machine used for mechanized forest operations throughout northern

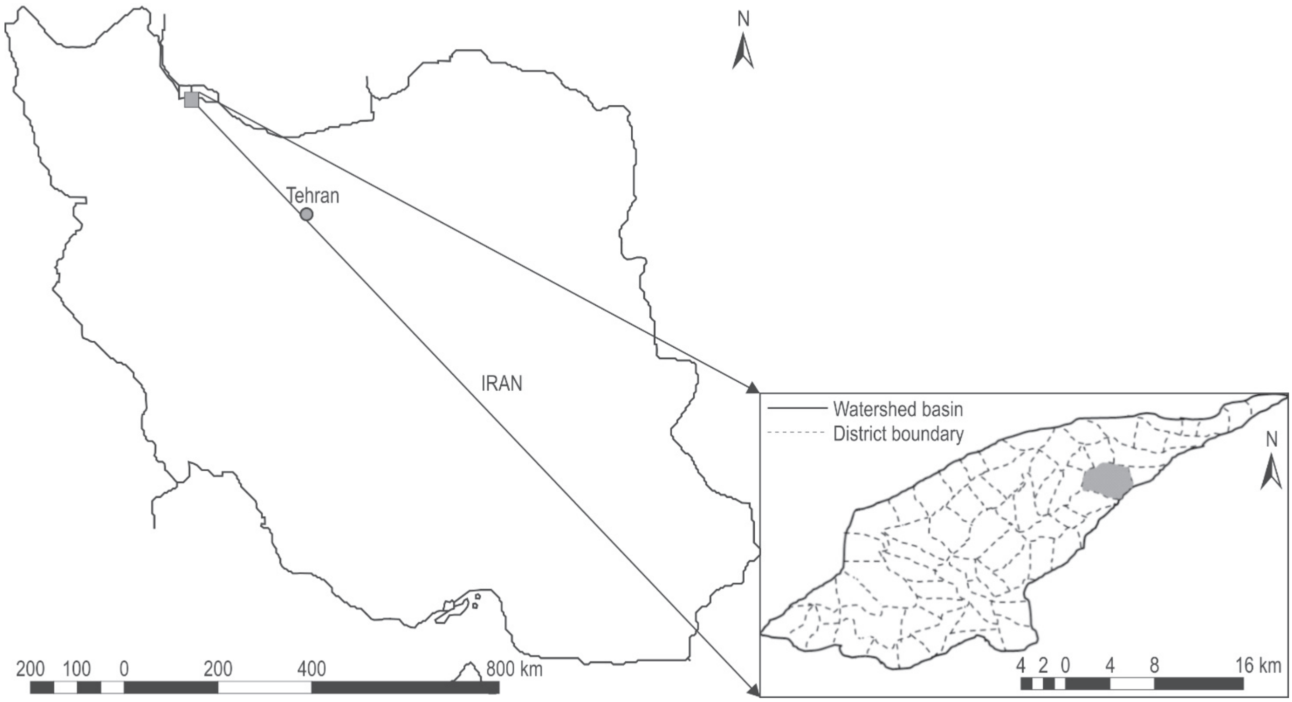

Fig. 1 Location of study area

Fig. 2 Rubber-tired skidder (Timberjack 450C) used in logging operations in a mountain forest of Iran

Table 2 Technical details of the Timber jack 450C rubber-tired cable skidder

Specifications	Timberjack 450C
Empty weight, kg	10,257
Number of wheels	4
Front tyres	24.5–32
Rear tyres	24.5–32
Average ground pressure, kPa	220
Engine power, kW	132
Manufacturing year	1998
Manufacturing location	Canada

Iran (Nikooy et al. 2013). The skidder was equipped with the engine model 6BTA5.9 (engine power of 132 kW) and was fitted with tires with the size of 24.5–32 inflated to 220 kPa (Fig. 2 and Table 2).

2.3. Experimental design and data collection

The effects of the number of skidder passes, skid trail slope and direction of skidding on soil properties were determined along a skidding trail and in undisturbed areas. A skid trail was selected with a longitudinal slope steepness ranging from 0 to 32% and no lateral slope. For the purposes of our study, the skidder, always loaded to its maximum load capacity, was used to extract 3 to 4 m long logs on this skid trail.

With regard to the longitudinal profile and maximum gradient of the skid trail, three slope classes were considered (<10%, 10–20%, and >20%). The slope class <10% included trail sections that ranged from 3–7% in gradient, gradient 10–20% contained a section within the range of 13–16%, whereas gradient class >20% contained sections within the range of 24–28%. Traffic frequencies of the loaded skidder were three passes for light traffic, seven passes for moderate traffic, and 12 passes for heavy traffic sections. Therefore, treatment plots included the combination of two levels of skidding direction, three levels of trail slope, and three levels of traffic frequency, thus forming 18 combinations of skidding direction, traffic frequency, and slope classes and each treatment was replicated twice (for a total of three tests), thus totaling 54 sample plots. Moreover, for control purposes, soil samples were taken from undisturbed areas that were not affected by skidding and at least 50–60 m (approximately 2 to 3 tree lengths) away from the skid trail to reduce side impacts. In total, 66 soil sampling plots were established: 12 control plots and 54 sample plots. Each plot measured 10 m long by 4 m wide, with a 5 m buffer zone between plots to avoid interactions (Fig. 3). In each plot, four sampling lines were drawn extending across the plot width, perpendicular to the skidder direction of travel, with 2 m buffer zones between the lines in order to avoid interactions. Three samples of 0–10 cm soil were collected at different points along each such line, one from the skidder left-hand wheel track (LWT), one between the wheel tracks (BWT), and one from the right-hand wheel track (RWT).

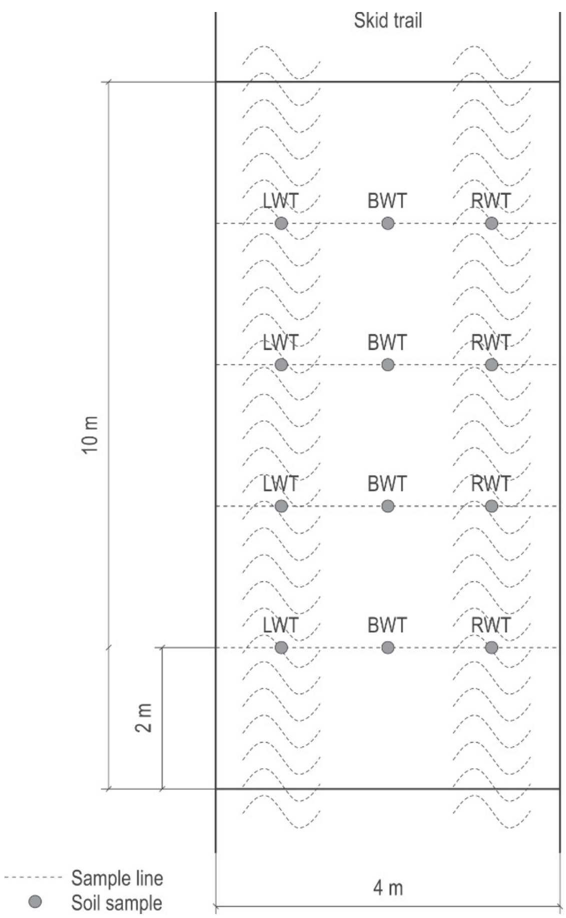

Fig. 3 Layout of an experimental plot

Soil samples weighing on average 310 g were collected with a soil hammer and rings (inside diameter 5 cm, length 10 cm). Samples were then placed in polyethylene bags, sealed, labeled, and transported to the laboratory, where they were promptly weighed to obtain wet mass. Soil samples were dried in an oven under 105°C until constant mass. Their moisture content was determined gravimetrically after drying (Kalra and Maynard 1991).

Total porosity was calculated using Eq. (1):

$$AP = (1 - D_b / 2.5) \quad (1)$$

Where:

AP total apparent porosity

D_b soil bulk density, and 2.65 (g cm^{-3}) is particle density.

Soil bulk density was calculated using Eq. (2):

$$D_b = W_d / VC \quad (2)$$

Where:

W_d weight of dry soil

VC volume of soil cores (196.25 cm^3).

2.4. Statistical Analysis

One-way and three-way ANOVA was used to assess the significance of observed differences in average bulk density and total porosity under different traffic levels, trail slopes, and directions of skidding, and to assess the significance of interaction effects. Tukey's *HSD* test was used to determine the significance of differences between average bulk densities and total porosities for different treatments (Zar 1999). All statistical calculations were performed using SPSS version 11.5.

3. Results

Soil bulk density and total porosity were measured as 0.69 g.cm^{-3} and 73%, respectively, and soil texture was found to be Clay-Loam along the general harvesting area (Table 1).

3.1. Dry bulk density

Following skidding, soil bulk density increased to 0.84–1.52 g cm^{-3} and was significantly affected by skid-

Table 3 Effects of skidding direction, skid trail slope and traffic frequency in the north mountainous forest of Iran. Analysis of variance (*P* values) of the effects of number of passes (NP), slope gradient (SG) and skidding direction (SD) class on dry bulk density and total porosity

Source of variable	*p* values	
	Dry bulk density	Total porosity
NP	≤0.005	≤0.005
SG	≤0.005	≤0.005
SD	≤0.005	≤0.005
NP×SG	0.476	0.815
NP×SD	≤0.005	≤0.005
SG×SD	≤0.005	0.413
NP×SG×SD	0.517	≤0.005

**p* values less than 0.05 are given in bold; variable interactions are denoted with »x«

ding direction, traffic intensity, slope gradient, the interaction of skidding direction × slope gradient, and skidding direction × traffic intensity (Table 3). The average soil bulk density in the undisturbed area was 0.69 g cm^{-3}, while that on the skid trail ranged from 0.95 g cm^{-3} (for 3 passes and a slope of <10%) to 1.52 g cm^{-3} (12 passes and a slope of >20%) for uphill skidding. The values observed for sites subjected to downhill skidding were lower, ranging from 0.84 g cm^{-3} (3 passes and a slope of <10%) to 1.45 g cm^{-3} (12 passes and a slope of >20%) (Table 4). Regardless of skidding direction, dry bulk density increased consistently with increasing traffic intensity on all slope gradients (Table 4) and with increasing slope gradient at all traffic intensities (Fig. 4).

Heavy traffic on slope gradients over 20% resulted in the highest dry bulk densities for both directions of skidding. Heavy traffic on slope gradients <10% resulted in dry bulk densities similar to those after moderate traffic on steeper slopes. Similarly, moderate traffic on slope gradients <10% resulted in bulk density values similar to those after light traffic on steeper slopes.

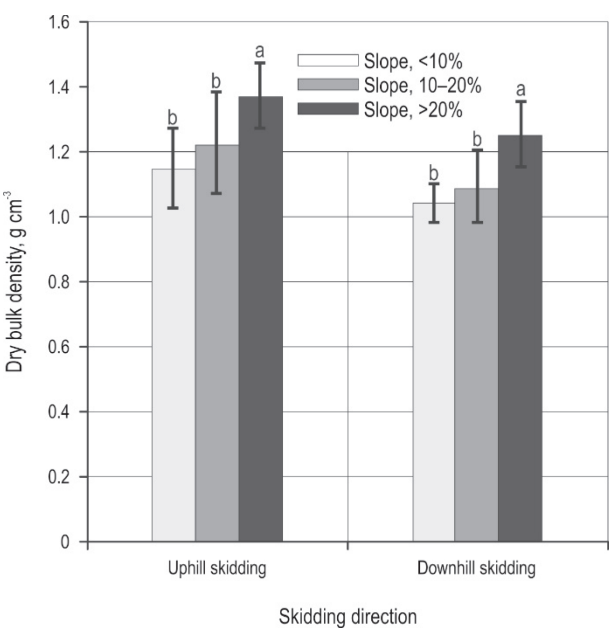

Fig. 4 Effect of skid trail slope on dry bulk density

Table 4 Effect of skidder passes on dry bulk density (g cm^{-3})

Skidding direction	Number of passes	Slope, %		
		(0–10)	(10–20)	(>20)
Uphill	3	0.95^{c}	1.03^{c}	1.22^{c}
	7	1.17^{b}	1.26^{b}	1.38^{b}
	12	1.33^{a}	1.39^{a}	1.52^{a}
Downhill	3	0.84^{c}	0.89^{c}	1.07^{c}
	7	1.04^{b}	1.11^{b}	1.25^{b}
	12	1.25^{a}	1.28^{a}	1.45^{a}

The majority of soil compaction along the skidding trail occurred during the skidder first few passes: the bulk density of the soil after the first three skidder passes was substantially greater than in control plots, regardless of slope steepness or skidding direction (Table 5).

Table 5 Dry bulk density increase (%) per skidding direction and slope gradient class compared to the previous traffic intensity level

Skidding direction	Number of passes	Slope, %		
		(0–10)	(10–20)	(>20)
Uphill	3	37.7	8.4	17.9
	7	69.6	7.7	7.5
	12	92.7	4.5	6.7
Downhill	3	21.7	5.9	20.2
	7	73.5	6.7	12.6
	12	81.2	2.4	10.4

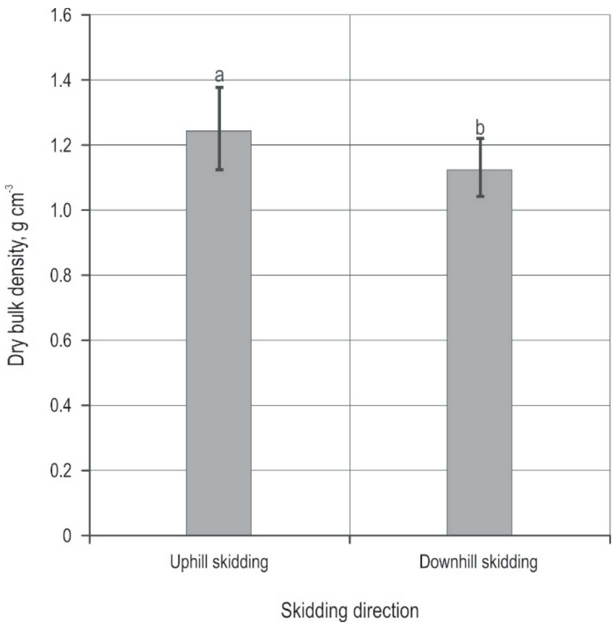

Fig. 5 Average bulk densities of skid trail sections with different skidding directions

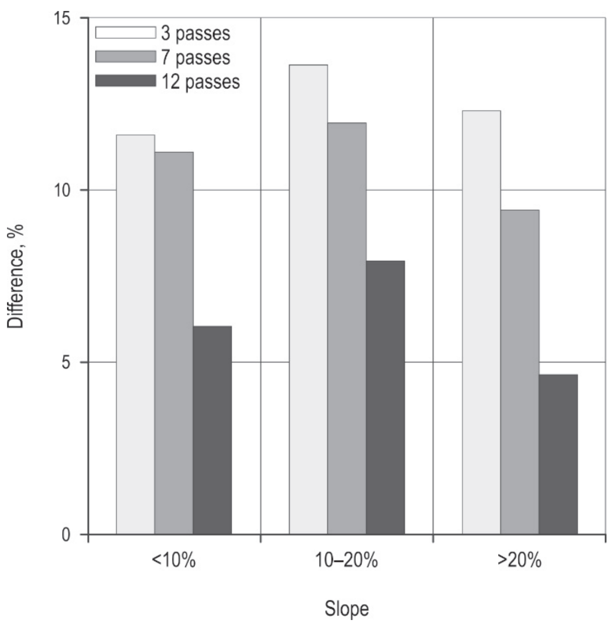

Fig. 6 Differences in soil bulk density between trail sections with similar slopes used for uphill and downhill skidding at the same traffic frequency

For all numbers of skidder passes and trail slopes, the dry bulk density increase due to uphill skidding was considerably greater than that caused by downhill skidding (Fig. 5).

This indicates that the direction of skidding during field operations has important effects on compaction. However, the difference in bulk density between the two directions of skidding decreased as the number of passes increased (Fig. 6).

3.2. Total porosity

Average total porosity was significant related to skidding direction, traffic intensity, slope gradient, the interaction of skidding direction × traffic intensity, and the interaction of all three factors (Table 3). The average total soil porosity was 73% on the undisturbed area but on the skid trail it ranged from 42% (after 12 passes on a slope of >20%) to 62% (after 3 passes on a slope of <10%) for uphill skidding. Downhill skidding produced slightly higher total porosity values than uphill skidding, ranging from 44% (after 12 passes on a slope of >20%) to 66% (after 3 passes on a slope of <10%) (Table 6).

Table 6 Effect of skidder pass numbers on total porosity (%)

Skidding direction	Number of passes	Slope, %		
		(0–10)	(10–20)	(>20)
Uphill	3	62.35^{a}	59.35^{a}	53.94^{a}
	7	55.62^{ab}	53.41^{ab}	48.51^{ab}
	12	49.34^{b}	48.63^{b}	42.81^{b}
Downhill	3	66.54^{a}	65.82^{a}	58.54^{a}
	7	59.42^{ab}	54.19^{ab}	52.86^{ab}
	12	53.27^{b}	53.04^{b}	44.13^{b}

Regardless of skidding direction, total porosity decreased consistently with increasing traffic intensity on all slope gradients and with increasing slope gradient at all traffic intensities (Table 6 and Fig. 7). Heavy traffic on slope gradients over 20% resulted in the lowest total porosity for both skidding directions. Heavy traffic on slope gradients <20% resulted in total porosity values similar to those after moderate traffic on steeper slopes. Similarly, moderate traffic on slope gradients <20% resulted in total porosity values similar to those after light traffic on steeper slopes. Regardless of skidding direction, the initial passes decreased total porosity the most; subsequent passes resulted in relative decreases that were more modest, particularly on steeper slopes (Fig. 6).

In addition, the total porosity of trail sections subjected to uphill skidding was significantly lower than

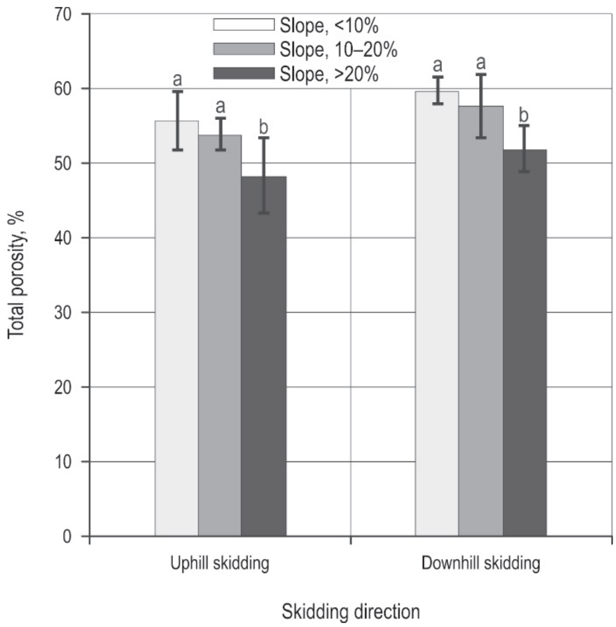

Fig. 7 Effect of slope on average total porosity

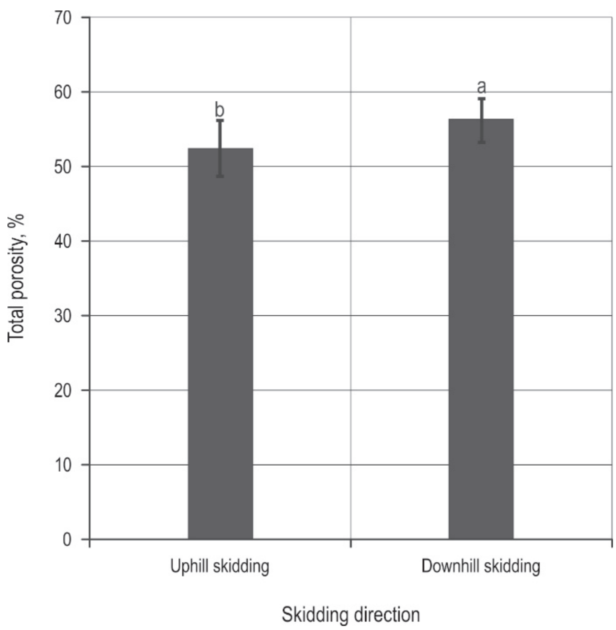

Fig. 8 Average total porosities of skid trails with different skidding directions

that of otherwise equivalent sections subjected to downhill skidding (Fig. 8).

4. Discussion

Compaction of the soil increases bulk density, reduces soil porosity, decreases infiltration rates, and lowers soil permeability (Froehlich et al. 1981). It has been well established that these changes in soil physical properties increase surface runoff and erosion, and create less-favorable soil environments for plant growth (Greacen and Sands 1980, Solgi et al. 2014). Careful planning of landing locations and skid trail systems before logging commences is intended to reduce damage to the soil and the residual stand.

The dry bulk density of trail sections used for uphill skidding was substantially higher than that for sections used for downhill skidding. The greater compaction caused by uphill skidding can be explained by the greater load on the skidder rear axle (Najafi et al. 2009, Jamshidi et al. 2008, Solgi et al. 2015b). In sections subjected to uphill skidding, steeper slopes were associated with higher bulk densities and lower total porosities, possibly because of the skidder lower speed when climbing steeper slopes. Jourgholami et al. (2014b) reported that differences in levels of compaction between uphill and downhill forwarding may be due to an uneven distribution of the load between the skidder axles or increased wheel slippage and vibration during upslope forwarding relative to downslope forwarding.

Soil compaction was also affected by trail slope, with dry bulk density increasing faster at higher slope levels. This is consistent with previous findings (Jamshidi et al. 2008, Solgi et al. 2013) and can be attributed to the difficulty of operating a skidder on steep terrain, which causes the machine to slip continuously and spend relatively long periods of time in each trail section, puddling and dragging the soil (Gayoso and Iroume 1991). When a skidder moves slowly on a steep slope, the top soil is more extensively vibrated and, therefore, more heavily disturbed than would be the case in a flatter area (Naghdi and Solgi 2014).

For downhill skidding, the dry bulk density increased with slope steepness independently of the traffic frequency. This may be because machines are driven more slowly on steeper trails for reasons of safety and to minimize the risk of accidents.

As shown in Table 5, the bulk density of the skidding trail soil is substantially greater than that in the control plots, even when only three skidder passes have been made. This is broadly consistent with the results of Ampoorter et al. (2007), who reported that more than half the total impact of skidding occurs after only three passes have been made and that further increases in the number of passes have much more modest effects on the bulk density (Ampoorter et al. 2007, Jamshidi et al. 2008, Solgi and Najafi 2014). According to Jamshidi et al. (2008), this may be because the compaction of the trail soil during the first skidder passes increases its shear strength, raising its load-bearing capacity. However, the threshold value above which further passes cause only minimal increases in bulk density is probably quite variable, because it will depend on multiple factors including the harvesting technique used, the system chosen, and the equipment used (e.g. animal extraction vs. mechanized extraction), among other things.

The bulk density threshold above which soil is too dense for plant roots to penetrate is considered to be between 1.40 and 1.55 g cm^{-3} for soils with light or medium textures (Kozlowski 1999). Our results indicate that the bulk density approached this critical level after 7 skidder passes in the case of uphill skidding and 12 passes for downhill skidding (Table 4). Naghdi and Solgi (2014) reached similar conclusions after examining various combinations of slope gradient, number of passes, and soil moisture levels.

The total porosity of the skid trail was considerably lower than that of the undisturbed control areas. For both skidding directions, total porosity decreased in conjunction with increases in skidder traffic frequency and skid trail slope. This study focused on the topmost 10 cm of soil, which is more sensitive to disturbance by machine traffic than deeper soil layers (Carter et al. 2007).

Increasing the number of skidder passes from three to seven had important effects on the total porosity. However, further increases from 7 to 12 passes had negligible effects.

5. Conclusions

This work reports the magnitude of changes in physical soil properties associated with different levels of skidder traffic, skidding directions, and slope gradients. Soil compaction during skidding operations increased the bulk density of the skid trail soil and reduced its total porosity. The initial three machine passes exerted the highest effect on soil properties, regardless of the skidding direction or the slope gradient. Increasing traffic frequency has been found to increase the magnitude of soil disturbance, but at a reducing rate. This suggests that unnecessary machine traffic should be kept to a minimum necessary level. On the contrary, the relationship between soil compaction and skidding direction implies that particular attention should be paid to uphill skidding, which causes greater levels of soil compaction than downhill skidding. The slope of the skid trail is another important factor; the results presented herein suggest that slopes of more than 20% should be avoided on skid trails where possible.

The results presented herein demonstrate the importance of the examined soil compaction factors and suggest the need to develop practices that will minimize soil compaction. The adverse effects of both skidding direction and slope gradient could potentially be addressed to at least some extent by training machine operators to improve and optimize their driving style. Such training could help minimizing soil compaction, especially in areas where steep slopes are prevalent. Forest managers can also contribute to forest soil protection by means of redesigning the forest road network and careful planning of forest operations. The combination of workforce training and targeted managerial initiatives are expected not only to reduce the impacts of ground skidding but also bring other benefits in the form of increased operational efficiency, reduced operational costs and higher safety during forest operations.

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