Original scientific paper

Effects of Skidder Passes and Slope on Soil Disturbance in Two Soil Water Contents

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Abstract

Skidding operations induce changes in soil physical properties, which have the potential to impact soil sustainability and forest productivity. Our objective was to investigate the effects of traffic frequency, trail slope, and soil moisture content on soil compaction, total porosity and rut depth. Treatments included a combination of three different traffic intensities (3, 7, and 14 passes), three levels of slopes (< 10%, 10–20% and > 20%), and two levels of soil moisture content (18% and 32%). Soil bulk density and total porosity were measured as 0.75 g cm^{-3} *and 71%, respectively, along the undisturbed area. The results show that bulk density, total porosity and rut depth on skid trails were significantly affected by traffic frequency, skid trail slope and soil moisture content. As the skidder passed, skid trail slope and soil moisture content increased, increasing significantly the average bulk density. Bulk density draws near the critical value after 7 and 14 passes, respectively, at higher and lower soil water content. At each moisture content, the increase of slope > 20% caused a significant increase of the average bulk density. Total porosity on the skid trail was measured from minimum 45% (14 passes and slope > 20%) to maximum 58% (3 passes and slope < 10%) at higher soil water content, and minimum 49% (14 passes and slope > 20%) to maximum 68% (3 passes and slope < 10%) at lower soil moisture content. Rut depth was recorded at 7 and 14 passes at high and low soil water content, respectively, and it increased with the slope. The results show that slope and moisture content had strong effects on soil disturbance.*

Keywords: bulk density, rutting, skidding, soil compaction, total porosity

1. Introduction

Mechanized forest harvesting operations have induced changes in soil physical properties with the potential to negatively impact soil sustainability and forest productivity (Powers et al. 1990). The most significant changes have been shown to occur in soil surface layers, which can restrict the movement of air and water into soil layers (Botta et al. 2006). Undisturbed forest soils have high macroporosity and low soil bulk density and are easily compacted by logging machinery (Lacey and Ryan 2000).

Soil compaction, often accompanied by rutting, is a typical process that may appear as a result of inappropriate use of heavy forest machinery. Rut formation may involve direct or indirect damage to the root system of trees and soil animals (Lindo and Visser 2004), and altered soil and climatic conditions may increase plant diversity (Buckley et al. 2003). Soil compaction involves the compression of pores, which leads to decreased porosity and pore continuity (Berli et al. 2003, Teepe et al. 2004). As a result, there is often an increase in dry bulk density (BD) (e.g. Miller et al. 1996), defined as the dry mass of the soil to its volume. In addition, smaller pore sizes reduce hydraulic conductivity, leading to a slower water infiltration and increased runoff. In general, gas exchange is also hampered (Gaertig et al. 2002), possibly affecting growth and activity of roots and soil organisms (Bathke et al. 1992, Zhao et al. 2010), and leading to an alteration of chemical processes (Woodward 1996, Ballard 2000). As pores become smaller, soil strength increases (Shetron et al. 1988). Nugent et al. (2003) found a 30–50% increase of the penetration resistance (PR) with machine traffic, a measure for soil strength. As root tips have to overcome soil strength to be able to elongate, root growth may be hampered (Greacen and Sands 1980), depending on soil type, water regime and tree species (Heninger et al. 2002, Dexter 2004).

The dimension of the impact varies according to many factors such as skidder passes, slope, site characteristics, harvesting machines, planning of skid roads and production season (Najafi et al. 2009, Jamshidi et al. 2008, Demir et al. 2007).

The number of machine passes is a factor that significantly influences the degree of soil damage (Jun et al. 2004). Machine passes have an important influence on soil structural characteristics, soil aeration and the soil water balance, and may therefore considerably affect soil organisms and root development. The initial passes cause the highest increase in soil compaction in relation to subsequent passes but these may lead to further soil disturbance by deepening the ruts.

During skidding on the steep terrain, a given load gets uneven weight balance on the axles (usually rear axle) and increases soil disturbance. Najafi et al. (2010) found that, during timber harvesting, terrain slope had a stronger effect on soil disturbance so that snig track related disturbance was greater on slopes > 20% than on slopes < 20%.

The potential for soil compaction is greater on wet soils than on dry soils. Botta et al. (2006) found that more severe compaction occurs from traffic on saturated soils than on dry soils.

The extent of severe disturbance from ground based harvesting systems varies depending on the slope and soil moisture content, although the effects of slope and soil moisture on soil disturbance have received less attention. The aim of this study was to characterize the effects of traffic intensity, skid trail slope and soil moisture content on bulk density, total porosity and rut depth in a northern mountainous forest of Iran.

2. Material and methods

2.1 Site description

The research was started in April 2013 at Sorkhkola forest, Mazandaran province, North of Iran between 36°11′ N and 36°17′ N and 52°17′ E and 52°57′ E. The area is covered by *Fagus orientalis* and *Carpinus betulus* stands. Canopy cover is estimated to 80%, the average diameter is 29.72 cm, the average height is 22.94 m and stand density is 220 trees/ha. Elevation is approximately 700 m above sea level with a north aspect. The average annual rainfall, recorded at the closest national weather station, was 810 mm. The maximum mean monthly rainfall of 110 mm usually occurs in October, while the minimum rainfall of 25 mm occurs in August. The mean annual temperature is 15 ºC, with the lowest values in February. Soil texture, analyzed by using the Bouyoucos hydrometer method (Kalra and Maynard 1991), was clay loam along the trail. The skidder type used in this study was a rubber tired skidder, HSM 904 – 4 wheels, tire/chain dimension 600/60–30.5, tire inflation pressure 250 kPa and weighing 8.71 Mg without load in the proportion of 60% on the front axle to 40% on the rear axle.

2.2 Experimental design and data collection

A skid trail 1 200 m long with downslope skidding direction was chosen for the experiments. In choosing the skid trail, attempts were made to select a trail that had different longitudinal slopes and no lateral slope. The longitudinal profile showed that the slopes of skid trail ranged from 0 to 36%. The factorial design was generalized to three factors and each factor was fixed. Three traffic frequencies (3, 7 and 14), three slope classes (0–10%, 10–20% and > 20%) and two soil moisture contents (18% and 32%) were applied with two replications or in total three test series (Jansson and Johansson 1998). In total, 54 plots (10 m × 4 m in size each) were set up in the study. The impacts of skidding on the surface soil layer (0–10 cm depth) were examined using bulk density, total porosity and rut depth in comparison to the undisturbed area.

In a given plot, samples were taken along four randomized lines across the wheel track perpendicular to the direction of travel with 2 m buffer zone between lines to avoid interactions. At three different points of each line (left track LT, between track BT and right

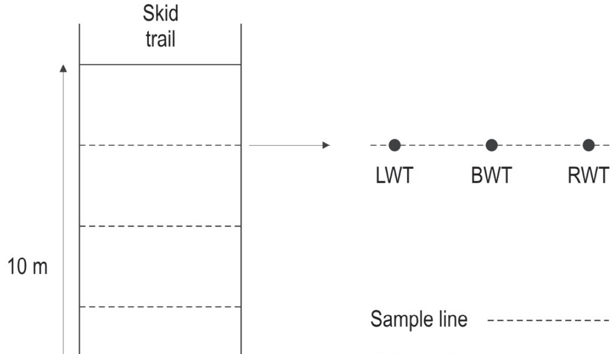

Fig. 1 Treatment set-up with sample lines within plots

track RT) one sample was taken from the 0–10 cm soil layer (Fig. 1). The soil samples were collected at the depth interval of 0–10 cm with a soil hammer and rings (5 cm in diameter, 10 cm in length). Samples were put in polyethylene bags and labeled. Collected samples, brought to the laboratory from the research area, were promptly weighed (soil samples). Soil samples were dried in an oven at 105 °C to constant mass (24 h). The moisture content in the soil samples was measured gravimetrically after drying in an oven (Kalra and Maynard 1991). Total porosity was calculated by Equation (1):

$$AP = \frac{1 - \frac{Db}{2.65}}{VC} \qquad (1)$$

Where:

AP total apparent porosity,
Db soil bulk density,
2.65 assumed particle density,
VC volume of the soil cores (196.25 cm^3).

Soil bulk density was calculated by Equation (2):

$$Db = \frac{Wd}{VC} \qquad (2)$$

Where:

Wd weight of the dry soil, g.

Ruts, at least 5 cm deep from the top of the mineral soil surface and 2 m long, were sampled. Rut depth was measured using a profile meter consisting of a set of vertical metal rods (500 mm in length and 5 mm in diameter), spaced at 25 mm horizontal intervals, sliding through holes in a 1 m long iron bar. The bar was placed across full width of the wheel tracks (four meters) perpendicular to the direction of travel and rods positioned to conform to the shape of the depression (Nugent et al. 2003). Rut depth was calculated as the average depth of 40 reads on 1 m bar (see Fig. 2).

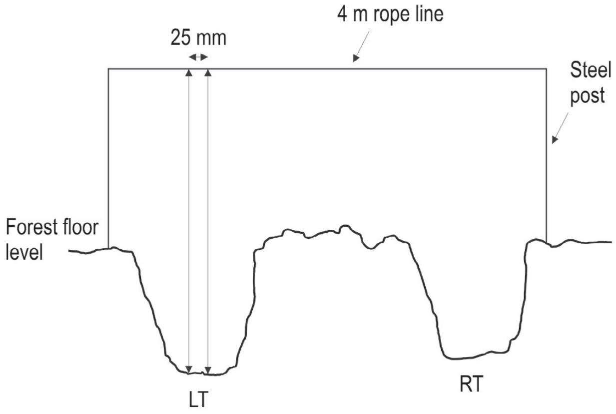

Fig. 2 Illustration of the technique used for rut depth measurement (LT: left rack trail, RT: right rack trail)

One-way and three-way ANOVA by SPSS software version 11.5 was used to assess the significant differences between average bulk density, total porosity and rut depth in different traffic levels, trail slope, and soil moisture content and their interaction effects. Duncan's multiple range tests was used to determine the significant differences between average bulk density, total porosity and rut depth in different treatments.

3. Results

Soil bulk density and total porosity were 0.75 g cm^{-3} and 71%, respectively, and soil texture was clay-loam along the undisturbed area.

3.1 Dry bulk density

The results showed that skidder passes, skid trail slope, and soil moisture content had significant effect on soil bulk density of skid trail, and however the interaction between them was not significant. The average soil bulk density on the skid trail was minimum 1.09 g cm^{-3} to maximum 1.48 g cm^{-3} at higher soil water content, and minimum 0.83 g cm^{-3} to maximum 1.34 g cm^{-3} at lower soil moisture content (Table 1).

Table 1 Effect of skidder passes on dry bulk density, g cm^{-3}

Passes	Soil moisture content, %					
	18			32		
	Slope, %			Slope, %		
	0–10	1–20	(> 20)	0–10	10–20	> 20
Undisturbed	0.73 ^{d}	0.72 ^{d}	0.77 ^{d}	0.74 ^{c}	0.75 ^{c}	0.79 ^{c}
3	0.83 ^{c}	0.84 ^{c}	1.1 ^{c}	1.09 ^{b}	1.12 ^{b}	1.29 ^{b}
7	1.087 ^{b}	1.09 ^{b}	1.23 ^{b}	1.26 ^{a}	1.32 ^{a}	1.42 ^{a}
14	1.21 ^{a}	1.24 ^{a}	1.34 ^{a}	1.31 ^{a}	1.37 ^{a}	1.48 ^{a}

Bulk density clearly increased with the increasing of slope at each tested traffic frequency. There were significant differences ($p < 0.05$) between treatments at terrain slope under and over 20 % (Fig. 3).

In all skidder passes and skid trail slope treatments, dry bulk density increased considerably with an increase in soil moisture content (Fig. 4).

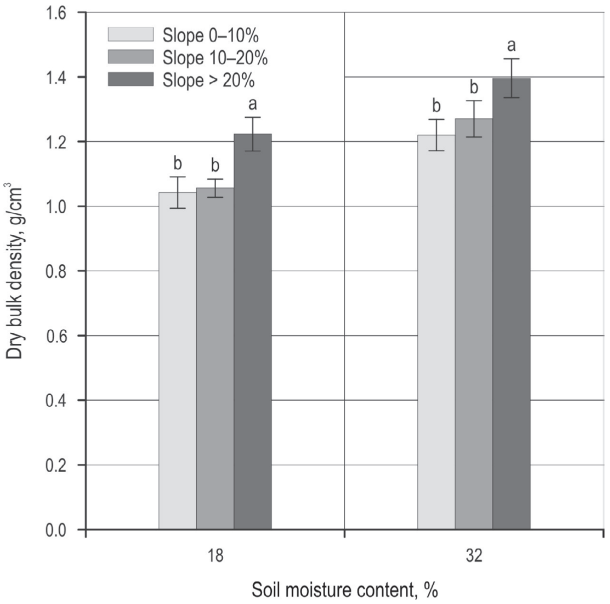

Fig. 3 Effect of skid trail slope on dry bulk density, g cm^{-3}

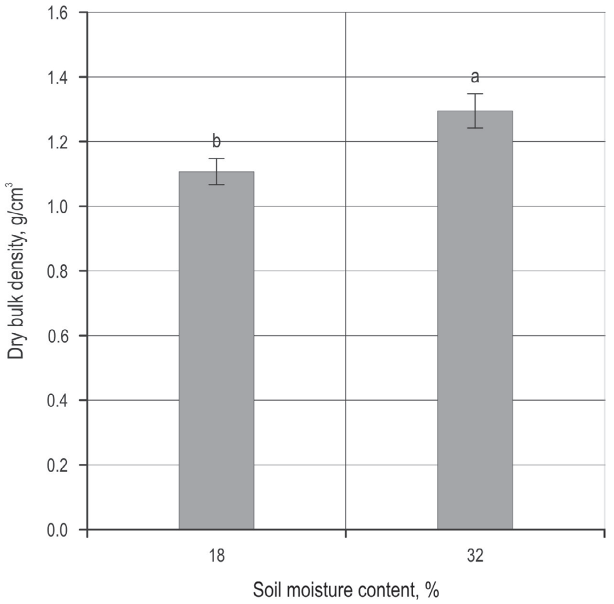

Fig. 4 Average bulk density of skid trail with different soil moistures

Table 2 Effect of skidder passes on total porosity, %

Passes	Soil moisture content, %					
	18			32		
	Slope, %			Slope, %		
	0–10	10–20	> 20	0–10	10–20	> 20
Undisturbed	71.52^{a}	71.76^{a}	70.02^{a}	71.5^{a}	71.29^{a}	69.94^{a}
3	68.54^{b}	68.06^{b}	58.62^{b}	58.80^{b}	56.43^{b}	51.29^{b}
7	58.81^{bc}	58.96^{bc}	54.62^{bc}	52.34^{c}	50.83^{c}	47.45^{c}
14	54.27^{c}	52.83^{c}	49.35^{c}	50.18^{c}	48.00^{c}	45.708^{c}

This indicates that, during the field operations, the soil moisture content is an important factor influencing compactibility.

3.2 Total porosity

Total porosity of the skid trail is considerably lower than the total porosity of the undisturbed area. The average total soil porosity was 71% on undisturbed area, and on the skid trail it was minimum 45% to maximum 58% at higher soil water content, and minimum 49% to maximum 68% at lower soil moisture content (Table 2).

Total porosity decreased with skidder traffic frequency, skid trail slope and soil moisture content. Porosity is inversely related to bulk density, meaning that a decrease in mean porosity comes with an increase in mean bulk density after skidding. Total porosity changes were influenced significantly by the number of skidder passes ($p < 0.05$), skid trail slope ($p < 0.05$), and moisture content ($p < 0.05$), and however the interaction between them was not significant ($p > 0.05$).

3.3 Rut depth

Rut depth increased significantly by the number of machine passes, skid trail slope and soil moisture content, and however it was not significantly affected by the interactions between them.

The results showed that, at higher soil water content, rutting began after 7 passes, and at lower soil water content, it began after 14 passes (Table 3).

In all soil water treatments, by increasing skid trail slope rut depth increased significantly (Fig. 5). Indeed, rut depths were significantly deeper for the steep slopes than the gentle slopes regardless of traffic intensity and soil water content.

Table 3 Effect of skidder passes on rut depth (cm)

Slope	Soil moisture content, %		
	18	32	
	Passes	Passes	
	14	7	14
0–10	8.5^{b}	7.4^{b}	15.2^{b}
10–20	13.7^{ab}	11.1^{ab}	24.6^{ab}
> 20	20^{a}	15.3^{a}	34.5^{a}

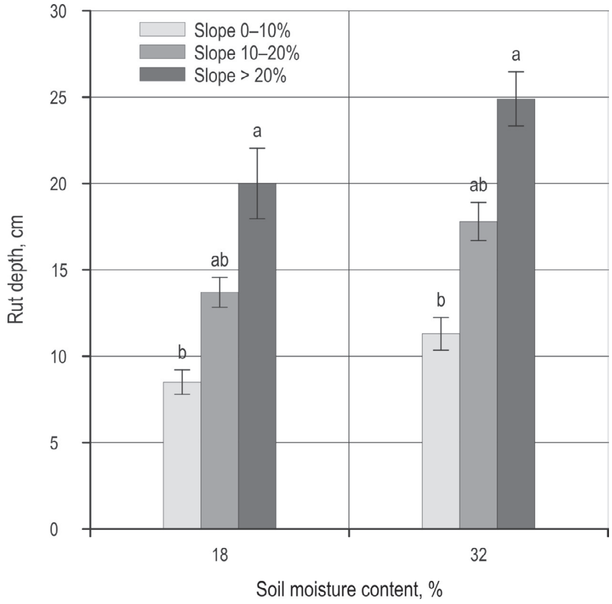

Fig. 5 Effect of slope on average rut depth, cm

4. Discussion

4.1 Dry bulk density

Most of the compaction, expressed as bulk density increase, occurs during the first pass. As shown in Fig. 6, bulk density of the skid trail seriously increased already after three passes of the skidder. Our results are in accordance with the results of Ampoorter et al. (2007) and Brais and Camire´ (1998), who found that bulk density increases more gradually with 50% of the total impact occurring after three passes. When the number of machine passes increases, the additional bulk density increment is negligible (Ampoorter et al. 2007). Botta et al. (2006), Eliasson (2005), Raper (2005), and Labelle and Jaeger (2011) reported that dry bulk density increased with skidder traffic frequency. The average dry bulk density comes faster at higher trail slope level (Fig. 3). Our results are in accordance with the results of Najafi et al. (2009), who found that slope affected deep disturbance caused by skidder logging. The increasing of bulk density in the higher trail slope may be associated with the lower speed of skidder on steep slope trails. When the skidder passes slower on a steep slope, obviously the top soil vibrates more and consequently causes more disturbance than on gentle trail.

The average dry bulk density comes faster at higher moisture content (Fig. 4). McNabb et al. (2001), and Startsev and McNabb (2000) reported that the winter harvested sites displayed a greater percent increase in bulk density than summer harvested sites. This occurs because the soil becomes wetter, water films weaken the interparticle bonds and reduce internal friction by lubricating the particles thus allowing the particles to slide together and compact by squeezing out air. However, the bulk density decreases at higher soil water contents (after the maximum density is reached) because with further addition of water, soil has greater pore water pressures and becomes less compactible (Mosaddeghi et al. 2000). Relative bulk density between 1.40 and 1.55 g cm^{-3} is considered as the critical level at which plant roots cannot penetrate into soils with light and medium texture (Kozlowski 1999). Our results showed that bulk density draws near the critical value after 7 and 14 passes, respectively, at higher and lower soil water content (Table 1).

4.2 Total porosity

Total porosity of the skid trail is considerably lower than the total porosity of the undisturbed area. Total porosity decreased with skidder traffic frequency, skid trail slope and soil moisture content. Porosity is inversely related to bulk density, meaning that a decrease in mean porosity comes with an increase in mean bulk density after skidding. When soil is compacted, total porosity is reduced at the expense of large voids (Greacen and Sands 1980). Motavalli et al. (2003) found that surface compaction significantly decreased total porosity both at the depth of 0–10 cm and 10–20 cm. The major differences in pore volume between slope treatments could probably be explained by greater soil compaction in the steep trail, which indicated that during ground skidding slope had a strong impact on soil porosity (Fig. 7). Besides skidder traffic frequency

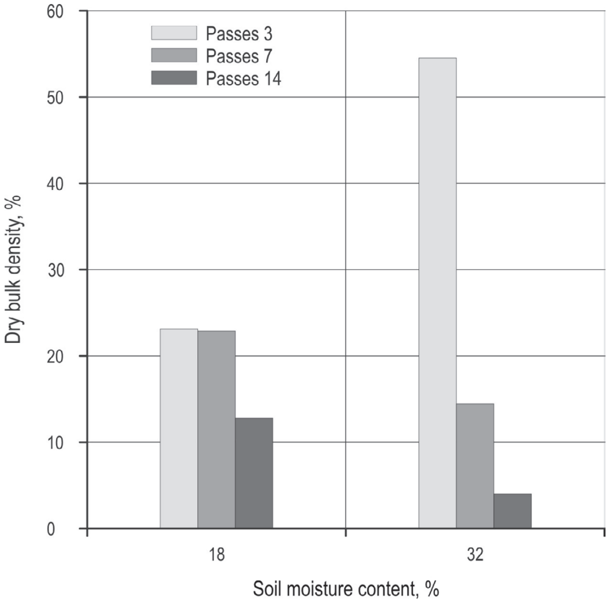

Fig. 6 Effect of traffic frequency on the increase of dry bulk density, %

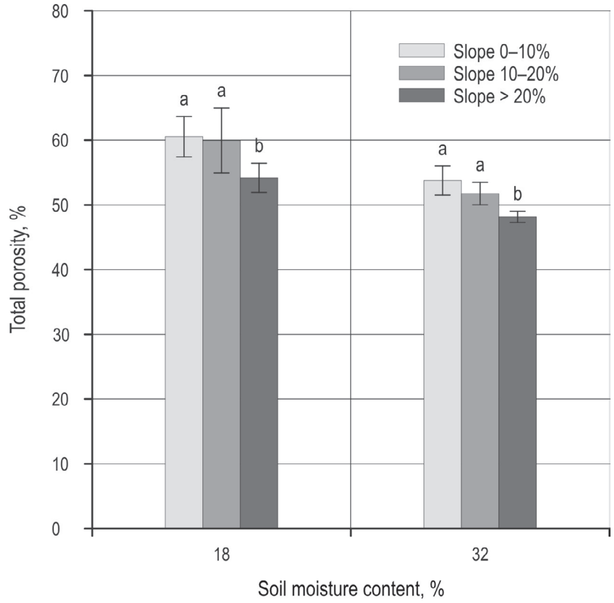

Fig. 7 Effect of slope on total porosity, %

and skid trail slope, total porosity decreased with soil moisture content. As with all skidder passes and skid trail slope treatments, by increasing soil moisture, total porosity was significantly decreased. Xu et al. (2000) reported that on the wet-weather harvested sites, macroporosity and total porosity decreased by 44% and 8%, respectively. In contrast, the changes of these properties on the surface of dry-weather harvested sites were much smaller (in the same arrangement and direction): 3% and 1%.

4.3 Rut depth

Rut depths were significantly ($p < 0.05$) correlated to traffic frequency, skid trail slope and soil moisture content. Positive correlation between rut depth and traffic frequency was in accordance with Eliasson (2005), Botta et al. (2006) and Najafi et al. (2009).

The results showed that by increasing skid trail slope rut depth were significantly increased. Indeed rut depths were significantly deeper for the steep slopes than the gentle slopes regardless of traffic intensity and soil water content. Our result was accordance with the study of Najafi et al. (2009).

The results showed that at higher soil water content rutting began after 7 passes and at lower soil water content it began after 14 passes. Rutting often occurs when traffic is applied to compacted soil (Startsev and McNabb 2000). Rollerson (1990) reported that rutting depths tended to be deeper in moist than in dry soil conditions, and the effect is usually higher with increasing traffic.

It can be concluded that soil disturbance is affected by several factors such as soil water content, wheel slip, vibration and number and duration of loading events. The decrease of total porosity and increase of bulk density and rut depth in the steep slope trail may be associated with the lower speed of skidder on steep slope trail. When skidder passes slower on steep slope, the top soil is obviously vibrated more and consequently it is exposed to more disturbances compared to gentle trails. Furthermore, when logs are pulled downhill, rear axle gets more loads, the radius of rear wheels decreases accordingly and barking slipping may occur because the rear compressed tires roll shorter radius than the front wheels (Najafi et al. 2009). This is in agreement with Davies et al. (1973) and Raghavan et al. (1977), who identified wheel slip on agricultural tractors. The wheel or track slip directly affected the soil structure and altered physical soil properties down to deeper depths. Spinning, digging and slipping may mix mineral soil and forest floor resulting in increased compaction and rutting and decreased total porosity.

This study was conducted with the overall objective of characterizing the effects of skidder passes, skid trail slope and soil water content on bulk density, total porosity and rutting. Compaction of soil under the impact of skidding caused the increase in bulk density rates on the skid road (Demir et al. 2007). As compaction increased, the rates of total porosity decreased. When soil is compacted, total porosity is reduced at the expense of large voids. There is a positive relationship between soil compaction and skid trail slope and number of passes. Therefore, the hypothesis that skid trail slope and skidder passes affect dry bulk density has been supported.

Soil moisture has significant effects on soil disturbance. One strategy to limit soil disturbances is to avoid traffic whenever the water content is higher. Skidding operations should be planned when soil conditions are dry so as to minimize rutting, but if skidding must be done under wet conditions, the operations should be stopped when machine traffic provides deep ruts.

Within the limits of experimental conditions, the following conclusions can be drawn and therefore applied for proper harvesting and management of forest ecosystems:

- ⇒ Skidding should be limited to the slope < 20%;
- ⇒ Only when traffic level and soil moisture content are high, rutting can occur;
- ⇒ Soil compaction, total porosity and rut depth are significantly affected by traffic intensity, skid trail slope and soil moisture content.

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