# The impacts of ground-based logging equipment on forest soil

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**ABSTRACT**: Soil properties can be affected by heavy equipment used for skidding but these impacts vary greatly with site conditions and operational practices. We assessed the effects of ground-based skidding on site disturbance and soil physical properties. We also tested the effects of skid trail slope and traffic frequency on soil compaction, total porosity, and moisture content. On average, about 30% of all harvested area was disturbed to varying levels. Intact forest floor (undisturbed) and light slash were the dominant surface conditions, covering an average of 68.9% of harvested area. Deep disturbed soils accounted for only just over 1.1% of observations. Results showed that dry bulk density, total porosity and moisture content were affected considerably on skid trails by traffic frequency and skid trail slope. Measurements of soil properties in the surface layer (0–10 cm) showed that bulk density is 57% higher and total porosity is 31% lower on the skid trail compared to the undisturbed area. Average moisture content has been measured as 35% on the skid trail versus 47% in the undisturbed area.

**Keywords**: dry bulk density; moisture content; skid trail slope; soil compaction; total porosity

Each harvesting system can cause soil degradation and distinct damage to remaining crop trees in forest ecosystems (Greacen, Sands 1980; Makineci et al. 2007).

Nevertheless, in commercially managed forests where stands are clear-cut and heavy machinery is used for harvesting and site preparation, the maintenance of forest soil sustainability is greatly questioned because the plant cover is disturbed and the risk of erosion intensifies (Aust et al. 1995; Hartanto et al. 2003). Site disturbance may result in degradation of soil properties (increase in soil compaction and decrease in soil macroporosity, infiltration) and may cause a decline in site productivity (McMahon 1995). Soil compaction and decreased total porosity are unavoidable consequences of ground skidding operations that can vary in intensity and distribution as a result of the interaction between machine and site factors at the time of harvest. The dimension of the impact varies according to many factors such as skidder passage, skid trail slope, site characteristics, harvesting machines, planning of skid roads and production season (Laffan et al. 2001; Demir et al. 2007; Najafi et al. 2009). The number of machine passes is a key factor that significantly influences the degree of soil damage. Several authors (e.g. Froehlich 1978; Brais 2001; Ampoorter et al. 2007) have studied the impacts of the frequency of vehicle passes on soil compaction. These studies show that most compaction occurs during the first few passes of a vehicle. Subsequent passes have a smaller effect, but may increase density levels and reduce non-capillary porosity to critical levels for the tree growth (McNabb et al. 1997). Krag et al. (1986) showed that during timber harvesting, slope steepness had a stronger effect on soil disturbance than the season of logging. Their data suggested that disturbance increased in both extent and depth with increasing slope. They also reported that snig track related disturbance was greater on slopes > 20% than on slopes < 20%, and log landing related disturbance was greater on slopes < 40% than on slopes > 40%.

Najafi et al. (2009) showed that slope steepness had a strong effect on the soil physical properties. They reported that in 3 passes, an increase of the skid trail slope from 10% to 20% corresponded to a decrease of 15%, 22%, and 67% in total porosity, water content and forest floor mass, respectively.

The negative correlation between bulk density and soil moisture content suggested a potential decrease in soil moisture at higher bulk densities presumably due to compaction (Carter, Shaw 2002). The negative impacts of wheeling tracks in forest soils upon soil aeration that control the respiration processes of microorganisms were documented by Schäffer et al. (2001). When air-filled porosity falls below 10% of the total soil volume, microbial activity and plant growth can be severely limited in most soils (Brady, Weil 2002). However, Shestak and Busses (2005) argued that compaction mainly reduces soil macropores, therefore affecting gas exchange rates between the soil and the atmosphere. They also suggested that microbial activity mainly occurs within soil aggregates and is relatively unaffected by moderate soil compaction.

The objectives of this investigation were to (*i*) assess soil disturbance after ground-based skidding and (*ii*) determine the impacts of soil disturbance and compaction on soil properties.

## MATERIAL AND METHODS

**Study site.** The study area, Tarbiat Modares University Forestry Experiment Station, is located in a temperate forest in the north of Iran, between 36°31'56"N and 36°32'11"N latitudes and 51° 47'49"E and 51°47'56"E longitudes and it is dominantly covered by *Fagus orientalis* and *Carpinus betulus* stands. Canopy cover was estimated 0.8, average diameter 29.72 cm, average height 22.94 m, maximum hauling distance 400 m and stand density 170 trees·ha$^{-1}$. Records show that 1,500 m$^3$ of timber was skidded in May 2007 and immediately thereafter the present study was conducted. The elevation is approximately 600 m a.s.l. with a northern aspect. At the time of skidding, weather conditions were wet with the average soil moisture content of 32%. Soil texture was analysed using the Bouyoucos hydrometer method and was determined to be clay loam along the trail. The machine used was a crawler tractor Onezhets 110 (Elektrostomana, Karlovo, Bulgaria).

**Experimental design for soil surface disturbance observations.** Soil disturbance was assessed using the method developed by McMahon (1995). The disturbance assessment comprises the classification of disturbance types at 1-m intervals within a 30-cm radius, along transects orientated at right angles to the direction of log extraction. According to McMahon (1995) a certain number of site observations are required within a setting or coupe to ensure a specified error limit on the results. For example, McMahon (1995) stated that 10,000 observations are required for an absolute error of 1%, 1,111 observations for an error of 3% and 400 observations for an error of 5%. For this study, it was decided that an absolute error of 3% would be sufficiently precise. Consequently, a total of 1,400 observations was completed at intervals of 1 m along the six transects. The first transect was located no further than the standard distance between transects from the external site boundary. The disturbance type at each observation point was recorded using a classification adapted from McMahon (1995) (Table 1).

Table 1. Visual disturbance classification system

| Disturbance type | Description | Code |
|---|---|---|
| Undisturbed | no evidence of machine or log passage, litter and understorey intact | 1 |
| Shallow disturbance | litter still in place, evidence of minor disruption | 2 |
| | litter removed, topsoil exposed | 3 |
| | litter and topsoil mixed | 4 |
| | > 5 cm topsoil on litter | 5 |
| Deep disturbance | topsoil removed | 6 |
| | erosion feature | 7 |
| | topsoil puddled | 8 |
| | rutted 5–15 (cm) deep | 9 |
| | rutted 16–30 (cm) deep | 10 |
| | rutted > 30 (cm) deep | 11 |
| | unconsolidated subsoil or base rock deposit | 12 |
| Slash/understorey residue | 10–30 (cm) | 13 |
| | > 30 (cm) | 14 |
| Non-soil (stumps, rocks) | | 15 |
| Compacted | evidence of tire, track and/or log passage | 16 |

**Experimental design for measurements of soil physical properties.** In this study, the impacts of skidding on the skid trail in the surface soil layer (0 to 10 cm depth) were examined using dry bulk density, total porosity and soil moisture, in comparison with the undisturbed area at the different levels of slope and traffic. There were twelve combinations of traffic intensity (3, 8, 13 and > 13) and slope classes (< 10%, 10–20% and > 20%) and each treatment was replicated thrice, so a total of 36 plots were obtained. The plots were delineated prior to skidding on a skidder route and each plot was 10 m long by 4 m wide. There was at least 5-m buffer zone between plots to avoid interactions. 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. The soil samples from the depth interval of 0–10 cm were collected with a soil hammer and rings (diameter 8 cm, length 10 cm). Samples were put into polyethylene bags and labelled. 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 for 24 h. Total soil porosity was calculated as Equation (1):

$$AP = (1 - Db/2.65)/VC \qquad (1)$$

where:

AP – total porosity,
Db – soil bulk density,
2.65 – assumed particle density,
VC – volume of the soil cores (502.4 $cm^3$).

The moisture content in the soil samples was measured gravimetrically after drying in an oven (Kalra, Maynard 1991).

An analysis of variance (ANOVA) was carried out on the data and means were analysed by Duncan's multiple range test.

## RESULTS

### Site disturbance

Results showed that most observations (70%) were slash cover (9%) and undisturbed soils (61%). Disturbed soils accounted for nearly 30% of observations with the most comprising shallow (18.5%) and compacted (9.8%) disturbed classes (Table 2). Deep disturbed soils accounted for only just over 1.1% of observations. Rutting affected 81% of the deep disturbance classes. Slash residual classes were distributed as 91% Class I (10–30 cm), 9% Class II (> 30 cm).

Table 2. Frequency of soil disturbance types

| Disturbance type | Frequency | Percentage |
|---|---|---|
| Undisturbed and shallow disturbance | 1,086 | 77.57 |
| Deep disturbance | 16 | 1.14 |
| Compacted | 138 | 9.85 |
| Slash/understorey residues | 125 | 8.92 |
| Non-soil | 35 | 2.5 |

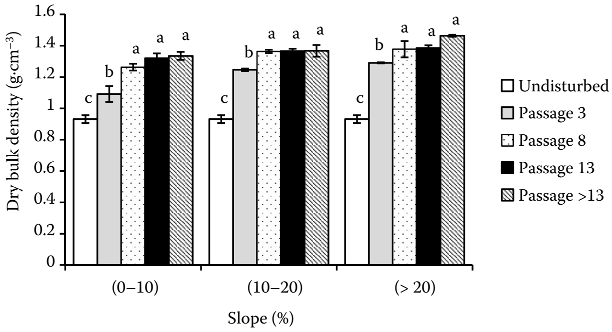


Fig. 1. Effect of skidder passes on dry bulk density

### Soil physical properties

**Bulk density**. Average soil bulk density on the skid trail was measured as minimum 1.09 $g\cdot cm^{-3}$ to maximum 1.46 $g\cdot cm^{-3}$and 0.93 $g\cdot cm^{-3}$ in the undisturbed area (Fig. 1). Average dry bulk density on the treatment with 3 passes and slopes of > 20% (1.29 $g\cdot cm^{-3}$) is higher than on the treatment with 8 passes and slopes of < 10% (1.26 $g\cdot cm^{-3}$). It showed that the slope of trail affects dry bulk density.

Soil compaction increased with the increasing of slope in a specific traffic (Table 3). Bulk density changes were influenced significantly by the number of skidder passes ($P < 0.01$) and slope ($P < 0.01$), but the interaction between numbers of skidder passes and slope was not significant ($P > 0.05$).

Table 3. Effect of slope on dry bulk density

| Slope (%) | Passage | | | |
|---|---|---|---|---|
| | 3 | 8 | 13 | > 13 |
| 0–10 | $1.091778^{b}$ | $1.262967^{b}$ | $1.319996^{b}$ | $1.335154^{b}$ |
| 10–20 | $1.246455^{a}$ | $1.363717^{a}$ | $1.365886^{a}$ | $1.367238^{a}$ |
| > 20 | $1.29054^{a}$ | $1.37795^{a}$ | $1.38571^{a}$ | $1.463736^{a}$ |

**Total porosity**. Total porosity on the skid trail was considerably lower than the total porosity in the undisturbed area. Total porosity decreased with skidder traffic frequency and slope (Fig. 2). Total porosity in the surface soil layer was reduced by as much as 44% (number of passes: > 13, and

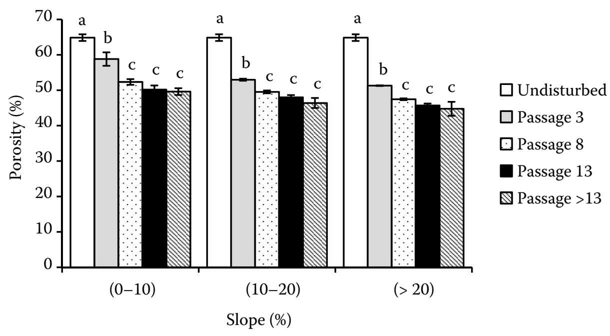


Fig. 2. Effect of skidder passes on total porosity

skid trail slope: > 20%) by soil compaction. 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 ($P < 0.01$) and slope ($P < 0.01$), but the interaction between numbers of skidder passes and slope was not significant ($P > 0.05$).

**Moisture content**. In the mineral soil, the effect of soil compaction on soil moisture content was significant ($P < 0.01$), results showing that soil compaction reduced water content by 27% after skidding (number of passes: > 13, and skid trail slope: > 20%) (Table 4).

Average moisture content has been measured as 35% on the skid trail versus 47% in the undisturbed area. Moisture content in each skidder traffic decreased with skid trail slope. Moisture content changes were influenced significantly by the number of skidder passes ($P < 0.01$) and slope ($P < 0.01$), but the interaction between numbers of skidder passes and slope was not significant ($P > 0.05$).

Table 4. Effect of slope on soil moisture content

| Passage | Slope (%) | | |
|---|---|---|---|
| | 0–10 | 10–20 | > 20 |
| Undisturbed | 47.15135[a] | 47.15135[a] | 47.15135[a] |
| 3 | 46.6657[a] | 40.92085[a] | 34.37761[a] |
| 8 | 37.1949[b] | 32.5077[b] | 33.98346[b] |
| 13 | 36.60237[b] | 34.17458[b] | 32.1006[b] |
| > 13 | 34.61648[b] | 31.87765[b] | 27.14273[b] |

## DISCUSSION

### Soil surface disturbances

Results showed that most observations (70%) were slash cover (9%) and undisturbed soils (61%). Disturbed soils accounted for nearly 30% of observations with the most comprising shallow (18.5%) and compacted (9.8%) disturbed classes. Deep disturbed soils accounted for only just over 1.1% of observations. In comparison with our study McMahon (1995) found 71% undisturbed and shallow disturbance, 4% deep disturbance, and 37% compacted, when rubber-tired skidders were used. Laffan et al. (2001) indicated that after logging by conventional ground-based skidding from steep slopes the most observations (> 70%) were slash cover (47%) and undisturbed soils (25%). Disturbed soils accounted for nearly 30% of observations with the most comprising slightly (17%) and moderately (10%) disturbed classes. Severely disturbed (subsoil exposed) soils accounted for only just over 1% with nearly all attributable to tree uprooting during logging operations. Heninger et al. (2002) found that soils with a thin topsoil (A and A-B horizons), therefore, are more likely to be classified as severely disturbed than are soils with a thick topsoil. Gondard et al. (2003) found 52% undisturbed and shallow disturbance, 3% deep disturbance, and 37% slash residues, when skidder and terraces were used, they also found 27% undisturbed and shallow disturbance, 0% deep disturbance, and 58% slash residues, when forwarder and terraces were used. Helvey et al. (1985) compared five different log retrieval systems (after hand felling) with respect to soil disturbance and erosion: tractor skidding over bare ground (< 30% slope), tractor skidding over snow (< 40% slope), cable skidding over bare ground, skyline (Wyssen skycrane, Reichenbach, Switzerland), and helicopter. They found that tractor skidding over bare ground caused the highest percentage of area with severe soil disturbance (36%), followed by cable skidding (32%), tractor skidding over snow (9.9%), skyline (2.8%), and helicopter (0.7%). They revealed that the logging tractor used for skidding is a very important factor, but that the presence of shallow or deep disturbances, and their intensity, depends also on environmental characteristics. McIver and Starr (2001) reported that the type of logging system and the time when logging occurs relative to soil moisture are both important in determining soil disturbance and sediment transport. Ground-based systems have a broad range of machinery configurations. Rubber-tired skidders are capable of producing more severe damage than tracked machines due to their ability to continue skidding under more severe terrain. Steel-tracked machinery is also generally considered to have a lower impact on soil than rubber-tired machinery due to lower static ground pressures (Hom et al. 2004). Murphy (1984) studied the effect of various types of machinery on the severity of soil disturbance. He found that a Clark 66 RTS (Ranger's Clark, Sherwood, USA) with its high ground pressure and fast speeds caused more severe soil disturbance than an FMC 100 STS (KMC-Kootrac/Kootenay Tractor, British Columbia, Canada). He also found that the Timbermaster TM70 (RTS) caused less severe disturbance than the Bombardier Muskeg (STS), although the Timbermaster exerted slightly higher ground pressures than the Bombardier Muskeg. This was probably because the Timbermaster had articulated steering while the Bombardier had controlled differential steering (Murphy 1984).

## Soil physical properties

**Bulk density**. Soil compaction was affected by skidding intensity and trail slope. Most of the compaction, expressed as bulk density increase, thus takes place during the first pass. As can be noticed in Fig. 1, a strong increase in bulk density for the skid trail already appears after three passes of the skidder. Our results are in accordance with the results of Ampoorter et al. (2007), 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) and Ampoorter et al. (2007) reported that dry bulk density increased with skidder traffic frequency. There are no significant differences in dry bulk density at 8, 13 and > 13 passes. Average dry bulk density comes faster at a higher slope level. At a lower slope level, bulk density is drawing near to the critical value after 8 passes, but at a higher slope level, bulk density is drawing near to the critical value after 3 passes. The increase of bulk density in the higher trail slope may be associated with the lower speed of skidder on slope steepness trail. When the skidder passes more slowly on slope steepness, obviously top soil vibrated more consequently get more complication with the comparison of gentle trail. Najafi et al. (2010) reported that compaction increased with increasing slope. They also reported that skid trail related disturbance was greater on slopes > 20% than on slopes < 20%.

Bulk density between 1.40 and 1.55 $g\cdot cm^{-3}$ is considered as the critical level at which plant roots cannot penetrate soils with light and medium texture (Kozlowski 1999).

**Total porosity**. Total porosity on the skid trail is considerably lower than the total porosity in the undisturbed area. Total porosity decreased with skidder traffic frequency, skid trail slope. 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 the soil is compacted, total porosity is reduced at the expense of large voids (Greacen, Sands 1980). Ares et al. (2005) reported that total soil porosity decreased 10 to 13% with compaction. Shestak and Busse (2005) reported that total porosity decreased 26% in the clay loam and 20% in the sandy loam with severe compaction. Motavalli et al. (2003) found that the surface compaction significantly decreased total porosity at both the 0–10 and 10–20 cm depths. Furthermore skidder traffic frequency, total porosity decreased with skid trail slope. As the skidder passes and the skid trail slope increased, the average of bulk density increased significantly, as a result total porosity decreased significantly. Xu et al. (2000) reported that on the wet-weather harvested sites, macroporosity and total porosity decreased 44 and 8%, respectively, and bulk density increased 19%. In contrast, the changes of these properties on the surface of the dry-weather harvested sites were much smaller (in the same arrangement and direction): 3, 1, and 2%.

**Moisture content**. Moisture content was affected by traffic intensity and skid trail slope. In skid trails soil moisture contents were low as a result of less pore space available for water infiltration and retention at elevated bulk density levels.

Tan et al. (2005) reported that the soil compaction reduced water content by 11% after forest floor removal, but did not affect soil water content with the presence of forest floor. Carter and Shaw (2002) reported that significant negative correlations were indicated for the relationship between bulk density and soil moisture content. The negative correlation between bulk density and soil moisture content suggested a potential decrease in soil moisture at higher bulk densities presumably due to compaction. Makineci et al. (2007) reported that the values of total porosity (47.42%) and moisture equivalent (21.26%) on the skid road are considerably lower than the total porosity (59.09%) and the moisture equivalent (27.22%) in the undisturbed area.

# CONCLUSIONS

This study showed that soil bulk density and surface disturbance regimes could be used as indicators for monitoring harvesting impacts on soils. Results of this study showed that approximately 30% of all treated areas were disturbed to varying levels. Compaction of soil with the impact of skidding has caused decreases in total porosity and moisture equivalent rates on the skid road. As compaction increased, the rates of total porosity and moisture content decreased. When the soil is compacted, total porosity is reduced at the expense of large voids (Greacen, Sands 1980).

There is a positive relationship between soil compaction and skid trail slope. The effect of slope on disturbance is in agreement with Krag et al. (1986) and Najafi et al. (2009). The damage may be reduced by avoiding steep skid trails > 20%, controlling the number of machine passes and by limiting the contact pressure imposed by wheels or tracks through proper selection of the size and type of using the traction mechanism (tires or tracks).

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