Effects of Skidder on Soil Compaction, Forest Floor Removal and Rut Formation

Efecto del arrastre en la compactación y remoción de suelo y en la formación de surcos

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Abstract

An extensive field trial was set up to examine the influence of traffic intensity (5, 10, and 15 skidding cycles) (i.e. pass back and forth on the skid trail) and skid trail slope (0-10, 10-20, and > 20)% on soil compaction, forest floor removal, and rut depth after logging. The results showed that dry bulk density and rut depth increased with the increase of traffic frequency and slope, but floor coverage decreased. Within each traffic treatment soil compaction raised with the increase of skid trail slope, so that significant differences in dry bulk density were observed between slopes lower than 20% and those greater than 20%. Bulk density has become quite close to the critical value after 15 cycles. We observed soil rutting on the treatments started with 10 cycles. Soil disturbance increased significantly on slopes with less than 20% inclination with a dry bulk density of 1.157 g cm^{-3} after 5 cycles compared to 0.923 g cm^{-3} on slopes lower than 10%. In addition the litter mass on the treatments with 10 cycles and slopes greater than 20% (386.586 kg ha^{-1}) was significantly lower ($p < 0.05$) than treatments with 15 cycles and slopes lower than 10% (545.382 kg ha^{-1}). Data suggest that disturbance increased earlier in the steep treatments than in less sloping conditions. The dramatic increase of soil disturbance on treatments with slopes greater than 20% may be associated with increasing load on the rear axle combined with slipping on steep slope trail.

Key words: bulk Density, Litter Mass, Rutting, Soil Disturbance, Skid Trail Slope.

Resumen

Se realizó un extenso estudio de campo para examinar la influencia de la intensidad de tráfico (5, 10 y 15 ciclos de arrastre) (es decir, pasar de ida y vuelta en la pista de arrastre) y de la pendiente del terreno de arrastre (0-10, 10-20 y más de 20)% en la compactación del suelo, remoción suelo del bosque y la profundidad de la huella después de la tala. Los resultados mostraron que la densidad de masa seca y la profundidad de las raíces se incrementan conforme lo hacen la frecuencia del tráfico y la pendiente y que la cobertura de suelo disminuyó. Dentro de cada tratamiento de tráfico, la compactación del suelo aumentó con el incremento de la pendiente del terreno, se observaron diferencias significativas en la densidad aparente seca entre la pendiente menor a 20% y la mayor a 20%. La densidad aparente se acerca a su valor crítico después de 15 ciclos. Se observó la formación de surcos en el suelo en los tratamientos de 10 ciclos. La perturbación del suelo aumentó significativamente en las pendientes con más de 20% de inclinación, con una densidad seca aparente de 1,157 g cm^{-3} después de 5 ciclos en comparación con 0,923 g cm^{-3} en pendientes menores a 10%. Se observó que la masa de desechos vegetales (hojarasca) en el suelo en los tratamientos con 10 ciclos y laderas de más de 20% (386.586 kg ha^{-1}) fue significativamente más baja ($p <0,05$) que en los tratamientos con 15 ciclos y laderas de menos de 10% (545,382 kg ha^{-1}). Los datos sugieren que la perturbación se incrementa primero en los terrenos empinados que en aquellos con menor inclinación. El considerable aumento de la perturbación del suelo en los tratamientos con pendientes de más 20% puede estar asociado con el aumento de la carga en el eje trasero combinado con el deslizamiento sobre el terreno empinado.

Palabras clave: densidad a granel, hojarasca, huella de las llantas, perturbación del suelo, pendiente del terreno.

Introduction

The use of heavy machinery to perform forestry activities such as logging has increased worldwide during the last decades. However, these machines may seriously influence the soil ecosystem as they induce rutting of the upper soil layers, and soil compaction (Najafi and Solgi, 2010; Ampoorter *et al.,* 2011). 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 (Rab, 1994; 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). Compaction involves a rearrangement and packing of the solid particles of the soil closer together, resulting in an increase in the bulk density. When dry bulk density increased, the reduction in total porosity (McNabb *et al.,* 2001; Frey *et al.,* 2009; Najafi *et al.,* 2009; Solgi and Najafi, 2014), tree height, diameter and volume growth (Tan *et al.,* 2006; Zhao *et al*., 2010) will be often observed. The effects of soil compaction can persist in a forest soil for several decades depending on soil texture, machine activity, soil water content, and other soil conditions at the time of harvesting (Kozlowski, 1999; Demir *et al.,* 2007; Ezzati *et al.,* 2012).

Apart from compaction, one of the major deficiencies also caused by the skid roads is loss of organic matter from the forest floor and aboveground level (Demir *et al*.; 2007). Mixing and/or removal of litter and soil may change the physical, chemical or biological properties of a soil. Organic material retention can significantly increase microbial biomass due to increased carbon availability for microbial metabolism (Mendham *et al.,* 2002). Forest floor removal increased the mean temperature in the mineral soil during the growing season (Tan *et al.,* 2005). One of the first visible signs that the soil is being harmed by vehicle traffic is excessive deformation of the trafficked area or rutting. Rutting often occurs when traffic is applied to soil when it is in a compactable condition. Ruts may also become channels for superficial water flow and thus cause erosion since the infiltration of rainwater is reduced (Startsev and McNabb, 2000).

The degree to which a forest soil is compacted by mechanized logging depends on several variables and characteristics, typical of the forest site (soil texture, soil organic matter content, slope), season (soil water content, soil temperature) or the harvesting activity itself (machine type, machine mass, traffic intensity) (Ampoorter *et al.,* 2010; Naghdi and Solgi, 2014). The number of machine passes is a factor that significantly influences the degree of soil damage. Several authors (eg. Ampoorter *et al.,* 2007; Jamshidi *et al.,* 2008; Najafi *et al.,* 2010) have studied the impacts of the frequency of vehicle passes on soil compaction. These studies showed that most compaction occurs during the first few passes of a vehicle. Subsequent passes have less, but may increase density levels and reduce non-capillary porosity to critical levels for tree growth (McNabb *et al.,* 1997).

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). Krag *et al.* (1986) and Najafi *et al.* (2009) found that during timber harvesting slope steepness had a stronger effect on soil disturbance so that disturbance was greater on slopes > 20% than on slopes < 20%. The extent of the severe disturbance from ground based harvesting systems varies due to slope although; the effects of slope on soil disturbance have received less attention. Here we assess the physical properties of soil from ground based harvesting systems on different traffic intensity over three slope classes (< 10, 10-20, and over 20)%.

Material and methods

Site description

The study area – Tehran University Forestry Experiment Station, located in a temperate forest in 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, is dominantly covered with *Fagus orientalis* and *Carpinus betulus* stands. Canopy cover has been estimated as 0.75, average diameter 35 cm, average height 22 m, and stand density 185 trees/ha. Elevation is approximately 850 m above sea level with a north aspect. The average annual rainfall recorded at the closest national weather station about 20 km distant from the research site is 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 lowest values recorded in February. At the study site, the selection silvicultural system was applied as a combination of group selection and single tree selection. Harvesting operation was performed by hand-felling and processing, followed by transportation to the roadside by a ground-based skidding system. The rubber-tired skidder was used to extract 3 m to 4 m long logs on drivable terrain of up to 35 percent slope. Records show that 1500 m^3 timbers were skidded in October, 2012 and immediately thereafter the current study was conducted. At the time of skidding, weather conditions had been dry with the average soil moisture content of 23%. The soil had not been driven on before the experiment.

The machine used was the 4WD Timberjack 450C rubber-tired skidder, weighing 11.4 t without load (axle weight proportion 55% on the front to 45% on the rear axle). The skidder was equipped with the engine model 6BTA5.9 (engine power of 177 PS) and was fitted with tires the size of 24.5–32 inflated to 220 kPa (Fig. 1).

Figure 1. Rubber-tired skidder (Timberjack 450C) used in logging operations in a mountain forest of Iran.

Experimental design and data collection

A skid trail of 4 m wide, which ran parallel to the slope, was selected for the experiments. The skid trail passing through the stand in the south–north direction has been used recently. The impacts of skidding on the surface soil layer (0 cm - 10 cm depth) were examined using dry bulk density, forest floor removal and rut depth in comparison to the undisturbed area at the different levels of slope and traffic. Nine treatments were imposed on skid trail, where the experimental variables were traffic frequency of 5, 10, and 15 skidder passes (one empty and one loaded pass) and slope of gentle (< 10%), moderate (10% - 20%) and steepness (> 20%) in the same tracks, with 5 m wide buffer zones between plots to avoid interactions. Plots were replicated three times, so a total of 27 plots with 10 m long by 4 m wide were delineated prior to skidding on skidder route of 600 m length. 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 track RT) one sample was taken from the forest floor and 0 cm - 10 cm soil (Fig. 2).

Forest floor samples were taken by collecting the entire forest floor of 1 m^2 soil surface. The soil samples

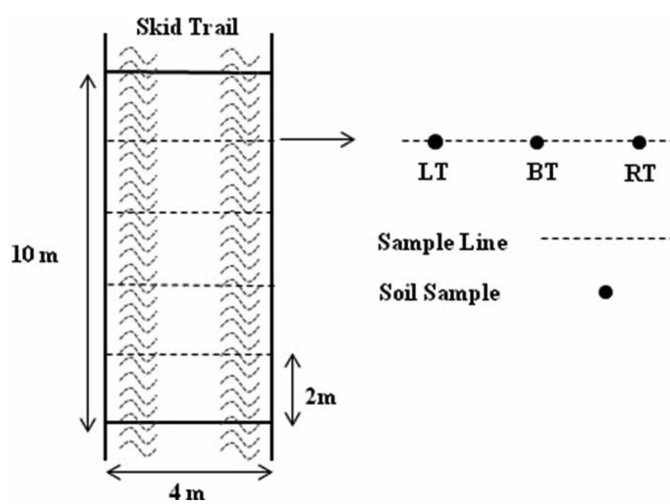

Figure 2. Sketch of the treatment set-up with the location of the sample lines within the plot.

were collected from the depth interval 0 cm - 10 cm with a soil hammer and rings (diameter 5 cm, length 10 cm). Samples were put in polyethylene bags and were labeled. Collected samples, brought to the laboratory from the research area, were promptly weighed (soil samples). Soil and forest floor samples were dried in an oven under 105 °C (24 h) and 65 °C (48 h), respectively. Soil texture in the laboratory was determined based on particle size analysis using the Bouyoucos hydrometer method (Kalra and Maynard, 1991).

Ruts of 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 (length 500 mm and diameter 5 mm), spaced at 25 mm horizontal intervals, sliding through holes in a 1 m long iron bar. The bar was placed across the wheel tracks perpendicular to the direction of travel and rods positioned to conform to the shape of the depression (Najafi *et al.*, 2009). Rut depth was calculated as the average depth of 40 reads on the 1 m bar (Fig. 3).

An analysis of variance (ANOVA) was carried out on the data and means were analyzed by Duncan's multiple range tests utilizing the SPSS 11.5.

Results

Dry bulk density and forest floor mass were measured as 0.815 g cm^{-3}, 3264.72 kg ha^{-1}, and soil texture was found Clay-Loam along the general harvesting area (Table 1).

Bulk density

Soil compaction clearly increased with the increasing of slope in a specific traffic. There were significant ($p < 0.05$) differences between treatments with slope of < 20% and those with slope of > 20% (Table 2).

For instance, difference between average dry bulk density on the treatments with 5 cycles and slopes of > 20% (1.157 g cm^{-3}) and those of treatment with 5 cycles

Table 1. Soil texture classes at a depth of 0 cm - 10 cm. The range of particle size was < (0.002, 0.002 - 0.05 and 0.05 – 2.0) mm for clay, silt, and sand, respectively.

Soil particle distributions (g 100 g^{-1})			
Clay	Silt	Sand	Soil texture
32	38	30	Clay Loam

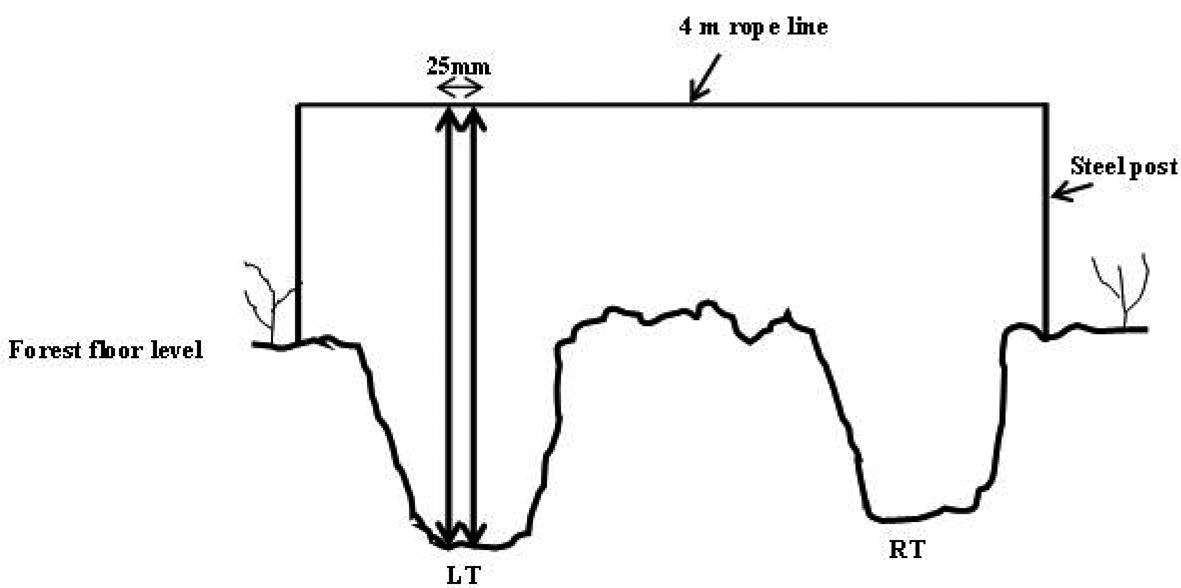

Figure 3. Illustration of the technique used for rut depth measurement. LT, left rack trail; RT, right rack trail.

Table 2. Effect of skid trail slope on dry bulk density (g cm-3)

Passes	Slope (%)		
	(0-10)	(10-20)	(> 20)
5	0.923 b	0.942 b	1.157 a
10	1.114 b	1.137 b	1.258 a
15	1.219 b	1.283 b	1.405 a

Table 3. Effect of traffic frequency on forest floor (kg ha-1)

Slope (%)	Passes		
	5	10	15
(0-10)	2665.68 a	1203.65 b	545.38 c
(10-20)	1755.73 a	754.39 b	286.64 c
(> 20)	1248.02 a	386.58 b	0 c

and slopes of < 10% (0.923 g cm^{-3}) was significant ($p < 0.05$). Depending on the traffic, considerable differences were found between treatments with regard to soil bulk density. Average soil bulk density on the skid trail has been measured as minimum 0.923 g cm^{-3} to maximum 1.405 g cm^{-3} and 0.815 g cm^{-3} in the undisturbed area. Dry bulk density reached 42% of the maximum obtained density in surface soils only after 5 cycles and increased with the increasing of traffic intensity (Fig. 4).

Forest floor

Forest floor removal in the skid trail occurred during the process of log removal and was highly variable in spatial extent and severity. Forest floor removal on skid trail ranged from a 19% decline of the forest floor (5 passes and slope of < 10%) to complete removal of the forest floor (20 passes and slope of > 20%) and both masses (Table 3) were significantly different ($P < 0.05$) from that of undisturbed area (3267.53 kg ha^{-1}).

In a given traffic, the lowest Forest floor mass was observed on the slope of > 20% (Fig. 5). Forest floor mass was significantly lower with 10 passes and slope of > 20% (386.586 kg ha^{-1}) compared with 15 passes and slope of < 10% (545.382 kg ha^{-1}). Forest floor mass also decreased with the increase of skidder traffic frequency (Table 3). Forest floor removal was affected significantly by number of skidder passes and slope ($P < 0.05$), but the interaction between those on and forest floor removal was not significant ($P > 0.05$).

Rut depth

The results showed that rut depth began by 10 passes and significantly ($P < 0.05$) was affected by the skid trail slope. The greatest rut depth (38.32 cm) was measured when the skidder passed 15 times on the trail with the slope of > 20%. Rut depths were significantly deeper for the steep slopes than the gentle slopes regardless of traffic intensity (Fig. 6).

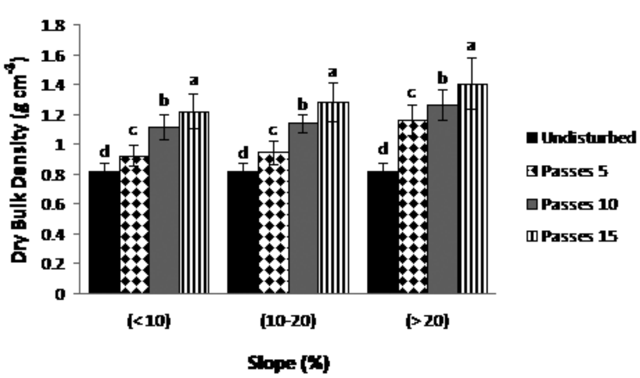

Figure 4. Effect of traffic frequency on dry bulk density (g cm-3)

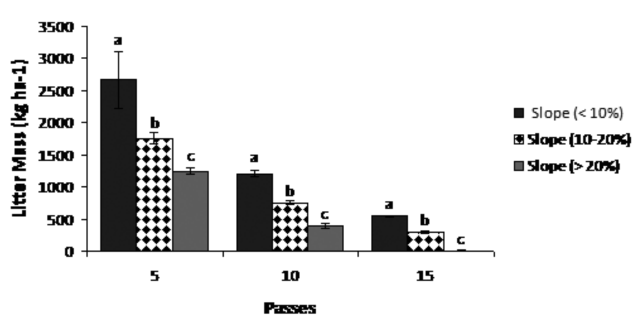

Figure 5. Effect of skid trail slope on litter mass (kg ha-1).

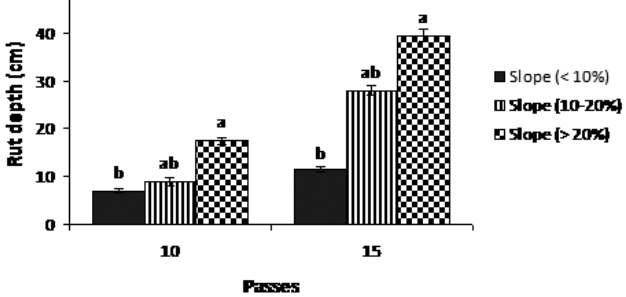

FIGURE 6. Effect of skid trail slope on rut depth (cm).

DISCUSSION

Bulk density

Ground-based skidding operations that transfer the weight of the machinery and its load logs onto a small soil surface area result in unavoidable soil disturbances, such as increased soil compaction and reduced soil porosity (Greacen and Sands, 1980). Although it has been well established that the magnitude of adverse soil disturbances depend on a variety of factors, such as the soil type, the terrain, the type of harvesting machinery employed, the weather conditions during the skidding conditions, and the expertise and care employed by the equipment operators used (e.g., Najafi *et al.,* 2009; Naghdi and Solgi, 2014; Solgi and Najafi, 2014). The average bulk density of the undisturbed soil at soil depths of 10 cm was about 0.815 g cm^{-3}. The average percentage of increasing in bulk density from undisturbed soil to the fifth, tenth, and fifteenth trips was 42%, 54%, and 72%, respectively. Dry bulk density has been affected by traffic intensity and trail slope. Soil was compacted faster on treatments of > 20% than those of < 20% (Table 2). There was no significant difference between treatments 5 passes and slope of > 20% and those 10 passes and slope of < 10% from a bulk density point of view. The strong effect of increasing slope of the skid trail on rates of dry bulk density increases that are faster on steeper slopes for the same number of equipment passes has also been observed in previous studies (Najafi *et al.,* 2009; Naghdi *et al.,* 2010). The increase of bulk density in the higher trail slope may be associated with the lower speed of skidders on slope steepness trail. When a skidder passes slower because of slope steepness, top soil vibrated more and consequently, got more complicated with the comparison of gentle slope trails. Furthermore, when logs were pulled on steep slope trails, usually the rear axle got more load and induced more pressure to soil compared with lower slope trails. Uneven load distribution caused slipping on the steep slope trail due to reduction of rear wheel radius. More pressure, slipping and lower speed dramatically increased soil disturbance on the steep slope trail (Najafi *et al.,* 2009). The studies of Davies *et al.* (1973) and Raghaven *et al.* (1977) identified wheel slip on agricultural tractors as causing significant compaction, and wheel slip from forest vehicles should therefore contribute to compaction.

Most of the compaction, expressed as bulk density increase, thus takes place during the initial passes. As can be noticed in figure 4, strong increases in bulk density (42%) for skid trails already appears after 5 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 3 passes. Bulk density between 1.40 g cm^{-3} 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 is drawing quite close to the critical level after 15 cycles (Table 2).

Forest floor

The undisturbed area's forest floor biomass was about three times higher than that of the skid trails' forest floor (284 kg ha^{-1} and 982 kg ha^{-1} respectively; see Table 3). The differences of forest floor weight are significant, even at the same traffic frequency under different levels of slope (Fig. 5). This shows that during skidding, slope steepness has a strong effect on the forest floor removal. Weight of forest floor decreased with the increasing of traffic frequency (Table 3). Less forest floor on the skid trail shows that the forest floor has been moved out by skidding. The skidder power decreases with the increasing of trail slope, especially slopes of greater than 20%. So when heavy logs are skidded, wheels spin and the skidder travels more slowly. Spinning, digging and slipping may mix mineral soil and litter resulting in increasing of displacement, rutting and decreasing of litter mass. In addition, some of the trees along the skidding trail had been cut during the opening of the trail to ensure easy transportation and skidding of the harvested timbers. The removal of trees would have resulted in a lower tree density along the skid trails compared with the undisturbed area, and this lower tree density could also have decreased the forest floor biomass (Demir *et al.*, 2007). Impact of skidding operations on the forest floor characteristics have been shown to be similar results by many researchers (Jurgensen *et al.,* 1997; Ballard, 2000; Arocena, 2000; Demir *et al.,* 2007).

Rut depth

Rut depths were significantly ($P < 0.05$) correlated with changes in skid trail slope. However, rutting was similar between the low and medium slopes as it was between medium and steep slopes. Positive correlation between rut depth and traffic frequency was in accordance with Eliasson (2005) and Botta *et al.* (2006). The fact that no significant effect of 5 passes was found on rutting could partly be explained by low water content on the day when traffic was applied. Rutting and rut depth are typically positively correlated with the soil moisture content at the time of harvest (McCurdy *et al.*, 2004; Najafi *et al.*, 2009). In fact, timing that logging and skidding relative to soil moisture content is an important determinant of soil disturbance and rutting, with higher levels of disturbances found when areas are harvested during wet weather than during dry weather (Aust *et al.,* 1998; McIver and Starr, 2001). Rut depth is a measure of severity of traffic or soil disturbance and the deeper the rut, presumably the more severely the soil is disturbed (Heninger *et al.*, 2002).

Conclusions

This study was conducted with the overall objective of characterizing the effects of skidder passes and skid trail slope on bulk density, litter mass and rut depth. Compaction of soil with the impact of skidding has caused 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 the large voids. There is a positive relationship between soil compaction by skid trail slope and passes. Therefore, the hypothesis that skid trail slope and skidder passes affects on dry bulk density, litter mass and rut depth was supported. The effect of trail slope on disturbance is in agreement with Botta *et al.* (2006), Najafi *et al.* (2009) and Solgi *et al.* (2013). Successful planning of skidding operations to minimize soil compaction will depend on knowledge of the distribution of soils in the area to be managed, coupled with knowledge on the response of each soil to compactive effort. There is a clear need to better understand the relationship between the forest soils and their susceptibility to soil disturbance from harvesting equipment.

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

- Bulk density, forest floor removal, and rut depth were significantly affected by skid trail slope and traffic intensity.
- Only on high frequencies (10 passes and over) of skidder, rut can occur.
- Skidding should be limited on slopes lower than 20%.

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Manuscript received on July 26th 2014.
Accepted on June 6th 2015.

This paper must be cited as:
Solgi, A., R. Naghdi and M. Nikooy. 2015. Effects of skidder on soil compaction, forest floor removal and rut formation. *Madera y Bosques* 21(2):147-155.