Impacts of Rubber-tired Skidder and Crawler Tractor on Forest Soil in the Mountainous Forests of Northern Iran

RAMIN NAGHDI*[1] AND SEYED ROSTAM MOUSAVI[2]

[1] *Department of Forestry, Faculty of Natural Resources, University of Guilan, Sowmeh Sara, P.O. Box 1144, Iran*

[*]*Corresponding author: E-mail: rnaghdi@guilan.ac.ir*

Tel.: +98 1344323599, +98 1344323600.

[2] *Department of Forestry, Faculty of Natural Resources, Urmia University, P.O. Box 165, Urmia, Iran*

Naghdi, R.* and Mousavi, S.R. 2016. Impacts of Rubber-tired Skidder and Crawler Tractor on Forest Soil in the Mountainous Forests of Northern Iran. *Baltic Forestry* 22(2): 375-381.

Abstract

The current study compared disturbances caused by two types of log-skidding machines, namely a rubber-tired skidder and a crawler tractor, on clay loam soil in forest. An extensive fieldwork was carried out to find out the impact caused by the combination of both machine types, traffic intensity (5, 10, 15, and 20 skidding cycles) and skid trail slope (0-15 % and >15 %) on soil compaction and forest floor after logging. The results showed that regardless of skidder type, bulk density of soil raised as traffic intensity and slope increased while the coverage of forest floor decreased. Within each traffic treatment soil compaction intensified with increasing skid trail slope, therefore significant differences in bulk density were observed between slope 0-15 % and > 15 %. Litter mass measured on the skid trail reached 2012 kg ha^{-1} at the maximum (five passes on slope with inclination of 0-15 %) and 54 kg ha^{-1} at the minimum (20 passes on slope > 15 %) for rubber-tired skidder, and 2489 kg ha^{-1} at the maximum (five passes on slope 0-15 %) to 470 kg ha^{-1} at the minimum (20 passes on slope > 15 %) for crawler tractor. The results showed that the number of passes and slope and skidder type had strong effects on the intensity of soil disturbance. The results suggest that the rubber-tired skidder causes soil disturbance with lower traffic intensity than the crawler tractor. The dramatic increase of soil disturbance caused by the rubber-tired skidder may be associated with higher static ground pressures.

Keywords: bulk density, forest floor, skidder type, skid trail slope, soil disturbance.

Introduction

Successful planning of skidding operations with minimized soil compaction depends on knowledge on the distribution of soil types in the area to be managed, as well as knowledge on the response of each soil to compaction pressure. It is important to know the relationship between the susceptibility of forest soils and the machinary and equipment to be used. Mechanized ground-based logging systems are widely used since they generally have provided a safer work environment, higher quality products, and greater labour productivity (Akay and Sessions 2001). In these systems, the forest products are generally transported from stump to the landing areas by skidders and forwarders, either rubber-tired skidders or crawler tractors. Ground-based logging systems may cause serious disturbance to the physical properties of forest soil due to soil compaction (Grace et al. 2006). The most significant changes occur on soil surface layers resulting in possible restrictions for 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). Soil compaction and reduction of total porosity are unavoidable consequences of skidding operations, which may vary in intensity and distribution due to the interaction between machine and site factors at the time of harvesting. The extent of the impact varies according to many factors such as slope, site characteristics, harvesting machines, traffic levels, planning of skid roads and production season (Bettinger et al. 1994, Demir et al. 2007, Najafi et al. 2009, Naghdi et al. 2010, Naghdi and Solgi 2014).

The number of machine passes is a factor that significantly influences the degree of soil damage. Several scholars (Froehlich 1978, Ampoorter et al. 2007, Najafi et al. 2010) have studied the impact of the frequency of machinery passes on soil compaction. These studies showed that the most severe compaction happens during the first few passes of the machinery (Sundberg 1988). Subsequent passes may damage the soil less, but they gradually increase the density levels and reduce non-capillary porosity to critical levels for tree growth (McNabb et al. 1997).

During skidding on steep terrain, a given load results in 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 stronger effect on soil disturbance than the number of machine passes, and the disturbance was greater on slopes with inclination over 20 % in comparison to slopes with inclination less than 20 %.

The type of machinery used in timber harvesting can be a significant factor in determining the extent of soil disturbance. Crawler tractors may have a lower impact on soil than rubber-tired skidders due to lower static ground pressures (Sheridan 2003). Murosky and Hassan (1991) found that a crawler tractor caused less increase in bulk density than two other rubber-tired skidders over a range of conditions and soil depths.

Compaction involves rearrangement and packing of the solid particles of the soil leading to an increase in bulk density. When bulk density increases, a decrease in total porosity (Rab 1994, McNabb et al. 2001, Najafi et al. 2009), tree height, diameter and volume growth (Murphy et al. 2004, Tan et al. 2006) are often observed.

Compacted forest soil due to harvesting operation can persist for several decades depending on soil texture, machine activity, soil water content, and other soil conditions at the time of harvesting (Kozlowski 1999, Rab 2004, Demir et al. 2007).

Apart from compaction, one of the major deficiencies also caused by the skid roads is loss of organic matter from the forest floor (Demir et al. 2007). Mixing or removal of litter and soil may change the physical, chemical or biological properties of soil. Organic material retention can significantly increase microbial biomass due to increased carbon availability for microbial metabolism (Mendham et al. 2002). Forest floor removal increases the mean temperature in the mineral soil during the growth season (Tan et al. 2005).

Accordingly, the aims of this paper were to (1) study compaction effects of rubber-tired skidder in comparison to crawler tractor on forest soils and (2) evaluate combined effects of traffic intensity on skid trail slope caused by logging operations using a crawler tractor and a rubber-tired skidder on bulk density and forest floor removal in the Hyrcanian forests of Northern Iran.

Material and Methods

Study site

The research was carried out in September 2012 in Sorkhkola forest, Mazandaran Province, Northern Iran, between 36°11'N and 36°17'N, and 52°17'E and 52°57'E. The tree stand in the study area was dominated by *Fagus orientalis* and *Carpinus betulus.* The cover of canopy reached 80 %, the average tree diameter was 29.72 cm, the average height was 22.94 m, and stand density was 220 trees ha^{-1}. The altitude was approximately 700 m above the sea level, slopes were exposed to the north. The average annual rainfall recorded at the nearest national meteorological station was 1,280 mm. The mean maximum monthly rainfall (120 mm) usually occurs in October, while the minimum rainfall (25 mm) occurs in August. The mean annual air temperature is +15 °C, and the lowest air temperatures are recorded in February. At the time of skidding, the weather condition was wet with average soil moisture content of 32 %. Soil texture along the skid trail was clay loam and was analyzed using the Bouyoucos hydrometer method (Majnonian and Jourgholami 2013). The soil had not been driven on before the experiment.

The machines used were crawler tractor “Onezhets 110” and rubber-tired skidder “Timberjack 450C” (Table 1). Both operators had several years of experience, and they performed all service and most of the repair work.

Table 1. Technical specification of crawler tractor “Onezhets 110” and four-wheel drive skidder “Timberjack 450C”

Characteristic	“Onezhets 110”	“Timberjack 450C”
Length (m)	6.2	6.4
Width (m)	2.6	2.4
Height (m)	3.20	3.15
Mass (kg)	12500	10275
Front tyres	-	24.5-32
Rear tyres	-	24.5-32
Length of Track (cm)	185	-
Width of Track (cm)	69	-
Ground pressure (kPa)	49	221
Power (kw)	88.26	130.1
Fuel tank capacity (dm^3)	140	232

For determination of the tyre /soil contact area and finaly ground pressure, prior to the trial, the two machines were weighed to obtain their total load. The tyre /soil contact area was measured on the experimental field by reversing or driving the machines into the field and spraying the area around the tyre with paint. A hydraulic lift was then used to raise the machine and the tyre impression outlined on a sheet of glass by placing the glass on the soil surface. The observed area free of paint was then transferred to paper and measured with a planimeter. Average ground pressure was estimated as the total axle load divided by the tyre–soil contact area for both tyres on the axle (Botta et al. 2009).

Experimental treatments and layout

A recently used skid trail with 1,400 m length and 4 m width running parallelly to the slope (south-north direction) was selected for the experiments.

The impacts of skidding on soil surface layer (0-10 cm depth) of the skid trail were examined using bulk density and mass of forest floor per ha at specified degrees of traffic and slope for both vehicles in comparison to undisturbed area. There were 16 treatments due to combination of traffic intensity (5, 10, 15 and 20), skid trail slope (0-15 % and >15 %) and machine types (crawler tractor and rubber-tired skidder). Each treatment was replicated three times, therefore 48 plots were obtained. The10 m-long and 4 m-wide rectangular shaped plots were delineated prior to skidding. There was at least 5 m buffer zone between the plots to avoid interactions. The soil samples were taken along four randomized skid trails 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 one sample at 0–10 cm depth below the forest floor. Moreover, for control purposes, soil samples were taken from the undisturbed area at 0-10 cm depth and forest floor without any visible impacts of skidding operations, at least 50 m away from the skidding road.

Forest floor samples were taken by collecting 1 m^2 of soil surface. The soil samples from the depth of 0–10 cm were collected using a soil hammer and rings (diameter=5 cm, height=10 cm). Samples were put in polyethylene bags and labeled. The collected samples were taken to the laboratory and subsequently weighed. Soil and forest floor samples were dried in an oven under 105 °C (24 h) and 65 °C (48 h), respectively (Turk et al. 2008).

An analysis of variance (ANOVA) was carried out on the data, and the means were analyzed by Duncan's multiple range tests utilizing the SPSS 16 software.

Results

Soil bulk density

The average soil bulk density measured on an undisturbed area was 1.155 g cm^{-3}. The average bulk density on the skid trail varied from 1.451 g cm^{-3} to 1.717 g cm^{-3} under impact of the rubber-tired skidder, and from 1.353 g cm^{-3} to 1.656 g cm^{-3} under impact of the crawler tractor. Both for crawler tractor and rubber-tired skidder, bulk density significantly increased with increasing traffic intensity and skid trail slope (Figure 1a and Figure 1b). The results showed that for both machine types (crawler tractor and rubber-tired skidder), the average bulk density under treatment with 15 passes and on slopes more than 15 % was higher than that of the treatment with over 15 passes and on slopes 0-15 % (Table 2). In addition, the slope of trail affected the bulk density. In all skidder passes and skid trail slope treatments, the bulk density increased considerably with a change in skidder type from crawler tractor to rubber-tired skidder (Figure 2).

Bulk density was significantly influenced by the number of skidder passes (p = 0.037), slope (p = 0.012), and machine type (p = 0.041), but the interaction between those variables was not significant (p = 0.147).

Forest floor

Forest floor removal on the skid trail caused by terrain transportation of timber was highly variable in the spatial extent and severity. In all traffic intensity and skid trail slope treatments, litter mass decreased considerably with a change in skidder type from crawler tractor to rubber-tired skidder (Figure 3).

The average forest floor was 3,053.68 kg ha^{-1} on undisturbed area, while on the skid trail it varied from 54.66 kg ha^{-1} to 2,012.22 kg ha^{-1} for rubber-tired skidder, and from 470.44 kg ha^{-1} to 2,489.66 kg ha^{-1} for crawler tractor (Table 3).

Figure 4 shows the influence of traffic intensity and skid trail slope on the mass of forest floor along the skid trail (Figures 4a, 4b). The highest forest floor removal was found on trails with the highest traffic intensity class and slopes over 15% . Forest floor removal by rubber-tired skidder was higher than that caused by crawler tractor in similar working conditions. The influence of the trail

Table 2. Influence of machine type, traffic intensity and slope on soil bulk density

Number of passes	Machine type			
	Rubber-tired skidder		Crawler tractor	
	Slope (%)			
	0-15	>15	0-15	>15
	Soil bulk density (g cm^{-3})			
5	1.451^b	1.511^b	1.353^d	1.404^d
10	1.632^a	1.677^a	1.468^c	1.547^c
15	1.664^a	1.698^a	1.591^b	1.632^b
20	1.691^a	1.717^a	1.627^a	1.656^a

Note: Bulk density values in the same column marked with the same lower case letter are not significantly different (p > 0.05).

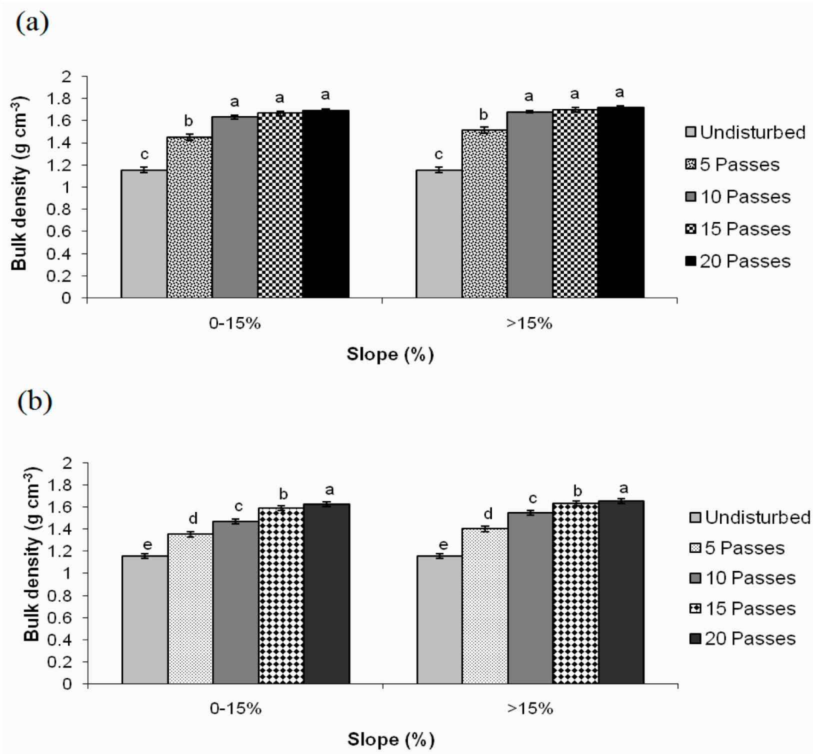

Figure 1. Effect of traffic intensity on soil bulk density under the influence of rubber-tired skidder (a) and crawler tractor (b). The error bars depict the standard error. Bulk density values marked with the same lower case letter in each slope class are not significantly different ($p > 0.05$)

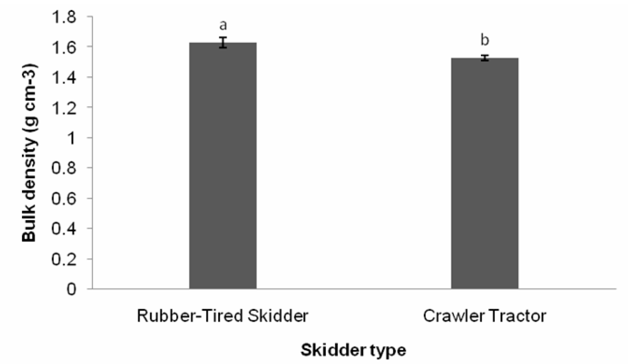

Figure 2. Effect of skidder type on average soil bulk density. The error bars depict the standard error. Bulk density values marked with the same lower case letter are not significantly different ($p > 0.05$)

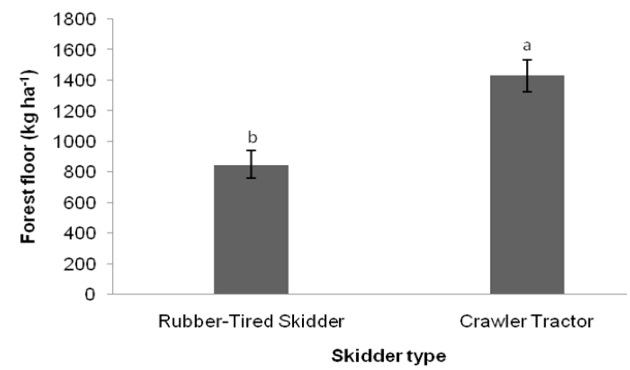

Figure 3. Effect of skidder type on average forest floor per ha. The error bars depict the standard error. Values marked with the same lower case letter are not significantly different ($p > 0.05$)

Table 3. Influence of machine type, traffic intensity and slope on the mass of remaining forest floor per ha

Number of passes	Machine type			
	Rubber-tired skidder		Crawler tractor	
	Slope (%)			
	0-15	>15	0-15	>15
	Mass of forest floor (kg ha^{-1})			
5	2012.22^{d}	1518.22^{d}	2489.66^{d}	2271.33^{d}
10	1276.55^{c}	745^{c}	1742.33^{c}	1490^{c}
15	675.33^{b}	307.11^{b}	1301.88^{b}	879.22^{b}
20	203.44^{a}	54.66^{a}	800.44^{a}	470.44^{a}

Note: Values in the same column marked with the same lower case letter are not significantly different ($p > 0.05$).

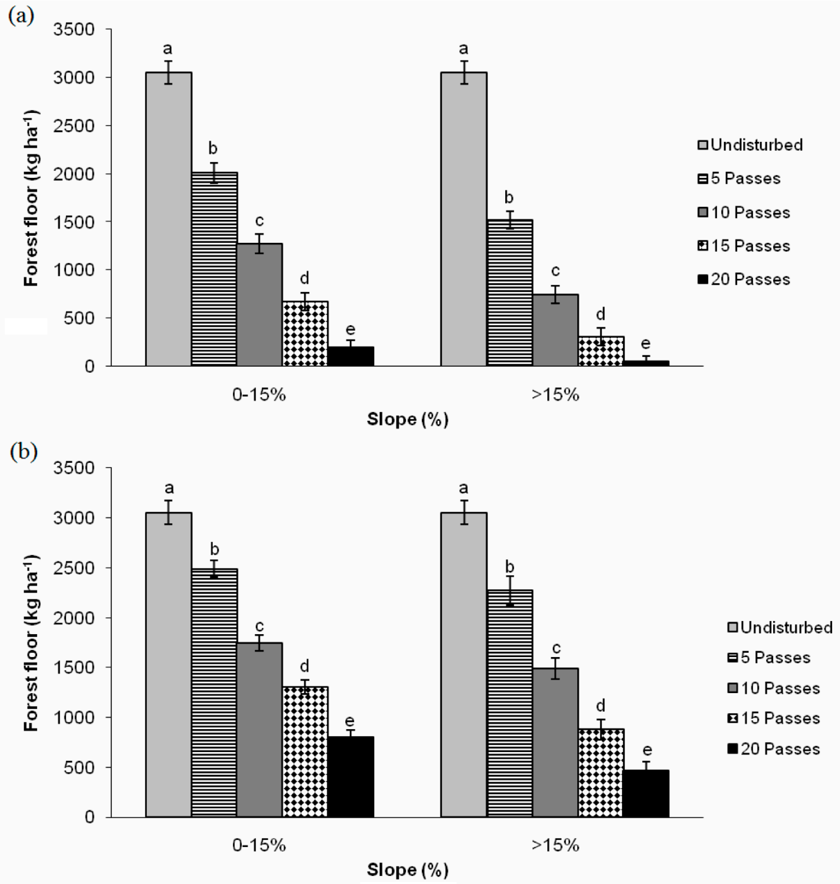

Figure 4. Effect of traffic intensity on the mass of forest floor for rubber tired skidder (a) and crawler tractor (b). The error bars depict the standard error. Values in the same slope class marked with the same lower case letter are not significantly different ($p > 0.05$)

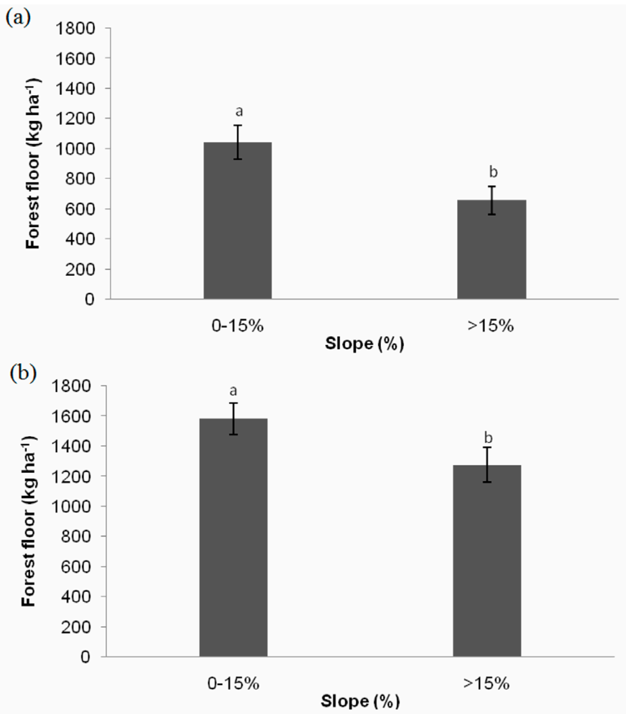

Figure 5. Effect of skid trail slope on the mass of forest floor for rubber tired skidder (a) and crawler tractor (b). The error bars depict the standard error. Values marked with the same lower case letter are not significantly different ($p > 0.05$)

slope on the mass of forest floor is presented in Figures 5a and 5b. With increasing slope, the mass of forest floor decreased for both vehicle types.

Statistically, the mass of forest floor was significantly influenced by the number of skidder passes ($p = 0.029$), skid trail slope ($p < 0.045$), and machine type ($p = 0.031$). Interaction between them was not statistically significant ($p = 0.362$).

Discussion

The results suggest that there are differences between two skidder types in terms of their influence on soil bulk density and the remaining mass of forest floor. According to our results, both increasing traffic intensity and increasing skid trail slope increased soil bulk density for both vehicle types. Similar results were obtained by Garrison and Rummell (1951), Krag et al. (1986), Eliasson (2005), Botta et al. (2006), Ampoorter et al. (2007) and Najafi et al. (2009). The increase in bulk density and negative effects on forest floor on steeper slopes have also been observed in other studies (Najafi et al. 2009, Naghdi et al. 2010, Solgi et al. 2014). This may be a consequence of the difficulties of skidding in steep terrain, where machines can slip continuously and remain in a given place for a longer period of time, resulting in more puddling and dragging of the soil (Gayoso and Iroume 1991). Most of the compaction, expressed as the increase of bulk density, takes place during the initial passes. As proved by this study, high increase in bulk density (28.2 %) for skid trails already appears after five passes of the skidder. Our results are in accordance with the results of Ampoorter et al. (2007), who found that the bulk density increases gradually with 50 % of the total impact occurring after the first three passes. The type of machinery is one of the most important factors determining the degree and the extent of compaction. The results showed that compaction created by rubber-tired skidder “Timberjack 450C” was significantly higher ($p < 0.05$) than that caused by crawler tractor “Onezhets 110”. Lower increase in bulk density by the crawler tractor may be associated with lower static ground pressure. Our results are in accordance with the results of Murosky and Hassan (1991), who found that a steel-tracked skidder (crawler tractor) caused lower increase in bulk density than two types of rubber-tired skidders over a range of conditions and at various soil depths. Rusanov (1991) found that crawler tractors compacted the soil less than wheeled skidders in similar sized classes.

In this study, the number of skidder passes, skid trail slope percent, and machine type significantly affected forest floor removal. Trail steepness has a strong effect on the forest floor removal during skidding. Slipping and slip sinkage may mix mineral soil and litter resulting in increased displacement, rutting and decreasing of litter mass. Similar results were found by other researchers (e.g. Johnston and Johnston 2004, Demir et al. 2007, Najafi et al. 2009). The intensity of soil disturbance may be influenced not only by the frequency of trips over the same tracks, but also by soil wetness, vibration, texture, and organic matter (Vogt et al. 1999). The decrease of forest floor mass and increase of bulk density on steep slope trails may be associated with higher slip ratio of skidder on steep slope trail. Furthermore, uneven weight distribution on steep slopes decrease the rolling radius of rear wheels, which increases the slip of the front wheels with lower axle load and higher rolling radius. This was noticed also by 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 a depth of 10 cm.

Conclusions

The study compared changes in the soil bulk density and litter mass due to timber haulage by two ground-based logging machines on two different slope classes and four traffic intensities. The results showed that there were differences between both machine types in terms of two key soil parameters, bulk density and the mass of forest floor. Compaction caused by rubber-tired skidder “Timberjack 450C” was significantly higher than that caused by crawler tractor “Onezhets 110”. Compaction of soil during skidding increases soil bulk density on the skid trail. With increasing compaction the soil porosity decreases. When soil is compacted, total porosity is reduced at the expense of the large voids. There is a positive relationship between soil compaction and skid trail slope and traffic intensity. Therefore, the hypothesis that skid trail slope and skidder passes have an effect on soil bulk density and litter mass removal was supported.

Acknowledgements

This paper represents part of a research project “Assessing the effects of various systems of wood extraction from forest on soil physical, chemical and micro-morphological properties and regeneration in the northern forest of Iran”, which was sponsored by the Iranian National Science Foundation, Depute of Science and Technology, Presidential Office. The authors are grateful to the Iranian National Science Foundation.

References

Agherkakli, B., Najafi, A. and Sadeghi, S.H. 2010. Ground based operation effects on soil disturbance by steel tracked skidder in a steep slope of forest. *Journal of Forest Science* 56 (6): 278-284.

Akay, A.E. and Sessions, J. 2001. Minimizing road construction plus forwarding costs under a constraint of soil disturbance. *International Mountain Logging and 11th Pacific Northwest Skyline Symposium*, Seattle, Washington, USA: 61-70.

Ampoorter, E., Goris, R., Cornelis, W.M. and Verheyen, K. 2007. Impact of mechanized logging on compaction status of sandy forest soils. *Forest Ecology and Management* 241 (1): 162-174.

Bagheri, I. and Naghdi, R. 2011. Effect of HSM 904 wheel skidder and Zetor crawler skidder on rutting and soil displacement. *Silva Balcanica* 12 (1): 113-120.

Bettinger, P., Armlovich, D. and Kellogg, L.D. 1994. Evaluating area in logging trails with a geographic information system. *Transaction of the American Society of Agricultural Engineers* 37 (4): 1327-1330.

Botta, G.F., Jorajuria, D., Rosatto, H. and Ferrero, C. 2006. Light tractor traffic frequency on soil compaction in the Rolling Pampa region of Argentina. *Soil and Tillage Research* 86 (1): 9–14.

Davies, D.B., Finney, J.B. and Richardson, S.J. 1973. Relative effects of tractor weight and wheel-slip in causing soil compaction. *Journal of Soil Science* 24 (3): 401-409.

Demir, M., Makineci, E. and Yilmaz, E. 2007. Investigation of timber harvesting impacts on herbaceous cover, forest floor and surface soil properties on skid road in an oak (*Quercus petrea* L.) stand. *Building and Environment* 42 (93): 1194-1199.

Eliasson, L. 2005. Effects of forwarder tyre pressure on rut formation and soil compaction. *Silva Fennica* 39 (4): 549–557.

Froehlich, H.A. 1978. Soil compaction from low ground-pressure, torsion-suspension logging vehicles on three forest soils. Oregon State University, Forest Research Laboratory, Corvallis, OR, Research Paper 36, 13 pp.

Garrison, G.A. and Rummell, R.S. 1951. First-year effects of logging on Ponderosa pine forest range lands of Oregon and Washington. *Journal of Forestry* 49: 708-713.

Gayoso, J., Iroume, A. 1991. Compaction and soil disturbances from logging in southern Chile. *Annals of Forest Science* 48: 63-71.

Grace, J.M., Skaggs, R.W. and Cassel, D.K. 2006. Soil physical changes associated with forest harvesting operations on an organic soil. *Soil Science Society of America Journal* 70: 503.

Johnston, F.M. and Johnston, S.W. 2004. Impacts of road disturbance on soil properties and exotic plant occurrence in subalpine areas of Australian Alps. *Arctic, Antarctic and Alpine Research* 36 (2): 201–207.

Kozlowski, T.T. 1999. Soil compaction and growth of woody plants. *Scandinavian Journal of Forest Research* 14 (6): 596–619.

Krag, R., Higgingbotham, K. and Rothwell, R. 1986. Logging and soil disturbance in southeast British Columbia. *Canadian Journal of Forest Research* 16 (6): 1345-1354.

Lacey, S.T. and Ryan, P.J. 2000. Cumulative management impacts on soil physical properties and early growth of *Pinus radiata*. *Forest Ecology and Management* 138 (1): 321–333.

Majnonian, B. and Jourgholami, M. 2013. Effect of rubber tired cable skidder on soil compaction in Hyrcanian forest. *Croation Journal of Forest Enginnering*, 34 (1):123-135.

McNabb, K.L., Miller, M.S., Lockaby, B.G., Stokes, B.J., Clawson, R.G., Stanturf, J.A. and Silva, J.N.M. 1997. Selection harvest in Amazonian rainforest: long-term impacts on soil properties. *Forest Ecology and Management* 93 (1): 153-160.

McNabb, D.H., Startsev, A.D and Nguyen, H. 2001. Soil wetness and traffic level effects on bulk density and air-filled porosity of compacted boreal forest soils. *Soil Science Society of America Journal* 65 (4): 1238-1247.

Mendham, D.S., Sankaran, K.V., Oconnell, A.M. and Grove, T.S. 2002. Eucalyptus globules harvest residue management effects on soil carbon and microbial biomass at 1 and 5 years after plantation establishment. *Soil Biology and Biochemistry* 34 (12): 1903-1912.

Murosky, D.L. and Hassan, A.E. 1991. Impact of tracked and rubber tired skidders traffic on a wetland site in Mississippi. *TASAE* 34 (1): 322-327.

Murphy, M., Firth, J.G. and Skinner, M.F. 2004. Long-term impacts of forest harvesting related soil disturbance on log product yields and economic potential in a New Zealand forest. *Silva Fennica* 38 (3): 279-289.

Naghdi, R., Bagheri, I. and Basiri, R. 2010. Soil disturbances due to machinery traffic on steep skid trail in the north mountainous forest of Iran. *Journal of Forestry Research* 21(4): 497-502.

Naghdi, R. and Solgi, A. 2014. Effects of skidder passes and slope on soil disturbance in two soil water contents. *Croatian Journal of Forest Engineering* 35 (1): 73-80.

Najafi, A., Solgi, A. and Sadeghi, S.H. 2009. Soil disturbance following four wheel rubber skidder logging on the steep trail in the north mountainous forest of Iran. *Soil and Tillage Research* 103 (1): 165–169.

Najafi, A., Solgi, A. and Sadeghi, S.H. 2010. Effects of skid trail slope and ground skidding on soil disturbance. *Caspian Journal of Environmental Science* 8 (1): 13-23.

Rab, M.A. 1994. Changes in physical properties of a soil associated with logging of *Eucalyptus regnan* forest in southeastern Australia. *Forest Ecology and Management* 70 (1/3): 215-229.

Rab, M.A. 2004. Recovery of soil physical properties from compaction and soil profile disturbance caused by logging of native forest in Victorian Central Highlands, Australia. *Forest Ecology and Management* 191 (1/3): 329–340.

Raghavan, G. S. V., McKyes, E. and Beaulieu, B. 1977. Prediction of clay soil compaction. *Journal of Terramechanics* 14: 31-38.

Rusanov, V.A. 1991. Effects of wheel and track traffic on the soil and crop growth and yield. *Soil and Tillage Research* 19: 131-143.

Sheridan, G.J. 2003. A comparison of rubber tired and steel-tracked skidders on forest soil physical properties. *Australian Journal of Soil Research* 41(1): 1063-1075.

Sundberg, U. 1988. Operational efficiency in forestry, Vol. 2. Kluwer Academic Publishers, Dordrecht, 170 pp.

Tan, X., Scott, X.C. and Kabzems, R. 2005. Effects of soil compaction and forest floor removal on soil microbial properties and N transformations in a boreal forest long-term soil productivity study. *Forest Ecology and Management* 217(2): 158-170.

Tan, X., Kabzems, R. and Chang, S.X. 2006. Response of forest vegetation and foliar $\delta^{13}C$ and $\delta^{15}N$ to soil compaction and forest floor removal in a boreal aspen forest. *Forest Ecology and Management* 222 (3): 450-458.

Turk, T.D., Schmidt M.G. and Roberts N.J. 2008. The influence of bigleaf maple on forest floor and mineral soil. *Forest Ecology and Management* 255 (2): 1874-1882.

Vogtal, D.J., Larson,B.C., Gordon, J.C. and Fanzeres, A. 1999. Forest Certification: Roots, Issues, Challenges, and Benefits. School of Forestry and Environmental Studies, Yale University, New Haven, Connecticut, CRC Press, Boca Raton London New York Washinton, D.C., 394 pp.

Received 06 May 2014
Accepted 30 September 2016