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Considering the soil compaction status on logging areas in a Hyrcanian forest

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ABSTRACT: This paper deals with the issue of soil compaction during timber harvesting operations on cutting areas. Soil compaction was assessed following the logging operation in Darabkola forest area by measuring soil bulk density. In this research, a completely random sampling method was used to assess the resulting changes in soil bulk density. Soil bulk density was measured using bulk density sampler on felling, bucking, delimbing and control areas. The results showed that the bulk density value in the top soil layer increased with increasing tree volume and was not dependent on the terrain slope on the felling area. Also, there was a significant relationship between the bulk density value of felling area and tree volume. Further analysis showed that there was no significant relationship between bulk density values on felling, bucking, delimbing and control areas. It was shown that careful harvesting planning, restriction, skidding and directional felling limited the soil compaction and helped the soil conservation.

Keywords: cutting area; slope; timber harvesting; tree volume

The goal of forest management is to sustain continual development of forest ecosystems that fulfil their productive and non-productive functions optimally. In order to achieve this goal, the full productive capacity of forest stands needs to be maintained while preserving all the natural processes and constituents in the soil, including microbiological organisms, physical properties, nutrient reserves and regeneration processes of the ecosystem (Gebauer et al. 2012). Timber harvesting is considered as a soil disturbing activity because it disturbs forest floor, exposes soils and may lead to sedimentation (Ballard 2000; Najafi et al. 2009; Lotfalian, Bahmani 2011; Alexander 2012). The compaction of forest soil is a source of soil disturbance during ground-based timber harvesting operations (Naghdi et al. 2007; Naghdi et al. 2009). Compaction has been shown to have a long-term negative impact on soil properties and tree growth rates particularly on the primary snig tracks, log landings and general areas where the subsoil has been disturbed (Rab 2004). The extent and severity of harvesting impacts depend on a number of factors, such as inherent soil properties, topography, the type of operation (i.e. whether the forest was selectively logged or it was clear felled, ground-based or cable-logged), the type of machinery used, the frequency of machine passes and the forest conservation practices being employed (Sowa, Kulak 2008; Demir et al. 2010; Serevadio 2010).

Compaction is perceived as one of the leading causes of soil degradation resulting from forest harvesting operations. Forest soil sustainability is at risk if mechanized harvesting operations cause soil damage. Therefore, soil compaction is a major concern whenever forest management activities involve heavy machines. Soil compaction during timber harvesting typically alters the soil structure and hydrology by increasing bulk density, breaking down aggregates, decreasing porosity, and altering infiltration capacity and by increasing soil strength, enhancing water runoff and erosion potential and finally water-logged soil (Goderfroid, Koedam 2004; Safih-Hdadi et al. 2009; Najafi, Solgi 2010).

Forest soil maintenance is a key factor for sustaining productive forests. Timber harvest activities cause forest soil disturbance that has implications for site productivity that range from beneficial to detrimental. Factors controlling the compaction intensity in soil include site conditions, general harvest operations, tire size, frequency of machine passes, the volume and axle weight of timber hauled, post-harvest site preparation, and characteristics of the harvest equipment (Reeves 2011). A review of literature shows that although much research has focused on impacts of timber skidding on the soil compaction in forests, timber harvesting has received little attention.

The most visible and tangible result of soil compaction is its impact on soil bulk density; however, the intensity of this effect can vary in different situations. Soil bulk density was used as a soil compaction index (Soltanpur, Jourgholami 2013). Although the soil compaction may benefit the growth of some plants, the harmful effects are much more common (Goderfroid, Koedam 2004). Furthermore, soil rehabilitation practices are expensive to apply; hence, a compaction evaluation method to better understand soil compaction effects is needed (Zhao et al. 2010). By attention to results of previous studies like Lipiec and Hatano (2003), Zhao et al. (2010), Ziaee and Roshani (2012) that bulk density is commonly used to characterize the state of soil compactness; soil bulk density was selected as an index of soil compactness to consider the soil status of logging area in this study. Therefore our study includes the following objectives:
– to characterize the soil bulk density after felling, bucking and delimbing operations and determine their correlation;
– to determine a correlation between tree volume and terrain slope in the cutting area with soil bulk density;
– to assess a linear regression between soil bulk density and terrain slope and tree volume of the cutting area, and compare soil bulk density values in the cutting, bucking and delimbing areas.

MATERIAL AND METHODS

Study area. The study site is located in the western Mazandaran province in northern Iran. This research was conducted in compartment 13 of district 1 of Darabkola educational research experiment station. The latitude, longitude and elevation ranges of this forest are 36°33'20" to 36°33'30"N, 52°14'40" to 52°31'55"E and 180–900 m, respectively. Mean annual precipitation is 700–750 mm. The mean annual temperature is 16.7°C, with the lowest values in January (7.5°C). The soil texture in the study area is clay-loam to clay-silt. The forest is composed of deciduous trees dominated by beech *(Fagus orientalis* Lipsky*)*, hornbeam (*Carpinus betulus* L.), alder (*Alnus subcordata* C.A.U.), Persian ironwood *(Parotia persica)*. A silvicultural system practiced in the study area was single-tree selection. The trees were felled using a hand saw and the extraction of short logs from the stump area to the roadside depot spot was done by a ground-based skidding system. The skidder type used in this study was 450 C Timberjack model.

Data collection. Compaction is strongly related to soil bulk density (Godifroid, Koedam 2004; Jamshidi et al. 2013). The impacts of harvesting operation on the surface soil compaction were examined using soil bulk density. In this research, a completely randomized design (CRD) was used to assess compaction in the study area. Bulk density data was sampled using a bulk density cylinder sampler (10 cm length, 9 cm diameter and 635.85 cm^3 volume). Soil bulk density was measured on felling area (about 1 m around the felled tree), bucking, delimbing and control areas. Forty samples were taken in each of the area. The soil samples were wrapped in labelled bags and taken to the laboratory. Soil bulk density was calculated using equation (1):

$$pb = \frac{w_s - w_{sr}}{v_c - v_{sr}} \qquad (1)$$

pb – soil bulk density (g·cm^{-3}),
w_s – weight of the soil (g),
w_{sr} – weight of the stone and root (g),
v_c – volume of the cylinder sampler (cm^3),
v_{sr} – volume of the stone and root (cm^3).

The terrain slope on the cutting area and the volume of felled trees were also measured.

Data analysis. Data were analysed using Statistical Package for the Social Sciences (SPSS) for Windows version 13. Linear regression analysis was used to determine the relationship of the terrain slope and tree volume as independent variables and soil bulk density in the cutting area as dependent variable. A similar approach was also used to assess soil bulk density on felling, bucking, delimbing and control areas. The Pearson correlation analysis was used to determine whether there is a correlation between (1) soil bulk densities on felling, bucking and delimbing areas, (2) soil bulk densities on felling, bucking, delimbing areas and the terrain slope, and (3) soil bulk densities of the mentioned area and the harvested tree volume.

RESULTS

The results of soil bulk densities on the logging and control areas are shown in Fig 1. The highest and the lowest mean value of bulk density occurred on felling and control area, being 1.228 ± 0.188 and 1.044 ± 0. g·cm^{-3}, respectively.

The results of correlation analysis (Pearson test) between soil bulk densities of felling, bucking and delimbing areas are shown in Table 1. No significant correlations were observed between soil bulk densities on felling, bucking and delimbing areas.

Correlations between the terrain slope, tree volume and bulk densities on felling, bucking and delimbing areas were also analysed by the Pearson test (Table 2). The results showed that there were significant and positive correlations between tree volume and soil bulk densities on felling areas. But there was no correlation between tree volume and soil bulk density of bucking and delimbing areas. However, the correlation between slope and soil bulk density was negative but no significant correlation was observed between the terrain slope and soil bulk density in the harvested area.

The results of linear regression analysis between bulk density on the felling area and tree volume are shown in Table 3. In the linear regression R = 0.912. R^2 = 0.833, adjusted R^2 = 0.828 and p value was significant (Sig = 0.000, α = 0.05).

According to this analysis, the equation was as follows (Eq. 2):

$$Y = 1.084 + 0.032\,x_1 \quad (2)$$

where:
y – soil bulk density of felling area,
x_1 – tree volume.

However, in the linear regression between the terrain slope and soil bulk density on the felling area (Table 3) R = 0.114, R^2 = 0.113, adj R^2 = –0.013 and P value was not significant (Sig = 0.483, α = 0.05).

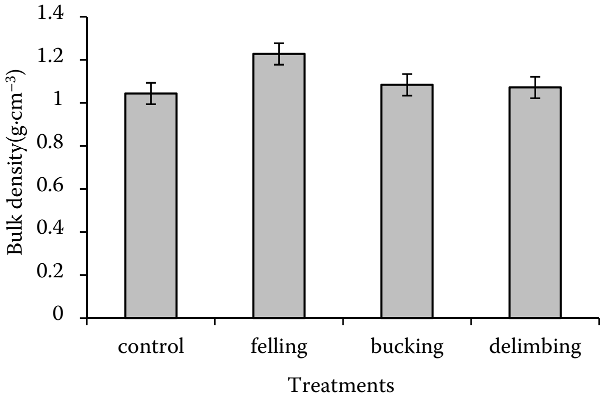

Fig. 1. Soil bulk density of the logging area

Also, the results of linear regression analysis of soil bulk density of felling, bucking, delimbing and control areas are shown in Table 3. In the linear regression R = 0.259, R^2 = 0.067, adj R^2= –0.010 and P value was not significant (Sig = 0.468, α = 0.05).

DISCUSSION

Timber harvesting is the integration of all operations related to the cutting of trees and the extraction of merchantable logs for subsequent processing into industrial products. Soil disturbance in forested ecosystems most commonly occurs from ground-based harvesting and site activities (Makinece et al. 2007; Najafi et al. 2010). The rate of soil disturbance (specially soil compaction) varies considerably depending on the method of felling, the type of soil preparation, the terrain condition, the timing of the activity and the preparation and personal responsibility of workers (Rab 2004; Demir et al. 2007; Makinece et al. 2007; Najafi et al. 2010). Soil disruption by harvesting is also affected by soil conditions during the activity (e.g. soil resistance, humidity, etc.), concrete features of the activities (e.g. frequency of passages) and the

Table 1. Pearson test of soil bulk densities on logging areas

Soil bulk density	Felling		Bucking		Delimbing	
	P	Sig	*P*	Sig	*P*	Sig
Felling	1	–	0.224	0.164	0.185	0.254
Bucking	0.224	0.164	1	–	0.171	0.293
Delimbing	0.185	0.254	0.171	0.293	1	–

Table 2. Pearson test of logging area, slope and tree volume

Variable	Felling		Bucking		Delimbing	
	P	Sig	*P*	Sig	*P*	Sig
Slope	–0.114	0.483	–0.207	0.200	–0.118	0.469
Tree volume	0.912**	0.000	0.179	0.269	0.229	0.155

Table 3. The results of linear regression analysis between variables

Model	Sum of square	df	Mean square	*F*	Sig
Bulk density on the felling area and tree volume					
Regression	0.464	1	0.464	189.023	0.000
Residual	0.093	38	0.002		
Total	0.557	39			
Terrain slope and soil bulk density on the felling area					
Regression	0.007	1	0.007	0.502	0.483
Residual	0.550	38	0.014		
Total	0.557	39			
Bulk density of felling, bucking, delimbing and control areas					
Regression	0.062	3	0.021	0.866	0.468
Residual	0.865	36	0.024		
Total	0.927	39			

impact (stress and vibration) on the soil by harvesters and forwarders (Han et al. 2009). Protecting the productive capacity of soil is a paramount goal of sustainable forest management.

Regarding the impact of logging on soil compaction, the authors like Rab (2004); Demir et al. (2007) reported on the impact of machinery, transit and traffic intensity on the soil condition. This research was quite different in some aspects as it studied the impact of harvesting operations on soil compaction. There was an impact on soil compaction related to the harvested tree volume, but the impact of the terrain slope was not significant. The results also showed that the entire harvesting operation, except for felling, had no significant correlation with soil bulk density. The bulk density value in the topsoil layer of felling area increased with increasing tree volume, but it was not influenced by the terrain slope of the felling area (Table 2). While Agherkakli et al. (2010) revealed that the bulk density increment was measured with an increase in traffic frequency, the increment varied between slope classes. Considering the effect of skidding on the soil status, Bagheri et al. (2012) also concluded that the average soil dry bulk density in a log track was higher than in other positions because of the heavy weight of a log exerting pressure on the soil. Hence, the significant increase in soil bulk density on the felling area could be related to the high volume of big trees on the felling area. Soil compaction decreases hydraulic conductivity, infiltration capacity and increases runoff (Makinece et al. 2007; Agherkakli et al. 2010). Soil erosion is influenced by the amount and velocity of runoff, rainfall intensity and distribution and so on; disturbances to a forested watershed, such as timber harvesting operations, can result in a large sediment input into downstream and considerable damage to soil productivity. All of these processes increase the soil recovery time. However, further analysis showed that there was a significant relationship between bulk density of the felling area and tree volume (Table 3). But there was no significant relationship between bulk density values and felling, bucking, delimbing and control areas (Table 3). It was also shown that the terrain slope of the cutting area did not significantly affect bulk density during felling, bucking and delimbing operations. Considering timber harvesting effects on a skid road, Makinece et al. (2007) revealed that there were crucial differences in the values of compaction and bulk density of the soil samples from the skid road and the undisturbed area. However, the results of Ampoorter et al. (2010) indicated that soil texture, traffic intensity and position in relation to the wheel tracks generally turned out to have an insignificant influence on the compaction that was not similar to the results of this study.

Aside from these findings, it is well known that the environment under which soils are formed and evolved such as weathering, rainfall and organic matter plays a major role in determining the bulk density of the undisturbed soil (Williamson, Neilsen 2000). These factors could be taken into consideration in future research. Moreover, the initial bulk density could also be included in future studies as it may negatively influence bulk density changes according to Ampoorter et al. (2012). Researchers reported other attributes of soil physical properties that are influenced by soil bulk density and contribute to productive functions of forest soils such as those related to (*i*) as a root growth promotion medium (*ii*) as a medium to accept, hold and supply water (*iii*) as a medium to hold, supply and cycle mineral nutrients (*iv*) as a medium to promote optimum gas exchange (*v*) as a medium to promote biological activity and (*vi*) as a medium to accept, hold and release carbon (Schoenholz et al. 2000).

By detailed assessment of a harvesting operation, one could quantify the areal extent and link the characteristics of harvesting operation to the changes in physical soil responses and soil recovery dynamics. As was shown, harvesting led to increased soil bulk density, soil resistance to penetration, delayed soil recovery and decreased growth in skid trails and harvest area compared to the control area; on the other hand, recovery of soil is a long-term process and key element for sustaining forest productivity. Therefore, from this point of view, it is entirely justifiable to do further research in such areas.

CONCLUSION

As the soil is an important environment for a variety of soil animals and for the roots of trees and herbs, soil damage should be prevented as much as possible. But the soil compaction is influenced by endogenous soil factors (distribution and size of soil elements, soil bulk density, pore continuity, water content, etc.) as well as exogenous factors (choice of equipment, loading of wood, length of loading, intensity and means of harvesting, etc.). The passage of forestry machines and cutting process cause the soil compaction leading to significant changes in the soil structure and moisture conditions. When the soil is compacted, soil bulk density increases, porosity and water infiltration decreases, erosion speeds up, and all of these processes lead to changes in plant physiology. Results indicate that the slope of the logging area may play a less important role in the soil compaction than tree volume. While we are unsure whether the result reflects a true relationship or is an artifact of our sampling scheme, we did not find any evidence of a relationship between the slope and soil bulk density in felling, bucking and delimbing areas. Also, the results indicate that tree volume could affect the soil bulk density of the felling area. Since a major portion of soil compaction occurred on the felling area, despite the careful planning of skidding operation, restriction of felling (directional felling) would be an effective strategy to minimize soil compaction. Therefore, designing harvesting operations (specially felling) with due consideration of strategies such as conservation of soil, fauna and flora could help limit the soil compaction in areas close to tree stumps, which is an important task for the protection and enhancement of forest biological diversity. But it is difficult to draw a definitive conclusion about the role of slope on compaction on the logging area. Hence further research is required in forests to collect adequate documentation of the impact of timber harvesting operations on soil properties to determine the relationship of cutting processes and soil properties. The long-term processes of soil recovery show the necessity of these researches.

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