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The Influence of Skidding Operations on Forest Soil Properties and Soil Compaction in Bartin, Turkey

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Abstract

Mechanized harvesting operations yield high productivity; however, it damages forest soils seriously. The objective of this study is to determine the impacts of skidding operations on topsoil physical and chemical properties at four different forest floors (tractor road, skid trail, harvesting area and undisturbed area) after a harvesting season. Also, the relationship between soil compaction and soil moisture of these areas were analysed. Soil compaction was estimated with the values of topsoil penetration resistance on two soil depth layers (0-5 and 5-10 cm). In total, 24 soil samples were taken to the laboratory for some physical and chemical analyses. Three soil moisture levels were delineated for the different forest floor areas ranging from 28% to 54%. Significant negative correlation between penetration resistance and bulk density, soil pH and calcium carbonate and significant positive correlation between penetration resistance and organic C, total N and C_{org}/N_{total} ratio were found. It was determined that four study sites shared similar features all having heavy clay (53.5-65.2%) soils. According to soil analysis, the lowest bulk density value (0.89 g/cm^3) was found in harvesting area and the highest bulk density value (1.15 g/cm^3) was found on the tractor road. Also, the highest content of organic C was found on the skid trail as 5.57% and the lowest content of organic C was on the tractor road as 1.52%. As the soil moisture content increases when penetration resistance decreases, mechanized harvesting operations should be arranged according to precipitation and soil moisture.

Keywords: Forestry, Forest soil, Harvesting, Skidding, Soil compaction, Tractor road

1. Introduction

An optimal wood skidding on forest floor requires planning adequate density networks of forest roads including skid trails, tractor roads and landings. Tractor and skid roads allow entering the forest in order to reach the nearest wood products and skidding these products to nearest forest road. Logs are generally brought to the landing site by skidding or forwarding, thus implying movement of vehicles through the forest. In recent years, these vehicles have become progressively more powerful and efficient but also heavier, with increasing impacts on soil (Horn et al., 2007; Cambi et al., 2015). A negative consequence of forest harvesting by ground-based logging equipment is soil compaction. Soil compaction is shown as a priority research area with respect to soil protection in European Union countries. Ground-based logging systems can cause serious disturbance to the physical properties of forest soil due to soil compaction (Grace et al., 2006). Compaction is one of the major causes of soil degradation from logging equipment (Brais, 2001; Akay et al., 2007). Soil compaction results in reduced porosity, which implies limitations in oxygen and water supply to soil microorganisms and plants, with negative consequences for soil ecology and forest productivity (Cambi et al, 2015).

Rubber-tired skidders often increase soil compaction, which leads to an increase in soil strength (penetration resistance) and bulk density (Akay et al., 2007). Soil penetration resistance is an important mechanical property that can be used as an indicator of soil compaction. The extent of disturbances resulting from ground-based timber harvesting systems varies according to factors such as the slope and terrain, timber harvesting machines, methods of designating skid roads, and harvesting seasons. Ground-based skidding may result in soil penetration resistance (Eroglu, 2012) and other structural changes in the soil that influence soil water retention and reduce soil aeration, drainage, and root penetration (Froehlich et al., 1986). Roads are liable to have multiple impacts on animals, plants and ecosystems functioning (Trambulak and Frissell, 2000; Avon et al., 2010, Melemez et al., 2013). Soil damage in forest roads, skid roads and landings includes the removal of the organic layer and topsoil, soil compaction, and erosion of the exposed soil

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(Demir et al., 2010). Soil compaction is a widespread degradation process in forest sites. Soil degradation occurring on the structural formation of a natural soil system by rainfall or mechanical outer forces generally results in soil particles to be rearranged tighter than its previous status (Turgut, 2012). 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 level of the impact varies according to many factors such as skidder passage, skid trail slope, site characteristics, harvesting machines, planning of skid roads and harvesting season (Laffan et al., 2001; Demir et al., 2007; Najafi et al. 2009; Solgi and Najafi, 2014).

In managed forests, the degree of forest floor and soil disturbance (e.g., soil compaction) and physical damage to the ground flora depend on the skidding method, skidding equipment, and soil conditions (Williamson and Neilsen, 2000). On flat or slightly sloping terrain, wheeled machines are generally preferred by virtue of their higher performance in terms of productivity and cost (Spinelli et al., 2012; Cambi et al, 2015). Therefore, skidding operations should be efficiently designed by considering not only the factors that affect logging costs and productivity (Melemez et al., 2014) but also the main factors that influence soil compaction. Logging systems using rubber-tired skidders can generate more soil compaction than any other logging systems (Startsev, 2001). Han et al. (2005) also reported that the largest increases in soil strength with logging machine traffic occurred at 10 cm soil depth and then followed by at 20 cm and 30 cm soil depth, respectively (Akay et al., 2007). Significant soil surface disturbance occurs as machine traffic traverses wet lands due to the low bearing capacity that results from high soil moisture contents and low soil strength. Soil compaction levels increase in response to increased bulk density and the degree of change depending on soil moisture condition (Carter et al., 2007). The main outcome is soil compaction, the severity of which depends on several factors, such as vehicle mass, axle/wheel/track load, contact area of the vehicle with the soil, slope of the terrain, tire pressure, dynamic shear forces, and soil characteristics and moisture (Jansson and Johansson, 1998; Alakukku et al., 2003; Bygden et al., 2004; Cambi et al., 2015).

The aim of this study is to determine the impacts of skidding operations on topsoil physical and chemical properties of four different forest floors (undisturbed area, harvesting area, skid trail and tractor road) and assess the relationship between soil compaction and soil moisture of these areas resulting from harvesting operations. For this aim, soil samples were collected from the skid trail, tractor road, harvesting area and undisturbed area. In the study, soil compaction was estimated by measuring the values of topsoil penetration resistance on two soil depth layers (0-5 and 5-10 cm) and some recommendations were presented in order to decrease the negative effects on forest soil caused by harvesting operations.

2. Materials and methods

2.1 Site description

The study area was located approximately 10 km northwest of Bartin province. Soil samples were taken on four different forest floors; undisturbed area, harvesting area, skid trail and tractor road. There was oak tree species (*Quercus robur* L) in the study area. The diameters of the oak trees at breast height ranged from 10 to 18 cm, and their overall heights varied from 5 to 10 m. The altitude in the study area ranged from 50 to 150 m above sea level, with an average of 100 m. In addition, the study area has a north-northwest aspect and a 5-10% slope. Based on the Thornthwaite method (Thornthwaite 1948), the study site had a humid, mesothermal climate with little or no water deficiency and was characterized as being similar to oceanic climate conditions. According to climatological data over the past 30 years (Turkish State Meteorological Service-TSMS, 2012), the average annual air temperature is 12.1 °C, the average temperature during the coldest month (January) is 4.0 °C, and the average temperature during the hottest month (July) is 21.4 °C. The average annual precipitation is 1,087.1 mm, with about 34% of the rainfall occurring during the autumn season (from October to December). The relative humidity is nearly 80%. The principal geological formation of the study site is calcareous limestone, which has a fine texture.

2.2 Soil sampling and analysis

Soil samples were collected in a completely randomized design and taken from 6 points in each location (Figure 1). Then, they were transferred into labelled plastic bags after they were collected from the topsoil at a depth of 0 - 5 cm as 8.1-cm diameter soil cores. In total, 24 soil samples taken to the laboratory for some physical and chemical analyses. Soil samples were air-dried, grounded, and sieved (<2 mm) and thereby prepared for analysis. The physical analyses to be studied were soil texture, moisture content, bulk density, particle density, and porosity, while chemical analyses to be studied were soil pH, calcium carbonate, electrical conductivity, organic carbon and total nitrogen. The moisture content of the soil was determined gravimetrically by drying the soil sample at 105 °C in an oven until it achieved a constant weight. The hydrometer method was used to calculate the particle size distribution of the soil (Bouyoucos, 1962). The pH of the soil in a 1:2.5 soil/water suspension was measured using a pH meter, and the electrical conductivity of the soil was determined with an electrical conductivity meter using a 1:5 soil/water extract. The organic C content of the soil was estimated using potassium dichromate oxidation, and the total N content was determined using Kjeldahl digestion. The Scheibler calcimeter method was used to measure the $CaCO_3$ content of the soil (Rowell, 1994). The bulk density of the soils (g/cm^3) was calculated measuring masses and volumes (Blake and Hartge, 1986). The particle density of the soils (g/cm^3) was measured using the Pycnometer method, and pore space was calculated using bulk and particle densities (Brady, 1990).

2.3 Penetration resistance measurements

Penetration resistance, recorded using a penetrometer, is used to assess the degree of soil compaction (Sinnett et al., 2008). Penetration resistance was measured to determine the extent of soil compaction using a soil penetrometer. A method using a cone penetrometer has been widely used to estimate soil strength during logging operations (Akay et al., 2007). A static cone penetrometer with a 30º cone has been recommended by the American Society of Agricultural Engineers (ASAE) as the standard measuring device for characterizing the penetration resistance of soils. The force is commonly expressed in megapascals (MPa). As the operator pushes down on the penetrometer, the note keeper records cone index values for each depth increment to evaluate the degree and depth of compacted layers (ASAE, 1999). Soil penetration resistance was measured at the same locations where forest floor samples were taken, and was measured at two different soil depths (0-5 cm and 5-10 cm) for four areas using the penetrometer. The penetration resistance measurements were taken on 6th November, 14th November and 16th December in 2014. A total of 24 penetration resistance measurements were taken in each of the four forest areas for soil moisture changes in different periods. Three soil moisture levels were delineated for the different forest floor areas as 20-30%, 30-40% and 40-50%.

2.4 Statistical analysis

Descriptive statistics and correlation matrix was calculated about soil properties and penetration resistances. The observed values for each of these physical and chemical properties on the undisturbed area, harvesting area, skid trail and tractor road were compared statistically at a 0.05 significance level with one-way ANOVA and Duncan multiple comparison tests. The data obtained were analyzed using descriptive statistics, correlation and comparison tests by using SPSS software. Also, variations of penetration resistance with respect to different soil moisture were determined for different soil depths (0-5 cm and 5-10 cm).

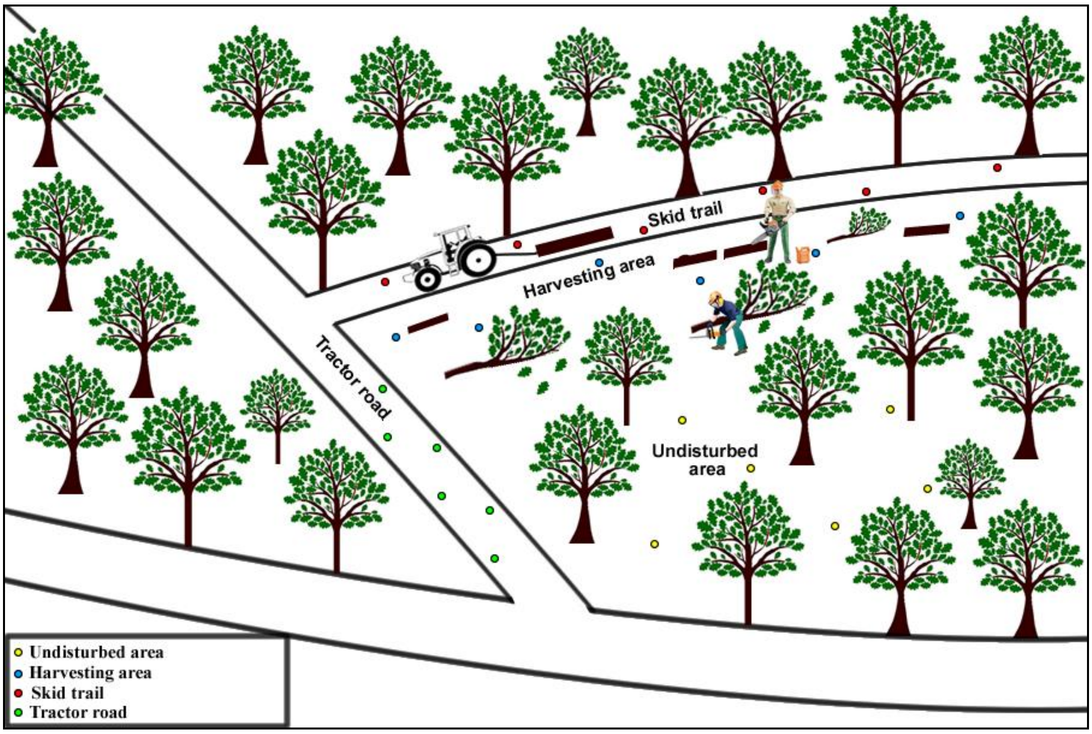

Figure 1. Illustration showing the points where soil samples were taken in the study site

3. Results and Discussion

Descriptive statistics including mean and standard deviation obtained from soil analyses related with soil physical and chemical properties are presented in Table 1. Results of the ANOVA and Duncan tests for four different forest soil floors are presented in Table 2. There is no statistically significant difference at 95% confidence interval among particle density, sand, silt, clay, electrical conductivity in undisturbed area, harvesting area, skid trail and tractor road. As statistically significant difference was found at 95% confidence interval among other soil properties.

Soil particle density ranged from 2.43 to 2.64 g/cm^3, and the highest particle density was found in tractor road. Soils that have low particle density contain high organic C (Brady, 1990; Plaster, 1992). The cause of the high particle density values of tractor road may be low organic C content of the area. According to soil analysis, the lowest bulk density value (0.89 g/cm^3) was found in harvesting area and the highest bulk density value (1.15 g/cm^3) was found on the tractor road. However the lowest pore space value (56.06%) was found in tractor road and the highest value (64.14%) was found in the harvesting area. The existence of the highest bulk density and the lowest pore space values in tractor road may arise from the fact that tractor road has lower soil compaction and organic C content than other areas. Measurements of soil properties in the surface layer (0–10 cm) demonstrated that bulk density is 57% higher and total porosity is 31% lower on the skid trail compared to the undisturbed area (Solgi and Najafi, 2014). Volumetric changes in soils occur either by inner forces (natural processes) such as wetting-drying or by outer forces (mechanical forces) including soil tillage and the use of heavy-machines (Aksakal, 2004). Reduction in soil porosity implied by compaction imposed by machine traffic in forest soils may amount to 50–60% (Ares et al., 2005; Ampoorter et al., 2007; Demir et al., 2007; Frey et al., 2009; Picchio et al., 2012; Solgi and Najafi, 2014). Soil compaction may also imply a strong reduction in air permeability. Frey et al. (2009) found that logging carried out by heavy machinery at 5–10 cm depth caused reductions in soil air permeabilities by 96% in case of deep rutting, 88% in case of churned, compacted and partly removed topsoil and 51% when no rutting was evident (Cambi et al., 2015).

Similarly, Kara and Bolat (2007) point out in their study that the organic C content of soil is a very important indicator of soil compaction. Furthermore, some of the factors influencing the soil porosity and bulk density are soil texture (sand, silt and clay), organic material content, soil depth and type of soil management (forest, range, agriculture) (Brady, 1990; Cepel, 1996; Coyne and Thompson, 2006). Additionally, Ampoorter et al. (2010) indicated that intensive machine traffic on clay soils led to the highest bulk density and the lowest porosity in these soils. It was determined that four study sites shared similar features all having heavy clay (53.5-65.2%) soils. The highest clay content (65.2%) was found in tractor road compared to other harvesting areas.

The pH of the soil in the study area ranges from mild to moderately alkaline acid. Tractor road soil lime content (8.03%) is in the middle limy class, and the others are in without-lime class. The presence of the high pH (7.79) and lime (8.03%) contents in the tractor road can arise from intensive traffic on the ground with limestone as parent material in the region. According to collected data, the highest soil electrical conductivity values were found in harvesting area and the lowest values were found in the skid trail. As the soils having electrical conductivity higher than 4 dS/m limit value are classified as saline (Sumner, 1995), the soils in the study site aren't considered saline when the values obtained in the study are compared with this limit value. Also, the highest content of organic C was found on the skid trail as 5.57% and the lowest content of organic C was on the tractor road as 1.52%. The reasons of soils on the tractor road containing lower organic C compared to other sites can be attributed to the factors such as the absence of a permanent vegetation on the site and the rapid decomposition of the organic material and being washed away by the precipitation as a result of mixing the soil constantly by tractor during the skidding of forest products out of the stand.

Table 1. Descriptive statistics (mean and standard deviation) related to soil physical and chemical properties

Soil properties	Undisturbed soil	Harvesting area	Skid rail	Tractor road
Particle density (g/cm^3)	2.48 ± 0.14	2.48 ± 0.04	2.43 ± 0.03	2.64 ± 0.15
Bulk density (g/cm^3)	0.96 ± 0.14	0.89 ± 0.14	1.04 ± 0.05	1.15 ± 0.08
Pore space (%)	61.50 ± 3.28	64.14 ± 2.60	57.23 ± 2.24	56.06 ± 5.15
Sand (%)	31.85 ± 9.29	31.09 ± 6.28	28.26 ± 4.10	22.58 ± 3.33
Silt (%)	14.59 ± 4.31	14.56 ± 0.04	17.97 ± 2.46	12.21 ± 2.60
Clay (%)	53.57 ± 12.94	54.33 ± 6.28	53.76 ± 8.59	65.20 ± 5.70
Soil pH (H_2O)	6.31 ± 0.35	5.64 ± 0.39	6.38 ± 0.16	7.79 ± 0.56
Calcium carbonate (%)	0.69 ± 0.24	0.58 ± 0.09	0.58 ± 0.18	8.03 ± 0.89
Electrical conductivity (dS/m)	1.78 ± 0.95	1.81 ± 0.53	1.44 ± 0.08	1.58 ± 0.59
Organic C (%)	4.13 ± 1.31	4.93 ± 0.11	5.57 ± 0.77	1.52 ± 0.17
Total N (%)	0.52 ± 0.06	0.63 ± 0.01	0.44 ± 0.05	0.38 ± 0.11
C_{org}/N_{total} ratio	7.73 ± 1.57	7.86 ± 0.25	12.78 ± 2.86	4.28 ± 1.43

Table 2. Results of the ANOVA and Duncan tests related to soil physical and chemical properties*

Soil physical and chemical properties	Undisturbed soil	Harvesting area	Skid rail	Tractor road	F-ratio	Sig.
Particle density (g/cm^3)	2.48^a	2.48^a	2.43^a	2.64^a	2.243	0.161
Bulk density (g/cm^3)	0.96^a	0.89^a	1.04^{ab}	1.15^b	4.806	0.034
Pore space (%)	61.50^{ab}	64.14^b	57.23^a	56.06^a	3.438	0.042
Sand (%)	31.85^a	31.09^a	28.26^a	22.58^a	1.011	0.437
Silt (%)	14.59^a	14.56^a	17.97^a	12.21^a	2.142	0.173
Clay (%)	53.57^a	54.33^a	53.76^a	65.20^a	1.475	0.293
Soil pH (H_2O)	6.31^a	5.64^b	6.38^a	7.79^c	31.622	0.000
Calcium carbonate (%)	0.69^a	0.58^a	0.58^a	8.03^b	183.76	0.000
Electrical conductivity (dS/m)	1.78^a	1.81^a	1.44^a	1.58^a	0.233	0.871
Organic C (%)	4.13^a	4.93^a	5.57^a	1.52^b	16.043	0.001
Total N (%)	0.52^{ab}	0.63^b	0.44^{bc}	0.38^c	6.986	0.013
C_{org}/N_{total} ratio	7.73^b	7.86^b	12.78^c	4.28^a	11.467	0.003

* Values in the same column followed by the same letter do not differ at a 0.05 level of significance

Total N content of soils was found in undisturbed area, harvesting area, skid trail and tractor road as 0.52%, 0.63%, 0.44% and 0.38%, respectively. Source of total N in soil is mainly composed of forest floor material (Ozbek et al., 2001). The main cause of the low total N contents in the tractor road is lower vegetation on the tractor road than on other areas. Measurements of soil properties in the surface layer (0-10 cm) showed that the C_{org}/N_{total} ratio (4.28) is lower on the tractor road compared to the skid trail (12.78). According to the C_{org}/N_{total} ratio results (<15) soil organic matter decomposes rapidly for all test areas (Kantarcı, 2000).

Descriptive statistics including mean and standard deviation related with soil moisture and penetration resistance on different periods are presented in Table 3. Soil penetration resistances range from 0.103-1.412 MPa in 0-5 cm depth, and 0.351-1.516 MPa in 5-10 cm depth. It was determined that soil penetration resistance decreased as moisture content of soil increased, whereas it increased as soil depth increased. The penetration resistance value of undisturbed soil strength at a depth of 10 cm was about 0.835 MPa (Akay et al., 2007). Forest harvesting activities, carried out in Yenice Forest District, increased compaction of soil layers; 82% for 0-5 cm depth and 17% for 5-10 cm depth at tree felling, 47% for 0-5 cm depth and 82% for 5-10 cm depth at ground skidding (Menemencioglu et al., 2013). Han et al. 2005 reported that logging equipment markedly increased soil strength at 10 and 20 cm soil depth, while increases in soil strength were ignorable at 30 cm soil depth.

On the other hand, it was determined that mean value of the soil penetration resistance decreased by 25% as moisture content of soil increased from 30 to 40%, and it decreased by 50% as moisture content increased from 30 to 50 in 0-5 cm depth. Similarly, the mean value of the penetration resistance decreased by 18% as moisture content of soil increased from 30 to 40%, it decreased by 22% as moisture content increased from 30 to 50% in 5-10 cm depth. This result implies that precipitation is more effective on topsoil compaction than lower soil layers. Makineci et al. (2007) reported that the values moisture content (21.26%) on the skid road is considerably lower than the moisture content (27.22%) in the undisturbed area.

Table 3. Descriptive statistics (mean and standard deviation) related to soil moisture and penetration resistance

Date	Soil moisture and penetration resistance	Undisturbed soil	Harvesting area	Skid rail	Tractor road
06 November 2014	Soil moisture (%)	32.19 ± 2.34	33.27 ± 4.70	38.34 ± 1.34	39.78 ± 4.82
	Penetration resistance (0-5 cm) MPa	0. 96± 0.24	0.86± 0.20	0.97 ± 0.14	0.23±0.07
	Penetration resistance (5-10 cm) MPa	1.09± 0.04	1.18± 0.17	1.13±0.06	0.51±0.21
14 November 2014	Soil moisture (%)	27.95± 2.24	23.74 ± 7.90	33.41± 2.23	28.07± 4.14
	Penetration resistance (0-5 cm) (MPa)	1.03 ±0.13	1.22±0.08	1.19±0.21	0.44± 0.09
	Penetration resistance (5-10 cm) (MPa)	1.24± 0.28	1.34± 0.12	1.33± 0.11	0.80±0.52
16 December 2014	Soil moisture (%)	38.25±1.81	48.35± 6.66	46.07±3.93	54.72±2.17
	Penetration resistance (0-5 cm) (MPa)	0.60±0.21	0.48± 0.24	0.53±0.16	0.25± 0.20
	Penetration resistance (5-10 cm) (MPa)	0.93 ± 0.10	1.08 ± 0.11	0.84±0.18	0.73±0.05

Correlation matrix between some soil properties and penetration resistances is presented in Table 4. In the table, statistically significant relationships at 0.05 and 0.01 levels are emphasized. There was a significant negative correlation between penetration resistance and bulk density, soil pH and calcium carbonate. In contrast, a significant positive correlation between penetration resistance and organic C, total N and C_{org}/N_{total} ratio was observed. It was also found that there was a significant correlation between penetration resistance and soil moisture. A negative significant correlation ($r = -0.601$, $p < 0.01$) was found between the moisture content (%) and penetration resistance at 0-5 cm soil depth (Figure 2). Although there is no strong relationship as in 0-5 cm depth, a negative significant correlation ($r = -0.403$, $p < 0.05$) was found between moisture content (%) and penetration resistance at 5-10 cm soil depth (Figure 2).

Table 4. Correlation matrix between some soil properties and penetration resistances

Soil Properties	Penetration resistance (0-5 cm)	Penetration resistance (5-10 cm)
Bulk density	-0.574	-0.701*
Soil pH	-0.656*	-0.859**
Calcium carbonate	-0.833**	-0.874**
Organic C	0.851**	0.779**
Total N	0.531	0.633*
C_{org}/N_{total} ratio	0.678*	0.539
Soil moisture	-0.601	-0.403

*, ** correlation is significant at the 0.01 and 0.05 level, respectively.

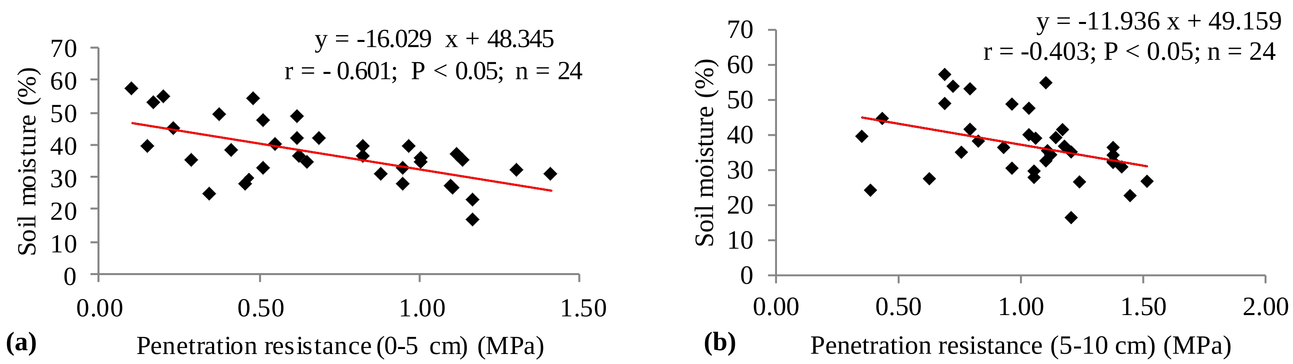

Figure 2. The relation between the penetration resistance and soil moisture for (a) 0-5 cm and (b) 5-10 cm soil depth layer

4. Conclusion

As a result of the study, it was found out that the forest harvesting operations had negative influences on soil physical and chemical properties in clay forest soil. The highest content of organic C was found on the skid trail and the lowest content of organic C was on the tractor road. On the other hand, it was determined that soil penetration resistance decreased as moisture content of soil increased whereas it increased as soil depth increased. Furthermore, penetration resistance values on tractor road were found to be lower than expected up to 10 cm depth compared to other forest harvesting areas. Therefore, further research should be carried out deeper than 10 cm in order to determine the negative effects arising from the load caused by tractor pressure on forest soil. Harvesting operations should be efficiently designed by considering influence soil compaction as an important factor.

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