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RESEARCH ARTICLE

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Soil compaction of various Central European forest soils caused by traffic of forestry machines with various chassis

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Abstract

Aim of study: The primary objective of this paper was to compare the effects of different types of forestry machine chassis on the compaction of the top layers of soil and to define the soil moisture content level, at which machine traffic results in maximum compaction.

Area of study: Measurements were conducted in eight forest stands located in Slovakia and the Czech Republic. The soil types in the stands subjected to the study were luvisols, stagnosols, cambisols, and rendzinas.

Material and methods: The measurements were focused on tracked and wheeled (equipped with low pressure tyres) cut-to-length machines, and skidders equipped with wide and standard tyres. The bulk density of soil was determined from soil samples extracted from the ruts, the centre of the skid trail, and the undisturbed stand. To determine soil moisture content, at which the soil is the most susceptible to compaction, the Proctor standard test was employed.

Main results: The moisture content for maximal compaction fluctuated from 12% to 34.06%. Wheeled machines compacted the soil to 1.24 – 1.36 g.cm^{-3} (30.3 – 35.4% compaction) in dried state. Bulk density of soil in stands where tracked machine operated was lower, ranging from 1.02 to 1.06 g.cm^{-3} (25.3% compaction).

Research highlights: All wheeled machines caused the same amount of soil compaction in the ruts, despite differences in tyres, machine weight, etc. Maximum compaction caused by forestry machines occurred at minimal moisture contents, easily achievable in European climatic conditions.

Keywords: soil compaction; bulk density; soil moisture content limits; cut-to-length machines; skidders.

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Introduction

The primary objective of research focused on the effect of the forestry machine traffic on soil is to describe a complex of soil's physical properties, which enable prediction of the soil's susceptibility to such load (Hildebrandt *et al.,* 1982). It is necessary to define the acceptable changes of key soil characteristics (Sommer, 1979). In terms of the protection of ecosystems or maintaining stand production capacity, the primary objective of forestry is to ensure a stable development of forest ecosystems and to preserve optimal productive and non-productive functions of forests. This can only be fulfilled by preserving all of the natural processes that occur in the soil, i.e. the activity of all microbiological organisms, the physical properties of the soil, the stocks of available nutrients and regeneration processes that take place in the ecosystem (Gebauer *et al.,* 2012).

Soil compaction is affected by a large number of endogenous and exogenous factors (Horn, 1988). The extent of soil compaction depends on soil characteristics and the pressure and vibration applied to the soil surface by forestry machines (Ole-Meiludie & Njau, 1989). Brais (2001) identifies machine induced soil compaction as one of the primary factors of soil degradation. Soil compaction is associated with significant changes in soil structure and soil moisture content (Standish *et al.,* 1998; Neruda *et al.,* 2008). The critical value of bulk density of soil ranges from 1.2 to 1.4 g.cm^{-3} (Lousier, 1990). Buchar *et al*. (2011) indicates that regarding acceptable disturbance caused by forestry machines, compaction to 1.3 – 1.7 g.cm^{-3} should be the limit. Šimon & Lhotský (1989) state that 1.35 – 1.70 g.cm^{-3} is the critical range of bulk density. Arshad & Coen (1992) state that critical range of bulk density is 1.4 – 1.8 g.cm^{-3}. Root growth in a majority of soil types is effectively stopped if these values are exceeded. According to Arnup (1999) soil susceptibility to compaction is defined by the following factors: the magnitude of the contact pressure applied by the vehicle, the instantaneous soil moisture content, the share of soil skeleton and sand particles, soil structure, bulk density of soil, soil porosity, and the current thickness of the topsoil. Anthropogenic soil compaction and the formation of ruts is the result of applying short-term contact pressure to the soil and drive wheel slippage caused by machine traffic in forest stands (Horn *et al.*, 2004). Skid trails and forest landings endure the most severe soil compaction during forest harvesting (Bob, 2002). Soil compaction may be more problematic in the modern age, given that the weight of the forestry machines (harvesters and forwarders) continues to increase (Langmaack *et al.*, 2002). The pressure applied to the top layers of soil causes breakdown of the soil's structural aggregates, which are then compacted. The compaction of soil aggregates results in a decrease in the number of pores and a reduction in the actual volume of the soil (Poršinsky, 2005). The thermal regime, the air and water balance, and plant nutrient transfer are all significantly affected (Arnup, 1999), the activity of microorganisms also decreases as the soil reverts to anaerobic conditions (Frey *et al.*, 2009). Soil compaction results in a decrease in the quantity of capillary pores and water permeability (Halvorson *et al.*, 2003), which accelerates surface water run-off along slopes and causes erosion (Owende *et al.*, 2002). The number and frequency of machine passages has a significant impact on the characteristics of the soil structure as well. The overall forest growth is affected, as soil compaction is reflected in a decrease of tree growth (Arvidsoon, 2001; Ampoorter *et al.*, 2007).

Soil compaction is often related to the formation of crust on the surface, which reduces water absorption and ultimately increases surface run-off (Malmer & Grip, 1990). The risk of local inundation increases where the run-off conditions cannot be modified (Jim, 1993). Experimental research showed that machine traffic increases the speed of surface erosion by 2 to 15 times its natural rate compared to the control plot and 85 % of total erosion occurs in the first year after such a disturbance (Lousier, 1990).

The consequences of machine traffic through the forest stands depend on the load bearing capacity of the soil on one hand and the loading of the soil by the machine on the other. Both of these factors are complex and highly variable. Soil load bearing capacity changes depending on the weather and the stand, which are primarily reflected in changes in instantaneous soil moisture content. Instantaneous soil moisture content has a strong influence on soil load bearing capacity. For this reason it is important to answer one question: what level of soil moisture content leads to maximal soil compaction?

Another important factor is soil loading, which changes according to the type of the machine. A machine is in balance, meaning it causes minimal disturbance, if the size of the contact area of the machine and its weight are appropriate. In such case the soil responds elastically to the soil and no visible ruts appear. Despite this, permanent damage is unavoidable if the machine moves repeatedly through one trail (Skoupý *et al.,* 2011). Ulrich *et al*. (2003) indicate that the most severe soil compaction occurs during the first to the third passage and after the fifth to tenth passage the soil is compacted to an extent that only minimal increments in bulk density occur.

The primary objective of this paper is to compare the extent of soil compaction caused by various types of forestry machines and to define the critical soil moisture content values, leading to maximum compaction resulting from the forestry machine traffic. Soil compaction is one of the most dangerous soil disturbance factors, particularly in highly productive stands, which can result in long-term reduction of tree growth. The greater the reduction in the growth of tree root systems, the smaller the increases in the tree growth (Halverson & Zisa, 1982; Tuttle *et al.,* 1988).

Material and methods

Measurements were conducted in eight forest stands located in Slovakia and the Czech Republic, where different types of machines were deployed. They were cut-to-length (CTL) machines, both tracked and wheeled, and wheeled skidders (Table 1). A GIS database provided by the National Forestry Centre was used to identify the soil types in the individual forest stands and their coordinates (Table 2). Thinning was carried out in two of the five stands, clear cut was performed in two stands, and shelterwood cut was performed in the last stand; the total

Table 1. Basic equipment parameters

Stand	Technology	Machines	Weight (kg)	Chassis type	Width of contact surface (mm)
2052	CTL	JD 1070D – JD 810D	14,100 – 10,970	wheeled	600 - 620
2027	CTL	JD 1070D – JD 810D	14,100 – 10,970	wheeled	600
805J13	CTL	Ponsse ERGO – Ponsse BUFFALO	17,200 – 17,400	wheeled	700 - 710
187C20	CTL	Neuson 132 HVT - Novotný LVS 5	14,400 – 4,475	tracked/wheeled	400 - 520
188	CTL	Neuson 132 HVT - Novotný LVS 5	14,400 – 4,475	tracked/wheeled	400 - 520
2051	Skidder	Zetor 7245 UKT	3,985	wheeled	280 - 420
574B11	Skidder	HSM 805 HD	9,200	wheeled	600
588	Skidder	HSM 805 HD	9,200	wheeled	600

Table 2. Overview of the details of the individual stands

Stand	GPS	Type of harvest	Volume of harvest (m^3)	Soil type	Soil texture
2052	48°40’37.95”N 18° 5’41.25”E	thinning 50 +	265.9	luvisol	clay – 9 %, silt – 11 %, sand 28 %, gravel – 60 %
2027	48°41’19.48”N 18° 5’38.19”E	thinning 50 +	232.6	40 % luvisol 60 % stagnosol	clay – 4 %, silt – 33 %, sand – 42 %, gravel – 21 %
805J13	49°49’59.69”N 14°46’25.71”E	clear cut	96.6	cambisol	clay – 2 %, silt – 38 %, sand – 37 %, gravel – 23 %
187C20	48°58’6.31”N 18°39’15.40”E	thinning < 50	90	20 % debris rendzina 80 % typical rendzina	clay – 1 %, silt – 46 %, sand – 31 %, gravel – 22 %
188	48°58’5.55”N 18°39’24.47”E	thinning < 50	190	10 % debris rendzina 90 % typical rendzina	clay – 4 %, silt – 46 %, sand – 48 %, gravel – 2 %
2051	48°41’9.31”N 18° 4’57.79”E	thinning > 50	95.4	luvisol	clay – 3 %, silt – 28 %, sand – 40 %, gravel – 29 %
574B11	48°35’25.84”N 19° 2’41.66”E	clear cut	411.3	95 % cambisol 5 % luvisol	clay – 17 %, silt – 44 %, sand – 22 %, gravel – 7 %
588	48°34’59.62”N 19° 3’16.79”E	shelterwood cut	215.2	40 % cambisol 60 % luvisol	clay – 5 %, silt – 65 %, sand – 26 %, gravel – 4 %

volume of harvest in the individual stands ranged from 90 to 411.3 m^3.

Soil samples were collected to determine the extent of soil compaction and soil moisture content in the investigated stands. These samples were collected from sample plots established across the stand based on the requirements of statistical sampling and the variability of the natural conditions in the stands (Scheer, 2010). In general the area of the sample plots was 10 % of the total area of the stand in stands up to 50 000 m^2. In stands larger than 50 000 m^2, the area of the sample plots was 5 % of the total area of the stand (Lukáč, 2005). The sample plots were located on skid trails disturbed by the machine traffic. The sides of the sample plots were 20 x 20 m or 20 x 40 m, depending on the type of machines employed in the individual stands. The sample plots were primarily selected because besides soil disturbance measurements, damage to the remaining stand was inspected too (not the subject of this paper).

The following equation was used to calculate the sample size (Šmelko, 2007):

$$i\% = \frac{n \times p}{P}$$

n × p – dimensions of all sample plots (m^2)
P – dimensions of the stand (m^2)

The following equation was used to determine the spacing between the individual sample plots (Šmelko, 2007):

$$s = 100 \times \sqrt{\frac{P}{n}}$$

P – stand area (m^2)
n – number of sample plots

The measurement locations for soil disturbance were positioned on two opposing sides of each plot, and were located on the skid trail. The measurement locations were: (i) in the ruts of the skid trail (one side); (ii) the centre of the skid trail (between the individual ruts); (iii) the undisturbed stand (control measurements). This allowed collection of two sets of material on a one sample plot and a total of six samples. In stands where the soil disturbance was not studied through the sample plot method (clear cut stands 574B11 and 805J13), measurement sites positioned on the skid trails were established with spacing of 5 m (Schürger, 2012). The measurement locations were the same as for the sample plot method.

Soil samples were collected from every measurement location in order to determine soil bulk density in its natural conditions. The samples were collected into 100 cm^3 Eijkelkamp cylinders. They were hermetically sealed in the cylinders to prevent any loss of moisture content. Samples were then weighed in laboratory conditions on calibrated laboratory scales with an accuracy of 0.1 g and dried at a temperature of 105ºC for 24 hours. Finally the mass of the samples in dried state and their moisture content were determined. Soil moisture content was calculated using the following equation (Hraško *et al*., 1962):

$$w\,\% = \frac{m_v - m_s}{m_s}$$

Soil disturbance was assessed from a total of 130 measurement locations. A total of 390 soil samples were collected from all measurement locations.

The Proctor standard test (STN 72 1015), was used to determine the soil moisture content, at which the maximum compaction is achieved. Laboratory analyses were conducted to define the soil texture (the percentage share of clay, silt, sand, and gravel) in the individual stands using sieving method to determine the share of material larger than 2 mm and the Casagrande method for the finer granular fractions (< 2 mm).

Moisture content, at which maximum soil compaction is achieved, is primarily influenced by soil texture and the share of clay, silt, and sand. Therefore it was influenced by the conditions at the measurement location. A 2.5 kg cylinder was used for the Proctor standard test. It was used to strike a layer of soil stored in a special container with a known volume from a height of 30 cm. Dried soil was sieved through 16 mm sieves and compacted in three layers by 25 strikes from the cylinder to each layer. The test was repeated several times at increased soil moisture content, with the sample of compacted soil weighed at each moisture content level. The measurement results were then plotted on a diagram where optimum soil compaction corresponding to maximum bulk density of the soil sample was determined. Proctor empirically proved that soils compact to different bulk densities by the same compaction work at different moisture contents. Dry soil creates clumps that do not break down during compaction and large pockets are formed in the soil. At low moisture, great friction is exerted by the grains as they move, which leads to imperfect compaction, and hence low bulk density. Increasing soil moisture beyond the optimum moisture content levels results in over saturation of the soil with water and subsequent decrease in bulk density. Water moves into the soil's pores and prevents further compaction.

The STATISTICA 10.0 software was used for statistical analyses of gathered data, namely multivariate analysis of variance (MANOVA) and Duncan's test.

Results

Soil compaction is one of the primary indicators of soil disturbance caused by machine traffic. On average the bulk density in ruts of the skid trails was 0.39 g.cm^{-3} (32 %) higher than the bulk density observed in the undisturbed stand. Wheeled CTL machines caused 34.7 % compaction in ruts of the skid trails compared to the control measurements (bulk density increased by 0.42 g.cm^{-3}), while the tracked CTL machine caused 34.9 % compaction compared to the control measurements (bulk density increased by 0.37 g.cm^{-3}), as shown in Figure 1. Skidders caused an increase in bulk density of 0.36 g.cm^{-3} (29 % compaction) in ruts of

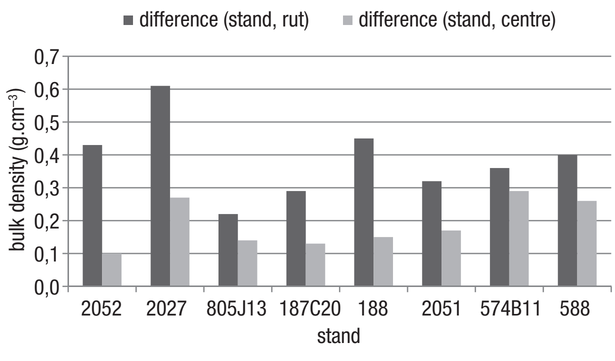

Figure 1. Differences in soil densities (g.cm^{-3}) in natural conditions (moist) caused by different types of chassis in the undisturbed stand, rut and centre of the forwarding line.

Table 3. Changes in soil density caused by various types of chassis

Stand	2052	2027	805J13	187C20	188	2051	574B11	588
chassis	wheeled	wheeled	wheeled	wheeled/ tracked	wheeled/ tracked	wheeled	wheeled	wheeled
Machine	harvester	harvester	harvester	harvester	harvester	Skidder	Skidder	Skidder
moisture for max. compaction (%)	16.87	15.93	12	28.08	34.06	15.34	21.9	27.95
moist stand g.cm^{-3}	1.21	1.10	1.32	1.05	1.07	1.14	1.43	1.16
moist rut g.cm^{-3}	1.64	1.71	1.54	1.34	1.52	1.46	1.79	1.56
moist centre g.cm^{-3}	1.31	1.37	1.46	1.18	1.22	1.31	1.72	1.42
dry stand g.cm^{-3}	0.96	0.90	1.12	0.82	0.83	0.95	1.05	0.97
dry rut g.cm^{-3}	1.31	1.36	1.35	1.02	1.06	1.24	1.35	1.29
dry centre g.cm^{-3}	1.05	1.12	1.27	0.91	0.90	1.09	1.28	1.18
stand moisture (%)	25.94	23.04	13.20	28.2	20.4	20.18	39.2	20.41
rut moisture (%)	25.48	26.36	11.17	31.5	32.4	18.60	33.6	20.92
centre moisture (%)	24.80	22.98	11.47	28.7	24.8	20.35	35.1	20.80

the skid trails compared to the control measurements, which in this case appears to be the lowest level of impact. Comprehensive data is shown in Table 3.

The level of compaction in the centre of the skid trails reached a lower value. Compared to the control samples from the undisturbed stand, wheeled CTL machines increased the bulk density by 0.13 g.cm^{-3} (10.7 % compaction), tracked CTL machine increased the bulk density by 0.21 g.cm^{-3} (19.8 % compaction), and skidders increased the bulk density by 0.24 g.cm^{-3} (19 % compaction). The highest level of compaction of soil in natural conditions was reached by tracked CTL machine. This was probably due to differences in soil moisture content and texture. MANOVA analysis was used to determine if statistically significant differences were present between soil bulk densities in their natural arrangements in the individual stands and in the measurement locations. The results of this analysis showed that there were statistically significant differences in density between the individual stands ($F = 36.23$; $p = 0.00$) and measurement locations ($F = 130.38$; $p = 0.00$) in the individual stands, which can be attributed to the variability of soil conditions (Figure 2).

The variability of soil moisture content serves as a bias. Soil moisture content varied from 11.2 % to 39.2 % in the individual stands when the measurements took place. The differences in moisture content manifested in differences of bulk densities of moist samples. The moisture level, at which the maximum compaction is achieved, was exceeded in all stands and varied in a range of 12 – 35 % based on the individual conditions and soil texture, therefore the maximum soil compaction occurred already after the first machine passage. MANOVA analysis was carried out to compare the soil

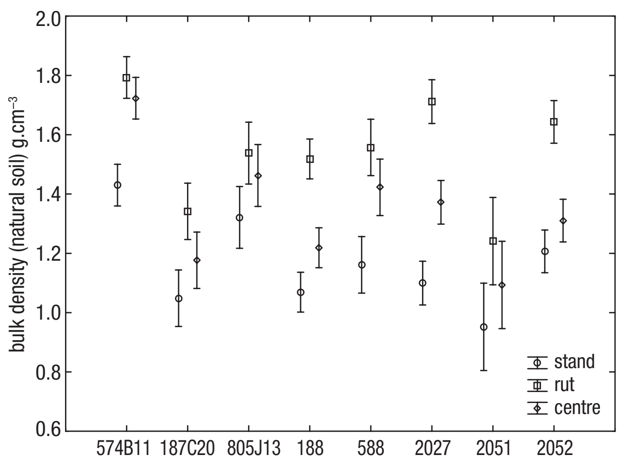

Figure 2. Average soil density values in natural conditions (moist) in the individual stands and measurement locations (vertical lines depicting 95 % confidence intervals).

moisture content between the measurement locations and the individual stands. The results of this analysis showed that statistically significant differences in soil moisture occurred between the individual stands ($F = 53.65$; $p = 0.00$), but did not occur between the measurement locations in the individual stands ($F = 1.98$; $p = 0.14$) (Figure 3). Average soil moisture content in the undisturbed stand was 23.8 %, 25.0 % in the ruts, and 23.6 % in the centre of the skid trail.

The dried soil samples were analysed in order to eliminate the moisture content of soil as a bias and to determine the extent to which surface soil compaction was the result of the different forestry machine types. The average bulk density of dried samples measured in the ruts of the skid trails was 0.30 g.cm^{-3} (32 %) higher than the bulk density measured in the undisturbed stand. Wheeled CTL machines caused 0.35 g.cm^{-3} (35.4 %)

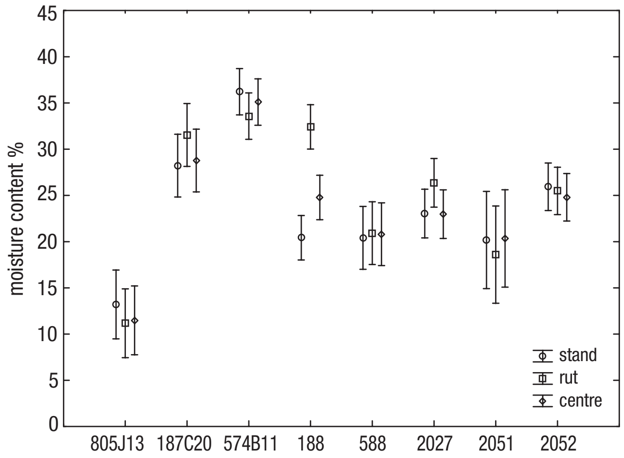

Figure 3. Average soil moisture values in stands and individual measurement locations (vertical lines depicting 95 % confidence intervals).

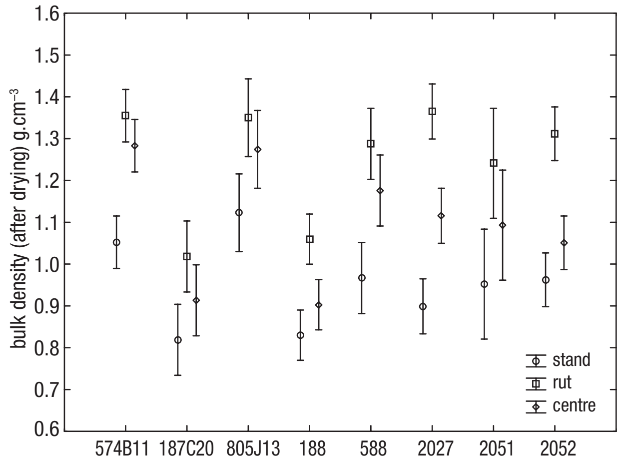

Figure 5. Average bulk density of dried samples in individual stands and measurement locations (vertical lines depicting 95 % confidence intervals).

increase of bulk density, tracked CTL machine caused a 0.21 g.cm^{-3} (25.3 %) increase of bulk density, and skidders caused 0.30 g.cm^{-3} (30.3 %) increase of bulk density compared to the control measurements. The tracked chassis proved to have the least effect on soil once the bias factor of moisture content was removed.

The increase of bulk density in the centre of the skid trail was 0.16 g.cm^{-3} (16.2 %) for wheeled CTL machines and 0.08 g.cm^{-3} (9.6 %) for tracked CTL machine; skidders compacted the soil to a higher level, which was primarily caused by skidding the load. They compacted the soil by 0.19 g.cm^{-3} (19 % compaction) (Figure 4).

The bulk densities of soil samples after drying fluctuated in range of 1.25 – 1.36 g.cm^{-3} for wheeled machines and 1.02 – 1.06 g.cm^{-3} for tracked machine. The results indicate that the wheeled chassis caused 25 % higher soil compaction compared to the tracked chassis. MANOVA analysis was used to compare the samples. The results showed that there were statistically significant differences in level of soil compaction between the individual stands ($F = 32.94$; $p = 0.00$) and measurement locations ($F = 97.54$; $p = 0.00$) in the individual stands (Figure 5). It is important to determine what variables contributed to refuting the hypothesis of the equality of the averages of bulk densities. The Duncan's test was used to analyse the dried soil samples from ruts. The test results show all combinations of changes in soil density between the samples from the ruts (Table 4). The Duncan test confirmed that in stands where wheeled machines were used (even with various types of machines used, different volumes of harvests, and different machine weight classes) the same level of soil compaction was reached (805J13, 574B11, 588, 2027, 2052, 2051). The bulk density varied in a range of 1.24 g.cm^{-3} – 1.35 g.cm^{-3}. The tracked chassis enabled a better weight distribution and caused lower compaction in stands 187C20 and 188 with the bulk densities ranging from 1.01 to 1.05 g.cm^{-3}. The results of this study indicate that maximum soil compaction occurred even at minimum surface soil loading and a minimum number of passages, even when wide and low-pressure tyres were used.

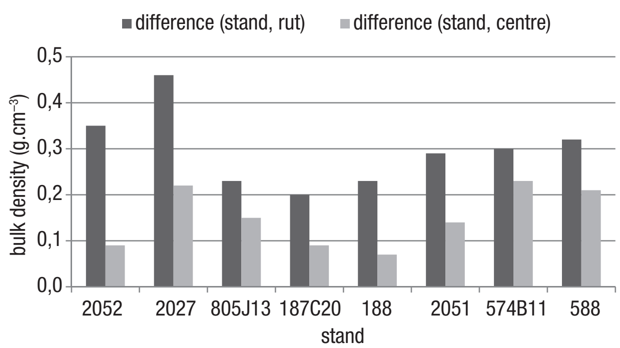

Figure 4. Differences in soil densities of dried samples (g.cm^{-3}) caused by different types of chassis in the undisturbed stand, rut and centre of the forwarding line.

Discussion

Soil bulk densities in their natural arrangement fluctuate between the individual measurement locations and stands, which was confirmed by multivariate analysis of variance (MANOVA).

A similar conclusion was reached by Williamson & Neilson (2000), who studied the soil compaction in ruts of the skid trails at a depth of 10 cm caused by skid-

Table 4. Duncan's test of bulk density of dried samples in ruts

Duncan test, average density in g.cm^{-3} (dry sample) Approximate likelihood of post hoc tests Error: between groups. PČ = 262.71, sv = 118.00								
stand	1 135.01	2 101.82	3 135.49	4 105.98	5 128.76	6 136.49	7 124.11	8 131.18
805J13		**0.000028**	0.941157	**0.000074**	0.373223	0.832586	0.132366	0.559490
187C20	**0.000028**		**0.000023**	0.525553	**0.000173**	**0.000018**	**0.001331**	**0.000066**
574B11	0.941157	**0.000023**		**0.000068**	0.356236	0.878481	0.125179	0.538930
188	**0.000074**	0.525553	**0.000068**		**0.001051**	**0.000047**	**0.006585**	**0.000396**
588	0.373223	**0.000173**	0.356236	**0.001051**		0.301393	0.478802	0.712963
2027	0.832586	**0.000018**	0.878481	**0.000047**	0.301393		0.100750	0.466744
2051	0.132366	**0.001331**	0.125179	**0.006585**	0.478802	0.100750		0.313442
2052	0.559490	**0.000066**	0.538930	**0.000396**	0.712963	0.466744	0.313442	

ders. The results of their study confirmed that soil bulk density increases by 62% compared to the control plots in the undisturbed stand after the first passage of forestry machines through the forest stands. Soil compaction and the formation of ruts in relation to the number of forwarder passages was the subject of a study by Proto *et al*. (2012), who determined that the first passage causes 20% compaction of the top layer of the soil. The issue of forest soil compaction was also the focus of a study by Leutz *et al.*, (1980), who investigated machines traffic in loess - clay sites. Measurements showed the changes in soil properties are caused by the machines traffic. Most of the soil disturbances and structural change is caused by the first passage of forestry machines (Steinbrenner, 1955; Jakobsen & Moore, 1981; Miles *et al*., 1981).

Makineci *et al*. (2008) investigated the impact of timber forwarding on soil at depths of 0 – 5 cm and 5 – 10 cm. The results of their study indicate that the bulk density of the dry soil samples from the ruts increases significantly compared to the samples from the control plots in the undisturbed stand. Eric (2006) reached a similar results while taking samples from depths of 5, 10, and 20 cm. Sakai *et al*. (2008) monitored the impact of forwarding operations using an eight-wheeled forwarder to compact the top layers of the soil at a depth of 0 – 40 cm with different charging pressures of tyres in relationship with the number of passages. Their results indicate that structural changes of soils happen after the first passage of the forwarder and that severe soil compaction appears after a total of eight passages of the machine.

According to the findings in this study, machines with wheeled chassis caused 29 – 34.7% compaction, with bulk density of moist samples ranging from 1.46 to 1.79 g.cm^{-3} compared to the control measurements in the undisturbed stand. The trend was the same for machines with tracked chassis, with lower bulk densities (1.34 – 1.52 g.cm^{-3}), but the same level of compaction (34.9%). When looking at the compaction of soil in natural condition, it would seem that the tracked chassis had no positive effect on soil disturbance. However the positive effect was found when dried samples were assessed. Machines with wheeled chassis caused 30.3 – 35.4% compaction (bulk density ranged from 1.24 to 1.36 g.cm^{-3}), whereas the compaction of soil in ruts formed by the tracked machine varied from 1.02 to 1.06 g.cm^{-3} and the level of compaction increased by 25.3%. The highest bulk densities for soil in the centre of the skid trails was reached in stands where skidders operated. This was due to the nature of skidding – semi-suspended loads caused increased compaction in this location in comparison with the compaction caused by CTL machines. An important note is that the critical value of compaction for tree root growth was exceeded in the skid trail ruts in all cases.

The greatest compaction occurs in the top 30 cm of the soil, which contains the majority of the root biomass (Sands & Bowen, 1978; Kozlowski, 1999). Skidder passage results in 41 – 52% compaction of the top soil layer (0-8 cm) (Kozlowski, 1999). Lousier (1990) found that the top layer of soil (0 – 10 cm) compacts by 15 – 60% in skid trails. According to this author, the compaction in deeper soil layers decreases but he observed some levels of compaction in depths of 30 cm and more. The highest level of compaction occurs after the first machines passage. The critical level of moisture content, at which the soil reaches maximum compaction maximum soil compaction according to Rab (2005) is in range of 39 – 49.2%. The results of our study indicated that maximum compaction in the top layers of soil occurred at lower moisture contents, i.e. from 12 – 34 %. Some authors investigated the relationship between bulk density and moisture content. Gerasimov *et al*. (2010) studied the effects of forwarder traffic on soil surface at various moisture contents and reached the conclusion that an indirect correlation exists between bulk density and moisture content, i.e. soil density decreases as moisture increases.

Soil moisture content served as a bias factor in bulk density assessment, which showed in the fact that when samples were evaluated in moist state, machines with wheeled chassis caused the same level of compaction when compared to tracked machines. When moisture content was removed, tracked machine proved to have smaller effect on soil compaction. The fact that all wheeled machines caused roughly the same level of compaction can be attributed to the physical properties of soils and a similar mode of transmission of the vibrations from the wheeled chassis to soil, when machines move through forest stands. Moisture content necessary for maximum compaction was exceeded in all samples taken from the stands. Simultaneously it was confirmed that in these conditions machines with wheeled chassis were able to compact soil to the maximum possible extent in a relatively small number of passages, because they did not have sufficient contact surface that would effectively distribute their weight. This was confirmed by the results from stands where the tracked CTL machine operated, where it caused a lower level of compaction. Average soil moisture contents were different in the individual stands and the statistical significance of these differences was confirmed by statistical analyses. Conversely, the differences of moisture in the individual measurement locations within the individual stands were minimal and statistically insignificant.

Conclusions

Before any forestry machine is allowed to operate in forest stands, the soil should be tested for whether or not the Atterberg plasticity limits of soil are exceeded in the stands. The soil moisture content also should be monitored throughout the whole forest harvesting process to ensure that the forest manager has enough information on the natural conditions and the susceptibility of soil to disturbance. These procedures along with classification of skid trails into trail types according to Lüscher *et al*. (2009) would give useful information to the forest managers during the decision-making process on whether or not to stop the harvesting process, to prevent excessive disturbance.

The number of passages on the skid trails was not considered in this study and the measurements took place in stands with different natural conditions. This area of research requires a larger, more extensive research, which would consider more machine types and various volume of harvest as well as consideration of the effects of harvesting remains on the soil compaction levels. A drawback of the used gravimetric sampling method is that it is only informative, providing information on bulk density of soil. Despite this, the submitted paper provides valuable objective results of the compaction levels reached by the given machines and in given natural conditions, confirmed by statistical analyses.

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