SOIL COMPACTION IN YOUNG STANDS DURING MECHANIZED LOGGING OF BIOFUEL AND ROUNDWOOD ASSORTMENTS

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Abstract
Impact of a variety of forestry machine types on soil compaction is evaluated in this study according to the measurement of soil penetration resistance at 0 to 80 cm depth. It is concluded in the study that soils with poor bearing capacity (PBC), comparably small penetration resistance and organic layer thicker than 5 cm are less vulnerable to soil compaction. The use of small-size forwarder Vimek 610 allows to reduce soil compaction to an insignificant level in comparison to the control sites, and most or ruts disappear within a few days in PBC conditions. Whereas John Deere 810E, which belongs to the middle-size class of forwarders, significantly compacts soil through the whole measured depth in similar conditions. Rottne F10B and John Deere 810E forwarders represent the same weight category, and soil compaction due to the use of these machines on soils with moderate bearing capacity (MBC) is similar too; however, on soils with weak (WBC) and good (GBC) conditions results are different, mostly due to a different amount of extracted roundwood in both trials. Tracked forwarder was used only in GBC conditions and the results demonstrated significant compaction only down to 22 cm depth. The trials confirm that the depth of the intensity of impact depends on the weight of the machine and amount of material extracted; however, additional measurement data are necessary to characterize the impact quantitatively in different conditions.
Key words: soil compaction, forwarding, penetration resistance.

Introduction

The demand for woody biomass as renewable material, including small dimension logs and solid biofuel is expected to rise in future. The growing demand can be met both, by increasing of planted areas of fast-growing trees and their hybrids (Jansons *et al*., 2013, 2014), as well use agroforestry systems (Rancane *et al*., 2014) and by more efficient extraction of wood during forest thinning operations, especially on soils with low bearing capacity which represents high bioenergy potential, but also considerable risk of harmful impact on the remaining stand during intensified extraction of biomass (Lazdiņš & Thor, 2009; Lazdiņš *et al*., 2013; Liepiņš *et al*., 2015). Specialized forest machinery including small forwarders is of crucial importance to increase the output of biomass from small size tree harvesting operations (Spinelli *et al*., 2010; Spinelli & Magagnotti, 2010).

The Vimek 610 forwarder is not unique in its 'small size' class, however, it is one of the few machines of this kind produced serially. The forwarder is equipped with the same engine as the Vimek harvester, front tires of the forwarder are slightly bigger and rear tires are smaller than those of the harvester. Clearance of the machine is 40 cm. Reach length 5 m, weight of fully loaded machine is about 10 tonnes (Lundberg, 2013).

Soil compaction during logging process has been studied since early 1970s. During the first trials it was proposed that soil compaction can have a negative impact on future stand development and health (Eriksson, 1981). Since that time many new studies have appeared; however, till nowadays there is no common vision about all processes interacting with the soil compaction and relationships between the stand growth and soil compaction. The studies in Latvia demonstrate that soil compaction has a long lasting effect and there is a considerable difference depending on the type of the machines. The most important is the type of forwarder used in the operations. The use of tracked forwarders results in a considerably smaller impact appearing only at a topsoil layer, but wheeled machines in the same conditions can compact soil down to 80 cm depth, even without visually identifiable signs of rutting (Lupiķis *et al*., 2014; Lupikis *et al*., 2015).

Knowing that tree roots are distributed mainly in the topsoil layer and the range of the distribution of roots considerably exceeds tree crown projection (Perry, 1982), it is obvious that not only the roots of trees growing near technological corridors (further in text – TC) have been damaged during forwarding, but also roots of those trees which are located more than 3 metres from TC. Damages of roots can cause tree infection. The most common infection of this type in Latvia is root rot, which is a well-known follower of the forest management activities, especially in coniferous forests (Kļaviņa *et al*., 2013).

Early studies on the soil compaction consider that it can improve soil water permeability (Barden & Pavlakis, 1971); more recent studies demonstrate considerable decrease of water movement speed in soil in compacted areas (Batey, 2009; Taghavifar & Mardani, 2014) approving the potentially harmful impact of the compaction on the hydrological properties of soil. Soil compaction also is a threat for plants and trees, because if soil penetration resistance is higher than 3 MPa then roots cannot or it is hard for them to penetrate those layers of soil (Lazdiņš, 2015) and in previous studies (Bassett *et al*., 2005; Cubera *et al*., 2009), the length of the main root system was constrained by soil compaction.

Soil compaction during mechanized logging is a result of direct and indirect impact of different factors. Some of them have been mentioned by Cambi M. *et al*., 2016, like soil texture and moisture; as well as content of organic matter, terrain, characteristics of wheels (type, size, shape and air pressure), weight of machine and the number of trips (DeJong-Hughes, 2003; Duiker, 2004; Wolkowski & Lowery, 2008; Cambi *et al*., 2015).

Different technical solutions are developed to reduce mechanical impact on soil. Constructors of forest machines are working on solutions to make logging machines more optimized for thinning operation, so to minimize the impact on soil and secure high productivity of the machines. The most commonly addressed solution is customization of chassis (increased size of wheels or replacement of wheels with tracks) to increase support surface and reduce maximum pressure on soil. Alternate trend is the increase of machine capacity to reduce cumulative pressure on soil due to bigger loads, as well as the opposite trend – development of small machines and optimization of forwarding process to move machines to a different category, where the key for reduction of the negative impact is planning of the forwarding trials (Sutherland, 2003; Sakai *et al*., 2008).

Freezing and thawing significantly decrease the penetration resistance in the upper layers of compacted soils according to several studies. Studies in the United States confirmed that after one winter containing several cycles of freezing and thawing the penetration resistance of farm soils was reduced by 73, 68, and 59% at depths of 0 to 10, 10 to 20, and 20 to 30 cm, respectively (Jabro *et al*., 2012, 2014). Similar results have been described by European authors (Özgan *et al*., 2015). Studies in Latvia have demonstrated that in deeper soil layers (below 40 cm) soil compaction can persist for decades (Liepiņa *et al*., 2014).

The aim of this study is to compare influence of different types of forwarders (conventional, small and tracked) on soil compaction in young forest stands with different soil bearing capacity, as well as to evaluate if the initial soil penetration resistance can be used to compare forwarding conditions.

Materials and Methods

Data collected from 34 forest stands from different regions of Latvia (Skriveri, Koknese, Vecumnieki and Talsi) are evaluated in this study. The main criteria for selection of stands was the height of an average tree (below 12 m) and management history (no pre-commercial thinning done before). Some of dry and wet forest site types Oxalidosa, Hylocomiosa, Caricoso–phragmitosa and Myrtillosa (Liepa *et al*., 2014) were represented with broadleaved dominant tree species (birch, black alder, grey alder). The age of those experimental objects varies from 10 to 16 years in inventory data.

Thinning and biomass extraction was done in summer and autumn, 2013. Impact of meteorological conditions, like precipitation on soil bearing capacity during forwarding was considered by measurement of soil penetration resistance at 0-80 cm depth. The penetration resistance was measured after forwarding on technological corridors and in untouched stand area using digital penetrologger, directly after forwarding. Measurements were done in pairs of plots, where 3...5 measurements (sub-plots) are done on technological corridor (TC and 3…5 measurements were repeated 3...5 m from a side of TC in similar conditions. The measurements of the penetration resistance in each TC was repeated at every 50 m. If the TC was shorter than 200 m, the sub-plots were located in denser network. In total, 5353 measurements were used in the study, respectively, in the group where soil bearing capacity is poor (PBC) it is 457; in the group of week soil bearing capacity (WBC) – 1351; in the group where soil bearing capacity is medium (MBC) – 2032, but in the group with a good soil

Table 1

Data classification for analysis

Soil bearing capacity	In text	Average penetration resistance at 0...80 cm depth (MPa)	Biomass forwarder			
			John Deere	Rottne	Timbear	Vimek
poor	PBC	0.5...1.0	X	-	-	-
weak	WBC	1.0...1.5	X	X	-	X
moderate	MBC	1.5...2.0	X	X	-	X
good	GBC	2.0...2.5	X	X	X	-

Table 2

Technical specifications of forwarders

Producer	Model	Power of engine (kW)	Drive	Own weight (tonnes)	Load capacity (tonnes)
John Deere	810 E	95	8 tyres	12.9	9.9
Timbear	Light logg C	97	4+2 caterpillar trucks	12.0	10
Rottne	F10B	116	8 tyres	12.9	9
Vimek	610	44	6 tyres	4.9	5

bearing capacity (GBC) - 1513. All measurement data from the control sites were split into 4 groups depending on the machine used for biomass transportation. Then the average soil penetration resistance at 0...80 cm depth was calculated for every control sub-plot to characterize soil bearing capacity and different forwarding conditions. Depending on the average values of the soil penetration resistance, all sub-plots were split into 4 soil bearing capacity groups (Table 1). The marking 'X' in Table 1 marks the conditions, where the specified forwarder is used. Further data analysis is done by comparison of the difference between the soils penetration resistance in the control and TC sub-plots.

The average extracted biomass from each TC in the trials was between 15 and 25 m^3. The influence of type of forwarder on soil compaction in different conditions (initial soil bearing capacity) was evaluated in the study. Considering the conclusion of several researchers on dominating role of forwarders in compaction of soil, the type of harvester is not evaluated in the study (Lazdāns, 2004; Eliasson, 2005; Gebauer *et al*., 2012). Technical specifications of forwarders are shown in Table 2.

Significance level was calculated with $p<0.05$; $\alpha = 0.05$, and descriptive statistics were carried out with the Microsoft Excel 2013 statistical software package.

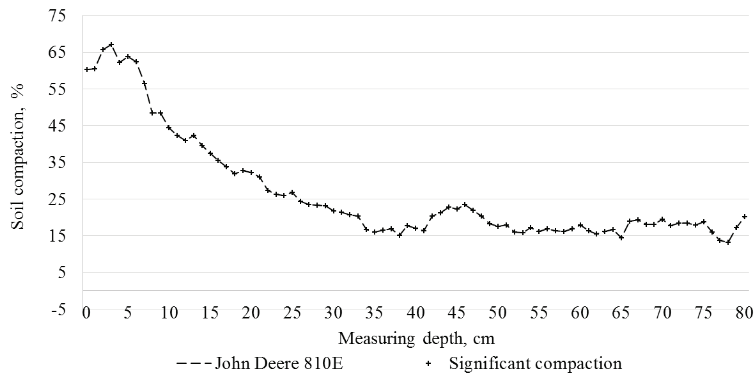

Figure 1. Soil compaction in comparison to control on soils with poor bearing capacity (PBC).

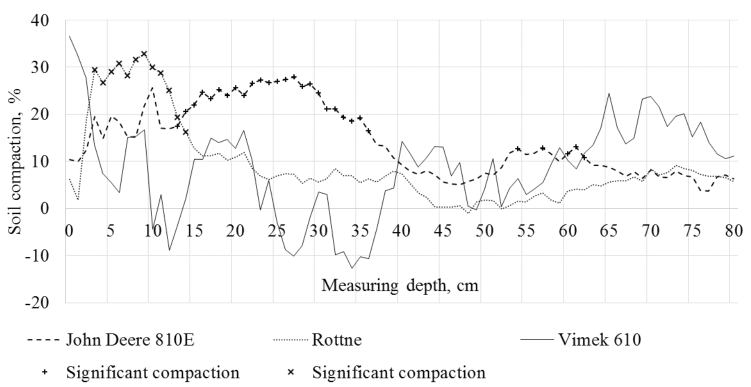

Figure 2. Soil compaction in comparison to control on soils with weak bearing capacity (WBC).

Results and Discussion

The results of the study demonstrate a different impact of the evaluated forwarders on the soil compaction in four groups of soil bearing capacity. In the first group of the soil bearing capacity (PBC) only John Deere 810E forwarder was used. Results in Fig. 1 demonstrate that average-class forwarder significantly compacted soil through the whole measured layer. Significant differences ($p<0.05$) have been detected down to 80 cm depth (marked with '+' in fig. 1). Soil compaction in the upper layers down to 18 cm depth exceed the control by 30%.

Fig. 2 summarizes results from the WBC group of soils. In this group forwarding was done with 3 forwarders – John Deere 810E, Rottne F10B and Vimek 610. Significantly compacted soil was found in areas where John Deere 810E forwarder was used (significant difference at 13...37 cm and 54...63 cm depth). In areas extracted by the Rottne forwarder significant difference between control and TC was detected only at 3...15 cm depth. Using the small Vimek 610 forwarder, no significant differences of the soil penetration resistance were found between the control and TC in WBC sites.

Fig. 3 demonstrates summary of the results in the MBC group of soils. Forwarding was done with 3 types of forwarders – John Deere 810E, Rottne F10B and Vimek 610. Significant compaction of soils is detected in all cases, but the most visible difference is found at a topsoil level. Significant compaction ($p<0.05$) of soil using John Deere 810 forwarder is found at 0...50 cm depth, using Rottne forwarder – at 0...38 cm depth, but in areas where roundwood is extracted using Vimek 610 – at 0...26 cm depth. The highest rate of compaction of topsoil within this group is found in sub-plots, where small-size Vimek 610 forwarder is used; however, the impact is relatively shallow. The reason for similar impact by the Vimek 610 can be due to a smaller surface area of tyres resulting in an increased pressure on soil. At the same time Vimek is affecting mostly the topsoil layer – below 26 cm depth the difference is insignificant. It means that soil can return to the initial condition during freezing in winter.

Figure 4 displays summary of the results in the GBC group of soils. In the GBC group forwarding of roundwood was done by three machines – John Deere, Rottne and Timbear. Significant compacted layers of soil are not detected deeper than 22 cm in sub-plots where Timbear was used. In case of John Deere, considerable compaction was found down to 18 cm depth, whereas in case of Rottne the soil was

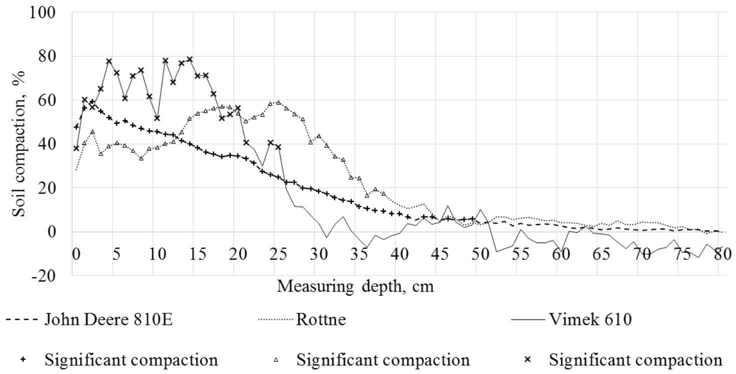

Figure 3. Soil compaction in comparison to control on soils with moderate bearing capacity (MBC).

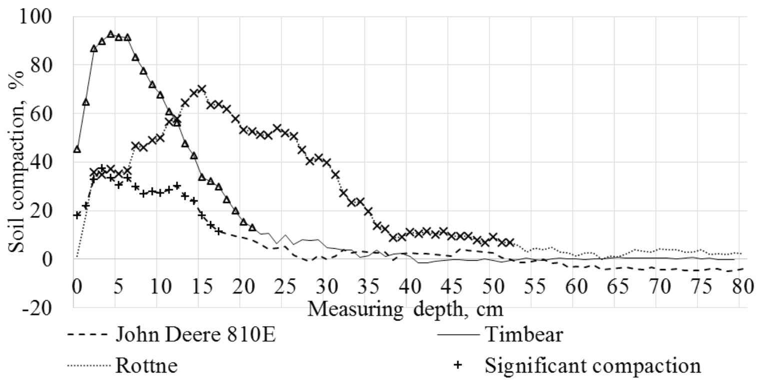

Figure 4. Soil compaction in comparison to control on soil with good bearing capacity (GBC).

significantly compacted down to 52 cm depth. John Deere and Rottne are very similar by the technical specification, but in stands where Rottne was used significant soil compaction is detected more than twice deeper in comparison to areas extracted by John Deere. Subsequent investigation explained this by considerably longer TC in stands extracted by Rottne, respectively more roundwood (25 m^3 in each corridor) was transported in these TC; respectively 10 passes instead of 6 passes with John Deere. In case of Timbear, significantly compacted soil layer is comparably shallow, because this machine is on tracked chassis, therefore has a larger contacting surface area resulting in smaller pressure. The result conforms with some of earlier studies, for instance by Bredberg, 1976, who compared machines on wheels with bogie-track and machine on tracks chassis with larger contacting surface area. However, he also concluded that the number of passes is an important factor to consider when comparing different types of the machines. While the number of forwarding passes is growing, the difference between tracked and wheeled machines is decreasing. The study results highlight the potential risk of soil damages while working in areas characterized by good bearing capacity, where no visible soil damages (ruts) (Sutherland, 2003) usually can be detected and, therefore, operators and foresters are not concerned about soil protection measures during forwarding. To avoid potentially harmful impact on soil, it is especially important in moderate and good conditions to establish strip-roads in a direction, which does not intercept with horizontal flow of groundwater to avoid accumulation of exceeding water, and to leave harvesting residues on TC to reduce the machine pressure on soil.

Figure 5 demonstrates soil compaction on TC in comparison with the control depending on the forwarder and a group of the soil bearing capacity at different soil layers. In case of John Deere 810E, the soil compaction and depth of compaction has reduced with an increase of the initial soil penetration resistance (bearing capacity). The level of compaction exceeding 20% in comparison to the control in soils with an average initial (control) penetration resistance of 0.5...1.0, 1.0...1.5 and 1.5...2.0 MPa is found down to 30 cm depth, whereas in the group of soils with initial soil penetration resistance of 2.0...2.5 MPa (GBC) it is observed only down to 10 cm depth. Although Rottne and John Deere forwarders are similar according to the technical specification, the results show a considerable difference between these machines. It is observed that soil compaction is decreasing with an increase of depth of the penetration on soils with smaller initial soil penetration resistance (0.5...1.0 MPa, WBC group of soils). Whereas if the initial soil penetration resistance is increasing (MBC and GBC group of soils), the tendency is different and down to a depth of 20 cm the level of soil

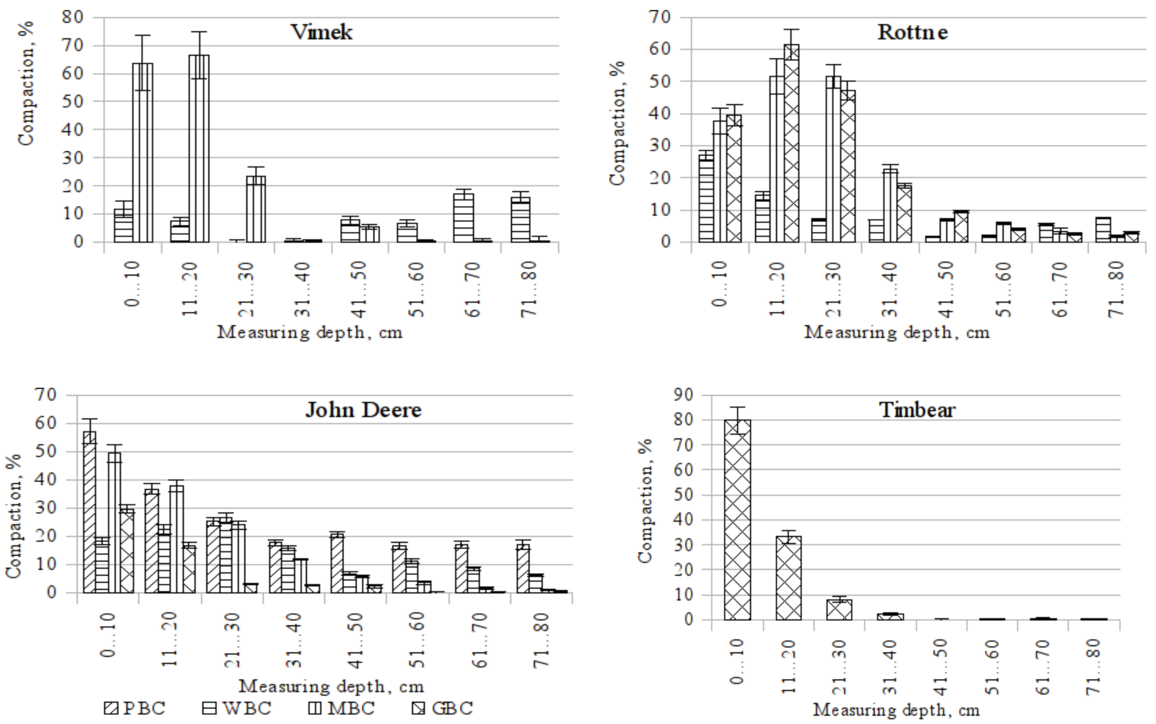

Figure 5. Soil compaction in comparison to control split by the forwarder and group of bearing capacity with standard error of mean.

compaction on TC increases, but in deeper soil layers it is decreasing. The soil compaction exceeding 20% in comparison to the control is observed down to 30 cm depth in the MBC group of soils and down to 10 cm depth in the WBC group.

In case of small-size forwarder Vimek 610, the most significant soil compaction is found in soils representing the MBC and WBC groups. Soil compaction exceeding the level of 20% in comparison to the control is found only in the MBC group of soils, while in the WBC group of soils it is not exceeding the level of 20 % throughout the whole depth of the measured soil layer.

There is relatively little data on Timbear forwarder. Only one type of conditions (GBC) is covered by the study. It is found that compaction exceeding the level of 20% in comparison to the control is not deeper than 20 cm and in contrast to other middle-size forwarders (John Deere and Rottne) the soil compaction is decreasing rapidly with an increase of depth of the measurement.

Soil compaction can be considered as a critical if the penetration resistance reaches 3 MPa. If the penetration resistance reaches this value, it means that roots of trees cannot penetrate the soil. However, the most important threat to future forest development, according to the recent studies, is not compaction itself, but the negative impact on horizontal flows of groundwater in soil (Lazdiņš, 2015). The level of soil compaction overreaching the critical value is found only in study sub-plots in the GBC group of soils, but it is found in both, the control and TC sub-plots. It should be noted that soil compaction due to off-road forwarding of roundwood usually has not significant influence on the development of roots in temperate climatic conditions. Researchers from different countries conclude that the main threat is disturbed horizontal flows of groundwater due to the soil compaction resulting in paludification of forests (Lousier, 1990; Malmer & Grip, 1990; Jim, 1993; Gebauer, 2012); however, empirical data on the influence in Latvia is limited.

Conclusions

1. Statistically significant soil compaction ($p<0.05$) down to 20 cm depth is found in the moderate bearing capacity and good bearing capacity groups of soils for all types of forwarders, whereas in the weak bearing capacity group of soils compaction exceeding 20% in comparison to the control is found for John Deere and Rottne forwarders down to 30 and 10 cm depth, respectively, but in case of Vimek the compaction of the weak bearing capacity group of soils is not detected.
2. Comparison of John Deere and Rottne forwarders highlights relationship between the number of passes and depth of compaction of soil and depth of significantly affected areas, but the study does not provide sufficient amount of data to evaluate this relationship for small-size forwarder and tracked forwarder.
3. Soil compaction due to the off-road forwarding of roundwood is found in all groups of soils, but areas with bigger soil penetration resistance are subjected to higher risk of the soil compaction than soils with smaller soil penetration resistance.
4. Tracked forwarder generates a relatively small impact located at a topsoil level, but the average impact at topsoil level is bigger in comparison to middle-size wheeled forwarders. The compaction of topsoil, which does not affect the growth of roots, should not be considered as negative impact, because according to the results of other studies it returns to initial status during several cycles of freezing.
5. The number of studies should be increased to evaluate the impact of compaction on horizontal groundwater flows; however, available information on the potential threats highlights need for careful planning of direction of technological corridors to avoid clogging of water flows in soil, and harvesting residues should be placed in TC to avoid compaction if there is risk of negative impact on water flows.

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