Impact of forest biomass for energy harvesting on soil compaction – Irish case study

J. Pohořalý[1], R. Klvač[1], T. Kent[2], M. Kleibl[1], E. Coates[2], B. Horgan[2]

[1]*Faculty of Forestry and Wood Technology,Mendel University in Brno, Brno, Czech Republic*
[2]*Waterford Institute of Technology, Waterford, Ireland*

ABSTRACT: An assessment of soil compaction caused by machinery used in stump and/or logging residue extraction for energy on soils typical of Ireland. We determined unaffected soil conditions and to find the compaction grade after timber harvesting and bundling activities, and to compare those results with stands where timber harvesting was followed by stump extraction for energy. The investigation was carried out in Ireland on three different locations which had a slightly different proportion of stones in their soils. Two of the soils were purely mineral soils, and the third was a mineral soil affected by anthropogenic activities. To ensure comparable results as much as possible, the moisture content of the soil on wet basis was investigated. Each location was purposely treated. Therefore, on each location plots were identified as follows: plots unaffected by operation (reference area), plots after timber harvesting, plots after timber harvesting and bundling operation, and plots after timber harvesting and stump extraction operation. According to the experimental design 40 repetitions on each of the three different treatments were set. The results showed that the compaction of soil occurred on plots after timber harvesting, but there was not a significant difference between compaction grades with and without logging residue bundling operation. However, once the site was extracted of stumps, the soil became too loose and no significant difference was found compared to unaffected soil.

Keywords: mineral soil; moisture content; penetration resistance; soil compaction; stump extraction

Management strategies that aim towards the highest forest land utilization have been adopted by managers in recent years. Historically, only timber was frequently utilized, but in many cases strategies which also utilize forest biomass for energy can be more profitable. A source of this material for energy can be found in stumps and root system. As a result, stump extraction for energy is becoming increasingly popular across the world (Saarinen 2006; Athanassiadis et al. 2011; Berch et al. 2012). However, these harvesting activities can affect the soil negatively. Changes in soil physical conditions (porosity, aeration) may impact on the growth and development of root systems. Gebauer (2005) presented the development of a spruce root system which had grown in compacted soil, and found a significantly lower (38%) root system area. This is because the root growth in soil needs to resist to axial and radial soil pressure and soil friction (Greacen 1986).

Rutting is a synergy problem of compaction by heavy logging systems passing on strip roads. Usually mineral soils with high bearing capacity are not significantly affected by rutting (like in this case). However, compaction may activate disturbances in gas exchanges in soil. In cases when the exchange of gases in soil is reduced, carbon dioxide ventilation decreases, and therefore it accumulates (Neruda 2010). Together compaction and rutting are mixing the soil. This affects both the activity of soil organisms, which is corresponding to soil structure and moisture content, and the intake of nutrition.

Soil quality is a topic which is increasingly becoming more and more popular. Generally, quality is assessed using three main aspects: physical, chemical and bio-

Supported by the Internal Grant Agency of Mendel University in Brno, Project No. 71/2012, by the Ministry of Industry and Trade of the Czech Republic, Project No. FR-TI4/139, by the Ministry of Education, Youth and Sport of the Czech Republic, Project No. OC10041, and dominantly by the COST Action FP0902.

logical. Those aspects are considered to be important for assessment of soil degradation or amelioration, as well as for the identification of management methods to ensure sustainable soil exploitation. According to Dexter (2004), soil physical conditions seem to be the most important because they have a high impact on the chemical and biological processes in soil.

Compaction caused by machinery, number of passes, soil type, and moisture content play an important role. No simple and exact device for measuring the impact of all the above mentioned factors on forest soils is available.

As for the most important information required of any harvesting system operation, it is the negative impact it will have on the soil. Curzon et al. (2014) studied the impact of soil compaction on forest productivity together with harvest residue recovery. They have found a significant influence on sandy soils, but no negative effect on clayey and/or loamy soils. Gondek (2014) studied Fluvisol with respect to soil compaction and fertilization (on agricultural land), Jourgholami et al. (2014) studied soil compaction and harvesting systems on brown forest soils, however mineral soils were not investigated in the above-mentioned studies. Therefore the aim of the study was to determine the compaction grade on mineral soils dominantly occurring in Ireland after three harvesting scenarios: (*i*) timber harvesting, (*ii*) timber harvesting with logging residue extraction (bundling), and (*iii*) timber harvesting with stump extraction.

MATERIAL AND METHODS

Three different locations were chosen: Coolbeggan West (Site 1), Corrandromaun (Site 2) and Lacken (Site 3). These sites are located in the south-eastern region of Ireland, close to the small village of Tallow, Co. Waterford. All sites are owned and managed by Coillte, the Irish state forestry company, and contained mature stands of Sitka spruce (*Picea sitchensis*), which were clear-felled in 2011. The main felling method used was a cut-to-length round wood harvesting to a top diameter of 7 cm by a Ponsse Beaver and extracted by a John Deere 810D (Deere & Company , Moline, USA) forwarder. Where residues were extracted, a John Deere 1490D (Deere & Company, Moline, USA) bundling machine was used, and the bundles were extracted using a John Deere 1110E (Deere & Company, Moline, USA) forwarder. Where stump harvesting occurred, the Caterpillar tracked excavator fitted with a Pollari stump extraction head was used (basic characteristics of the vehicles are presented in Table 1).

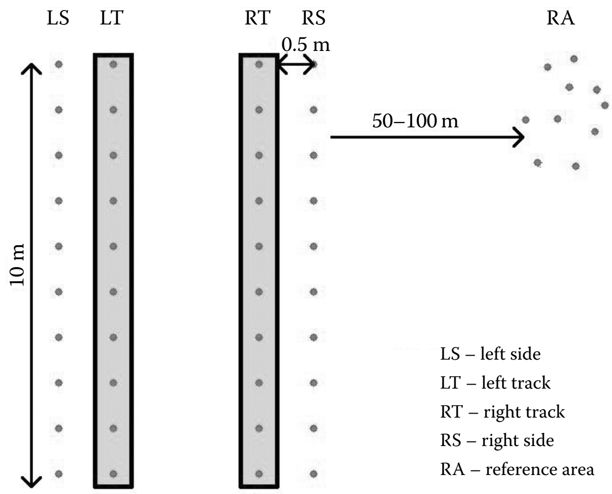

Fig. 1. Sketch of experimental design

On each of these sites, four treatments (three treatments plus reference area) were measured. All treatments were purposely designed to be located next to each other and on each treatment 40 repetitions were measured according to the experimental design (treatment A and B, Fig. 1) or randomly (treatment C and reference area).

– **Treatment A**. CTL harvesting and brash removal. Timber was harvested by a Ponsse Beaver harvester and extracted by a John Deere 810D forwarder and the brash mat was collected by a John Deere 1490E bundler and bundles were extracted using the John Deere 1110E brash bundle forwarder. Measurements were carried out on a moderately used strip roads, with no other tracks converging on it.

– **Treatment B**. CTL harvesting only. Timber was harvested by a Ponsse Beaver harvester and

Table 1. Basic characteristics of applied vehicles

	Weight (kg)	Type of chassis	No. of wheels (if wheeled chassis)
Ponsse Beaver	17,100	wheeled	6
John Deere 810D	11,500	wheeled	8
John Deere 1490D	23,000	wheeled	8
John Deere 1110E	17,300	wheeled	8
Caterpillar	21,000	tracked	

extracted by a John Deere 810D forwarder. The brash mats on the strip roads were intact. Measurements were carried out on a moderately used strip road, with no other tracks converging on it.

– **Treatment C**. CTL harvesting & stump removal. Timber was harvested by a Ponsse Beaver harvester and extracted by a John Deere 810D forwarder. Later the stump extraction was done by a Caterpillar tracked excavator fitted with a Pallari stump extraction head working between strip roads. The disturbed ground was made even by the excavator, so no tracks or holes were visible.
– **Reference area**. No harvesting or machine passes. In this control area, the trees were still standing and no machine passes took place. These areas were selected where it was clear no machines had passed or disturbed the ground during harvesting.

Different authors have used various devices such as deflectometer (Klvač et al. 2010), permeameter (Rejšek et al. 2011), penetrometer (Kleibl et al. 2012) etc. However, the application of a penetrometer for soil compaction determination can be preferable from aspects of time consumption and economics.

The compaction grade caused by machinery was measured by a cone penetrometer (Eijkelkamp, Giesbeek, The Netherlands). Penetration resistance measurements were repeated 40 times for each plot. The number of passes was not monitored, the harvesting sites were evaluated generally. The procedure for measuring by a penetrometer, as presented by Matys et al. (1990), was slightly modified for the manual penetrometer used during the study. Soil penetration resistance was measured using a cone type with 1 cm^2 cone base area and 60° top angle. The values of soil resistance to the penetrating point were measured by a pressure gauge (a component of the instrument). The penetration rate was approximately 2 cm per second – with the equal pressure exerted onto both handles. The device automatically recalculated the penetration force from a penetrometer, and recorded data in MPa for each centimetre of depth. The soil compaction was measured up to 40 cm depth in cases where the soil allows such deep measurement. However, due to the lack of adequate repetitions from deeper layers, the regression evaluation and expression in charts were carried out up to 25 cm.

Each site was evaluated individually. Plots where harvesting activities were carried out were measured in greater detail, i.e. in the track and out of the track. This was purposely chosen due to the predictable higher compaction in tracks.

Reference areas were identified on each site. The nearest stand without operation was chosen, but finally all were evaluated together as one reference site. The number of repetitions was tripled, which offered higher precision of the site to which all results are compared.

– **Penetration resistance** on plots where strip roads were visible (treatment A and B) was measured exactly in the track made by the machine wheels (left, right) and 50 cm to the outside of the track (left side, right side). On the reference area, and on treatment C, points for penetration were chosen randomly (Fig. 1). Coincidentally, almost the same experimental design had already been used and published by Ezzati et al. (2012) with positive results. However, Ezzati's et al. publication was not known to the authors of this study at the time of data collection, and as such was not directly adopted for this study. The method in this paper was created spontaneously during the site visit and method planning.
– **Soil moisture content** was measured with a hygrometer and soil samples were collected for laboratory tests to validate the hygrometer results. The soil samples for moisture content evaluation were collected from two depths under the strip road, i.e. at a depth of 5 and 15 cm. 15 samples from each depth were collected on each site. Wet soil samples were weighed in laboratory conditions to the nearest 1 g, and inserted into an oven where they were dried at a temperature of 105°C (± 2°C) for 24 h or until the weight becomes constant. The soil samples were re-weighed after drying, and the moisture content was calculated (SOP Number: METH 001.00).

The initial analysis was done with the use of pivot tables and graphs. Relations and dependences between the depth and penetration resistance were assessed using the GraphPad Prism 5 program (Motulsky 2007). Outliers were eliminated using the ROUT method (Motulsky, Brown 2006). This method is based on robust non-linear regression and the assumption that variation around the curve follows a Lorentzian distribution rather than a Gaussian distribution (based on a suggestion of Press et al. 1988). Having fit a curve using robust non-linear regression, a threshold is needed to decide when a point is far enough from the curve so that an outlier can be declared. All methodology is described in detail in Motulsky and Brown (2006). The authors state that their method identifies outliers from non-linear curve fits with reasonable power and few false positives (less than 1%).

In all cases, the quadratic function used for the regression model was in the following Equation 1:

$$y = a + b \times x + c \times x^2 \quad (1)$$

where:

x – explaining (independent) variable,

y – explained (dependent) variable,

a, b, c – coefficients.

The respective statistical assessments include *a*, *b* coefficients established by the regression analysis, 95% confidence interval (shaded in the final graph), R^2 – determination coefficient, number of analysed points and number of outliers.

A comparison matrix was created where different sites were set in rows and different treatments were set in columns. Each of the individual curves within the cell was compared to the reference area.

RESULTS

The soil type was classified according to FAO nomenclature (Anonymous 2006). All soils were mineral soils. Detailed soil nomenclature is mentioned in Table 2 according to Rejšek (2013 personal communication).

To be able to compare not only sites but also treatment types, the matrix of charts is presented in Fig. 2. Rows represent different sites (1, 2 and 3) and columns represent specific treatment types (A, B and C). The results of the statistical analyses are presented in Table 3 for the entire site and treatment combinations including the reference area.

Evaluating all of the combinations, the following interpretations were made:

– the compaction grade on the strip road is visibly higher in the tracks compared to out of the track. Only on site 3/treatment B is the compaction grade in the track and out of the track almost on the same level (Fig. 2). This was due to the fact that the proportion of skeleton (large stones) in soil was the highest on site 3, which may affect the measuring process. This is supported also by wider 95% confidence interval which means significantly higher disproportions between measured data in repetitions,

– out of the track (which means 50 cm to the outside of the track), the compaction occurs generally in deeper layers (deeper than 5 cm). Top layers (up to the 5 cm of the depth) are not affected of compaction and are comparable to the conditions of reference area in this study. The combination of site 3/treatment B did not give any adequate results here as well.

– generally, there was no significant difference between the compaction grades on treatments A and B. This is probably because of the high sensitivity of mineral soils.

– results from the stump extraction plots show no visible difference between the reference area and the treated areas. In addition, sites became looser compared to the reference area. This was probably due to the fact that uprooting may make the soil looser; and because the soil surface was levelled out/smoothed by the excavator, no tracks or holes were visible. Some deep tracks were covered with fresh loose soil, which may have affected the measurements.

Table 2. Soil type classification (Rejšek – personal communication, 2013)

Site	Treatment	Soil type	Reference area soil type
1	A	stagnic cambisol	entic podzol
	B	stagnic podsol	
	C	dystric cambisol	
2	A, B, C	anthrosols	anthrosols
3	A	entic podsol	gleyic cambisol
	B	haplic podsol	
	C	stagnic cambisol	

The moisture content of the soil was measured at two different depths of 5 and 15 cm so that the result will be comparable. Two different measuring methods were used. Firstly, a hygrometer was used and three measurements at each depth were recorded from which the mean value was calculated. This method, however, is not supported in literature because of the low correlation with precise moisture content assessment using Kopecky's metal rings (laboratory tests). The second method used consisted in direct sampling and oven drying. Two soil samples at each depth were collected in plastic bags and evaluated in laboratory conditions. This evaluation should give more representative results and are given as moisture content on wet basis. All results documenting the moisture content of soil are shown in Table 4.

DISCUSSION AND CONCLUSION

The quality and precision of soil compaction measuring were discussed by Motavallie et al. (2003). In their paper, they demonstrated significant differences of penetrometer used. However, the aim of this study was not to exactly measure

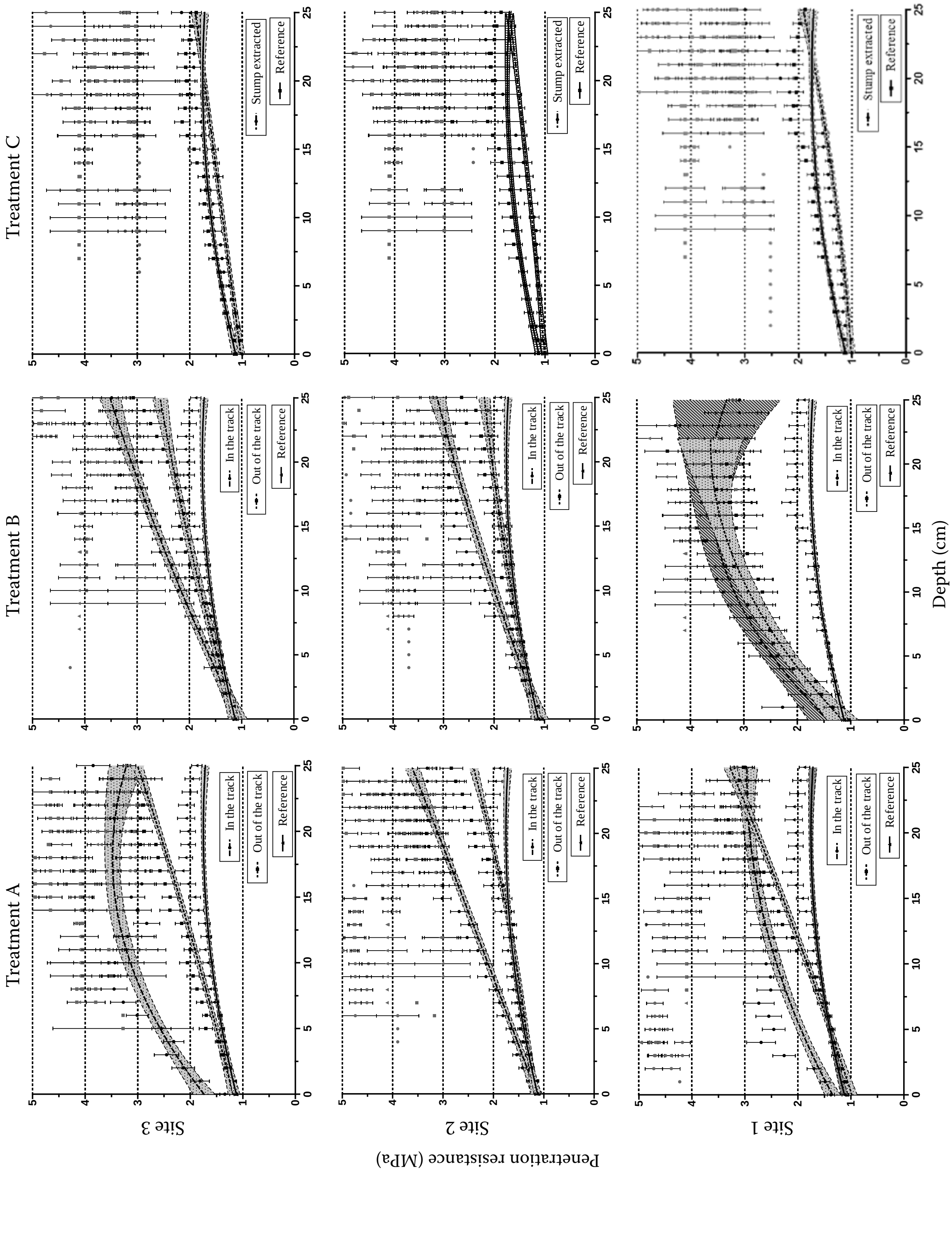

Fig. 2. Compaction grade comparison matrix

Table 3. Regression analyses of soil penetration resistance for all plots

Identification	Regression coefficients of equation $y = a + bx + cx^2$			R^2	Analysed points/ No. of outliers
	a	*b*	*c*		
Site 1.a – in the track	1.739	0.19370	−0.0053880	0.2099	571/0
Site 1.a – out of track	1.190	0.06009	0.0004998	0.5177	908/58
Site 1.b – in the track	1.050	0.11920	−0.0008202	0.5598	436/8
Site 1.b – out of track	1.123	0.07184	−0.0005749	0.0384	491/16
Site 1.c – stump extracted	1.025	0.03489	−0.00001084	0.4216	475/36
Site 2.a – in the track	1.143	0.09469	0.0001567	0.5521	811/36
Site 2.a – out of track	1.192	0.02672	0.0008513	0.3785	976/53
Site 2.b – in the track	1.069	0.09887	−0.0006669	0.5168	452/31
Site 2.b – out of track	1.161	0.05423	−0.0005276	0.3354	489/16
Site 2.c – stump extracted	1.008	0.02415	0.0001488	0.3707	474/41
Site 3.a – in the track	1.347	0.13280	−0.0027310	0.3185	571/39
Site 3.a – out of track	0.982	0.07905	0.0005106	0.5667	871/36
Site 3.b – in the track	1.423	0.24180	−0.0066370	0.2140	235/0
Site 3.b – out of track	1.151	0.22740	−0.0052290	0.3088	300/0
Site 3.c – stump extracted	1.018	0.01742	0.0007398	0.4259	437/77
Reference	1.124	0.06251	−0.0015550	0.1992	932/76

x – depth (cm), *y* – penetration resistance (MPa), *a, b, c* – parameters

the compaction grade, but to compare the effect of various technologies of forest biomass processing. Therefore no specific demands were put on the type of penetrometer and cone.

The identification of impact and return of the soil into the close to normal conditions was dealt with in the study of Kleibl et al. (2014). In their study, the return of the soil was investigated using similar material and method with relevant outputs and finally the impact of forest operation was clearly visible. Therefore the material and method were adopted from their study and later slightly modified according to unique conditions in Ireland.

The cone on the penetrometer should ideally be validated as being no different from a reference cone calibre after each plot is measured during the study. In this project, the cone was compared to the calibre at the beginning and at the end of the survey. The difference was not higher than 1%. Within this project, there were up to 800 measurements planned, and therefore the authors accepted a slight difference (up to 1%) during measurements.

The high number of measurement repetitions (40 repetitions on each of the 3 sites) ensured a high level of precision in the results. However, it was very difficult to find clearly unaffected soil. Plenty of previous activities such as treatment of the stands, silviculture of the stands, harvesting activities, tourism and/or game management had a high impact on almost all the area. Therefore, the

Table 4. Results of moisture content in soil

Identification	Hygrometer		Laboratory tests*	
	5 cm	15 cm	5 cm	15 cm
Site 1.a – in the track	43.6	36.9	31.0	23.3
Site 1.a – out of track	52.9	39.3	59.4	33.2
Site 1.b – in the track	47.3	41.8	30.1	27.5
Site 1.b – out of track	59.3	52.9	46.7	37.1
Site 1.c – stump extracted	44.6	42.3	28.0	26.5
Site 2.a – in the track	60.8	43.2	46.2	35.0
Site 2.a – out of track	49.4	43.6	43.5	30.3
Site 2.b – in the track	60.6	47.0	53.8	40.5
Site 2.b – out of track	42.9	40.9	25.2	29.3
Site 2.c – stump extracted	45.3	41.1	33.0	30.6
Site 3.a – in the track	51.5	31.1	37.7	25.8
Site 3.a – out of track	59.2	38.1	56.8	28.7
Site 3.b – in the track	78.1	51.2	56.3	57.3
Site 3.b – out of track	50.5	31.6	43.1	24.7
Site 3.c – stump extracted	67.1	34.7	49.1	24.3
Reference areas	65.1	46.1	60.8	39.0

*moisture content wet basis

authors cannot fully ensure that the reference area was not affected by these impacts also. Soil probe measurements were taken on each site/treatment combination. All treatment types were affected historically by anthropogenic activities. There is hardly any forest land in Ireland that was not at least historically harvested and newly replanted. Anthropogenic activities were still visible on site 2, according to the soil type determination. This may be demonstrated by a relative straight curve of compaction, instead of the more parabolic curve on site 1 and 3. However, those activities were carried out at least 30 years ago, and therefore the return of the soil into the natural conditions worked positively for the authors with respect to the relevance of the chosen reference area.

All the soils were identified as a mineral soil. The heterogeneity of soil types is visible from the results. Even though the heterogeneity plays a role, generally, the trends within each treatment type were comparable across all sites only with small excesses.

The results from the penetration resistance and soil sample analyses give expected grades of compaction with respect to the treatment type. In higher layers of soil, the difference is smaller; the difference between compaction grades is more visible with the increasing depth of soil layers.

During harvesting, usually only timber is removed from the site, and tree tops, branches and stumps are left behind. However, one of the ways how to maximize profit from forest land use is higher utilization of forest biomass, which can be used for energy. Therefore, management systems exploiting stumps and branches can be applied. Based on the results of this study, it seems that the stump extraction may positively affect soil physical conditions from the compaction and rutting aspects. However, this study did not take into the consideration any other impacts of stump harvesting such as nutrition, water management, biological or chemical activities, mixing of soil horizons etc., which definitely increases an anthropogenic influence on the soil.

Acknowledgement

The authors also wish to express their thanks to Coillte for providing a possibility of data collection and co-operation during the site and experimental design preparation.

References

Ampoorter E., van Nevel L., de Vos B., Hermy M., Verheyen K. (2010): Assessing the effects of initial soil characteristics, machine mass and traffic intensity on forest soil compaction. Forest Ecology and Management, ***260***: 1664–1676.

Anonymous (2006): IUSS Working Group WRB. World Reference Base for Soil Resources 2006. 2nd Edition. World Soil Resources Report 103. Rome, FAO: 145.

Athanassiadis D., Lindroos O., Nordfjell T. (2011): Pine and spruce stump harvesting productivity and costs using a Pallari KH 160 stump-lifting tool. Scandinavian Journal of Forest Research, ***26***: 437–445.

Berch S.M., Curran M., Dymond C., Hannam K., Murray M., Tedder S., Titus B., Todd M. (2012): Criteria and guidance considerations for sustainable tree stump harvesting in British Columbia. Scandinavian Journal of Forest Research, ***27***: 709–723.

Curzon M.T., D'Amato A.W., Palik B.J. (2014): Harvest residue removal and soil compaction impact forest productivity and recovery: Potential implications for bioenergy harvests. Forest Ecology and Management, ***329***: 99–107.

Dexter A.R. (2004): Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma, ***120***: 201–214.

Ezzati S., Najafi A., Rab M.A., Zenner E.K. (2012): Recovery of soil bulk density, porosity and rutting from ground skidding over a 20-year period after timber harvesting in Iran. Silva Fennica, ***46***: 521–538.

Gebauer R. (2005): Porovnání struktury orgánu smrku ztepilého (*Picea abies*/L./Karsten) (zejména kořenových systémů) za různých abiotických a biotických podmínek. [Comparison of Norway spruce (*Picea abies* /L./ Karsten) organs structure (especially root systems) in different abiotic and biotic conditions.] [PhD Thesis.] Brno, Mendelova univerzita v Brně: 122.

Głab T., Gondek K. (2014): The influence of soil compaction and N fertilization on physico-chemical properties of Mollic Fluvisol soil under red clover/grass mixture. Geoderma, ***226–227***: 204–212.

Greacen E.L. (1986): Root response to soil mechanical properties. Trans International Congress Society of Soil Science, ***5***: 20–47.

Jourgholami M., Majnounian B., Abari M.E. (2014): Effects of tree-length timber skidding on soil compaction in the skid trail in Hyrcanian forests. Forest Systems, ***23***: 288–293.

Kleibl M., Klvač R., Lombardini C., Pohořalý J., Spinelli R. (2014): Soil compaction and recovery after mechanized final felling of Italian coastal pine plantations. Croatian Journal of Forest Engineering, ***35***: 63–71.

Kleibl M., Klvač R., Pohořalý J. (2012): Strip road compaction caused by logging technology (measured by penetrologger and deflectometer). In: Pentek T., Poršinsky T., Šporčič M. (eds): Proceedings of 45th International Symposium on Forestry Mechanization. Forest Engineering: Concern, Knowledge and Accountability in Today's Environment. Zagreb, 8–9 October 2012. Zagreb, Forestry Faculty of Zagreb University: 1–9.

Klvač R., Vrána P., Jiroušek R. (2010): Possibilities of using the portable falling weight deflectometer to measure the bearing capacity and compaction of forest soils. Journal of Forest Science, ***56***: 130–136.

Matys M., Ťavoda O., Cuninka M. (1990): Poľné skúšky zemín. [Field Tests of Soils.] Bratislava, ALFA: 301.

Motavalli P.P., Anderson S.H., Pengthamkeerati P., Gantzer C.J. (2003): Use of soil penetrometers to detect the effects of compaction and organic amendments in claypan soils. Soil and Tillage Reserch, ***74***: 103–114.

Motulsky H.J., Brown R.E. (2006): Detecting outliers when fitting data with nonlinear regression – a new method based on robust nonlinear regression and the false discovery rate. BMC Bioinformatics, ***7***: 123.

Motulsky H.J. (2007): GraphPad Prism. Version 5.0. San Diego, GraphPad Software. Inc.: 294.

Neruda J., Kadlec J., Ulrich R., Cudzik A. (2010): Soil carbon dioxide concentration and efflux changes in ruts after heavy machine passes. [CD-ROM]. FORMEC: 1–8.

Press W.H., Teukolsky S.A., Vettering W.T., Flannery B.P. (1988): Numerical Recipes in C: The Art of Scientific Computing. New York: Cambridge University Press: 994 .

Rejšek K., Buchar J., Vaníček I., Hromádko L., Vranová V., Marosz K. (2011): Results of dynamic penetration test - an indicator of the compaction of surface soil horizons by forestry machinery. Journal of Forest Science, ***57***: 439–450.

Saarinen V.M. (2006): The effects of slash and stump removal on productivity and quality of forest regeneration operations – preliminary results. Biomass and Bioenergy, ***30***: 349–356.

Schäffer J. (2005): Bodenverformung und Wurzelraum. In: von Teuffel et al. (eds): Waldumbau für eine zukunftsorientierte Waldwirtschaft. Berlin, Springer: 345–361.

SOP Number: METH 001.00. Standard Operating Procedure, Soil Water Content Determination, Sacramento, California Department of Pesticide Regulation: 4.

Received for publication July 25, 2014
Accepted after corrections October 29, 2014

Corresponding author:

Ing. Josef Pohořalý, Mendel University in Brno, Faculty of Forestry and Wood Technology, Department of Forest and Forest Products Technology, Zemědělská 3, 613 00 Brno, Czech Republic; e-mail: horek@centrum.cz