Results of dynamic penetration test – an indicator of the compaction of surface soil horizons by forestry machinery

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ABSTRACT: The objective of research was, on the basis of the exactly predefined input parameters of upper soil horizons of selected forest soils, to perform accurate measurements of the impact of soil loading by tested forestry machinery using the dynamic penetration test. The measurements by the dynamic penetration test in conditions changed by the wheel traffic of forestry mechanization were performed at three localities of the Křtiny Training Forest Enterprise, Masaryk Forest, a special-purpose facility of Mendel University in Brno. The dynamic penetration test was performed with a lightweight dynamic penetrometer. The methodology of the research is based on assessing the ability of soils to resist dynamic penetration of a rod with a cone, in relation to their lithological composition and physicomechanical properties; the measurement itself is defined by the ISO 22476-2 (2005) standard. Penetrometer measurements were repeated in the period after a harvesting operation and again 6 months later, i.e. in October 2007, April 2008 and October 2008. The results of the field dynamic penetration test and the results of laboratory testing of main soil physical parameters are presented in figures and tables. Besides the naturally variable soil compaction on geologically different substrates, the obtained original results document differences in the impact of particular forestry machines. In conditions of the identical geological substrate, the results indicate that the universal wheeled tractor had a more negative influence on the compaction of surface soil horizons compared to the multi-axle harvester and the forwarder.

Keywords: dynamic penetration test; soil compaction; soil mechanics; lightweight dynamic penetrometer

The dynamic penetration method is one of the oldest geotechnical research methods (Matys et al. 1990), which was used to determine the bearing capacity of subsoil: it was first described in the work Comprehensive Guidelines to the Art of Building (Vollständige Anweisung zu der Civil Bau-Kunst) by Nicolaus Goldmann in 1699 as a method of driving a coned rod into soil with a hammer. Before World War II, A. Kumm developed a dynamic penetration test with the dynamic part of the penetrometer having the constant weight of 5–8 kg and the fall height of 50 cm; the testing rod was 15 mm in diameter, with a pyramid-shaped end. In the 1950s, devices allowing the penetration of a sampling cylinder were designed. Unification of the dynamic penetration test in European countries was facilitated by the German standard DIN 4094 in 1977.

The specific aim of the performed investigation was to assess the applicability of the dynamic penetration test as a method for the study of compaction of the upper forest soil horizons. The basic theoretical source is a key comparative study of Marshall et al. (2001). The present state of the art in the field of soil compaction was taken over partly from the work of Lebert et al. (2007), partly from

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Cetin et al. (2007). Significant issues regarding a broader environmental perception of the problem of soil surface compaction were presented by the authors on the basis of discussion papers of Tullberg (2001) and Kirby (2007). As a material for comparison from the historical point of view, the authors chose the PhD thesis of Etana (1995). The state of the art in the field of application of the dynamic penetration method with emphasis on the lightweight penetration set was described in the review of literature and the following discussion of the own results represented by Vaníček and Vaníček (2008) and normative material ISO 22476-2 (2005), based on the German standard DIN 4094 (Matys 1990).

To discuss the currently used low-impact hauling technologies in Czech forestry (Report on the State of Forests and Forestry in the Czech Republic by 2009/2010), the authors of this chapter used the findings of Malík and Dvořák (2007), Oliva (2008), Vavříček et al. (2008), and Klvač et al. (2010).

As regards the measuring itself, it is necessary to say that the penetrometer is an appliance able to examine and eventually also to record the individual layers of subsoil. It works on the principle of a steel cone that is driven into the soil which resists the penetration. As each soil unit is characterized by different resistance due to variability of physical, hydrophysical and soil-mechanical properties of the upper soil horizons, the use of this appliance allows to assess the thickness as well as compaction of the upper soil horizons through mathematico-physical relations (Vaníček, Vaníček 2008). The measurements were performed with dynamic penetrometer. The principle of its function is that the falling component (dynamic part of the penetrometer) passes an exact amount of kinetic energy to the solid part (static part of the penetrometer, linkage with a cone), which then vertically penetrates into the soil profile. The measured data are standardly obtained by counting the number of hits necessary to reach a specified depth (standard depth unit). The authors of this paper used a modification "depth per hit", with the aim to obtain more precise information on compaction in smaller depth intervals than can be provided by the standard method. The evaluation graphs had to be adapted to this modification (the authors of the chapter did not consider the average number of hits for cone penetration by 20 cm – usually the average number of hits is calculated and taken as 100%). The construction of dynamic penetrometers is based on the application of the standard ISO 22476-2 (2005) for differentiation of dynamic penetrometer light DPL (dynamic part of the penetrometer up to 10 kg; fall height 0.5 m), dynamic penetrometer medium DPM (dynamic part of the penetrometer up to 30 kg; fall height 0.5 m), dynamic penetrometer heavy DPH (dynamic part of the penetrometer up to 50 kg; fall height 0.5 m) and dynamic penetrometer super-heavy DPSH (dynamic part of the penetrometer up to 63.5 kg; fall height 0.5 m–0.75 m). Lightweight portable dynamic penetrometer is made either with automatic drive, hydraulic drive or with manual drive. The record is taken either manually (aimed at registration of depths), by means of laser beam or by ultrasound, with editing directly into a data logger.

As regards the significance of such measurement, we can say that in contrast to agriculture, the field of forestry has fulfilled production and social roles of forests over decades with a strong (for central-European conditions) emphasis on ensuring the ecological stability of forest stands (Míchal 1992) in the conditions of variable effectiveness of external factors affecting the long-term ability of forest ecosystems to maintain their parameters by internal self-regulated mechanisms (resistance) or to restore the original state after disturbance (resiliency). Soil is the basic abiotic component of terrestrial ecosystems (Rejšek et al. 2009): especially with regard to a potentially negative impact of forestry machinery traffic on the persistence of production conditions, the problem of soil productivity maintenance becomes a subject of increased interest among forestry professionals. The introduction of mechanization machines into harvesting operations took a longer time in Czech forestry; by the 1980's, mechanization consisted mainly of log hauling equipment that used previously constructed forest roads and therefore it did not cause any significant damage to forest soil. Only in connection with the development of harvester technologies, forestry machines started to be employed in all phases of forest production and thus they operate on an ever increasing part of soil assigned to fulfil the roles of the forest (Law on Forest 1995). Besides, the impact of hauling equipment itself, in connection with advancement of its functions linked to changes of its technical parameters – mainly of total weight, speed of travel, number of axles, and the use of tracked or tracked-wheel technology – has been gaining significance over the last thirty years, also in relation to the network of hauling roads and potential emergence of erosion rills in crowns of these roads (Malík, Dvořák 2007).

It is clear that specific hauling machines of different adhesion weight and different tractive efficiency provoke pressures in the soil that spread to sides and to depth and have different impacts on the soil body impairment in different soil units (especially clay vs. sandy soils and waterlogged vs. non-waterlogged sites), in different types of forest sites (especially flat terrain vs. slope and terrain with obstacles vs. terrain without obstacles) – under different impacts of actual meteorological conditions in the conditions of locally specific mesoclimate of the forest stands in questions, when it is mainly the high soil water content that determines reversible vs. irreversible compaction of upper soil horizons.

An example of considering the potential impact of hauling equipment on forest soil is the Ecowood partnership classification (Owende et al. 2002), ranking forest soils into the following four categories according to their bearing capacity: solid soils, average bearing soils, soft soils and very soft soils. The criterion of this classification is the magnitude of pressure not generating measurable damage: solid soils are not damaged even at the pressure of 80 kPa, average bearing soils maintain the same state of soil environment at pressures between 60 kPa and 80 kPa, soft soils between 40 and 60 kPa; very soft soils are damaged even by simple walking (the foot of an adult exerts the pressure of about 40 kPa on soil). However, the presented categorization is much more complex from the viewpoint of forestry as besides the soil compression due to machine traffic and subsequent origination of a rut, it is necessary to consider the chassis properties of a moving machine, so called slipping, and also the pressure spreading on a base of the travel medium in direct relation to the resistance of the base during the traffic of the studied forestry machinery. From the aspect of soil science, two parameters are of key importance – grain size and water content of the upper soil horizons.

From the forestry point of view, it is possible to look at the negative impact of hauling machinery on forest soil from three aspects: mechanical damage to roots of forest woody species, compaction of upper soil horizons and increase in the mechanical resistance of soil to root growth. Nevertheless, the study of soil mechanics provides information that can be used for assessment of the process of compaction as well as for determination of a decrease in the availability of particular nutrients, oxygen and water, and, on the other hand, of an increase in the carbon dioxide concentration in soil caused by the reduced rate of CO_2 output (produced by respiration of soil biota and plant roots, mineralization of organic matter and decomposition of carbonates) from forest soil.

It is clear that for the above-mentioned goal it was necessary to start from determination of critical values of particular factors. The limiting values are such values that cause a disturbance of soil regimes and functions if they are exceeded – specifically, Lhotský (2000) considered the following parameters to be critical for forest soils:

– bulk density: 1.3–1.7 $g\cdot cm^{-3}$; it depends on the particle size distribution of a particular horizon,
– minimum air capacity/aeration: 10–12%,
– relative capillary water content (by volume): 80%,
– bulk density limiting the root growth: 1.5 to 1.7 $g\cdot cm^{-3}$,
– content of silt particles (0.01–0.05 mm): 20%.

Therefore, the impact of hauling technology on physical, hydrophysical and soil-mechanical properties is directly linked to water content in topsoil and to water contents (by both mass and volume) of surface horizons, as well as to the pressure generated by the traffic of specific forestry equipment; these factors then determine the influences of distribution of this pressure in soil to the contact areas of secondary structural elements – soil aggregates. Neruda et al. (2008) explicitly stated that the pressure of 0.15 MPa affected the soil environment to the depth of approximately 0.35–0.40 m and that the more yielding and wetter the soil, the greater the depth of pressure effect. The same authors just as explicitly set the depth of the ruts generated by forestry machinery traffic to the limit of 10 cm, which is regarded as acceptable soil damage. Besides, the impact of hauling technology on physical, hydrophysical and soil-mechanical properties is also conditioned by so called technological properties of soil – soil consistency and its components, soil elasticity and plasticity. Here a rule is applicable that the upper soil horizons with high elasticity tend to restore their original level of physical, hydrophysical and soil-mechanical properties after being disturbed by forestry mechanization traffic, while the upper horizons with high plasticity are irreversibly compacted. The process of compaction proceeds in two phases, i. e. in the first versus repeated passes: the first pass causes predominantly the plastic (permanent) deformation, in the second phase (repeated passes) mainly the elastic deformation occurs as the load affects soil horizons with previously changed properties (Lhotský 2000). In this context it is necessary to stress the role of root systems of forest woody species (Ulrich et al. 2003): where the upper soil horizons are reinforced with root systems of undergrowth, the elasticity of the specific horizons is increased and irreversible damage after one pass is minimized. However, in the case of repeated passes, permanent damage is rightly expectable: Ulrich et al. (2003) reported the greatest soil compaction to occur with the first to the third pass, but after the fifth to the tenth pass the compaction consolidates to such an extent that a further increase of bulk density is minimal.

Forestry mechanization traffic affects the forest soil both directly and indirectly, having a fundamental impact on its physical, hydrophysical and soil-mechanical properties. These properties are inherent in the soil structure; that, in return, has a key role in the air and water regime of forest soils and hence also in their production capacity (Rejšek 2003). The influence of hauling technology on the soil structure can be quantified quite specifically as shown in Table 1. It is a very significant characteristic from the aspect of forestry (especially with respect to the fulfilment of social roles of forest): after multiple mechanical disturbance of its structure, the soil becomes permanently unstructured, losing the ability to regenerate (Kutílek et al. 2000), which makes the danger of soil structure damage even more serious. Its seriousness is evident from the fact that the root space serves for an exchange of ions, movement of water and exchange of gases. Therefore, the traffic of forestry mechanization changes water and air regimes of soil by causing defects in the soil structure (Table 1).

Lhotský (2000) explicitly characterized the negative influences as follows:

- deficit of oxygen for plant roots induces an overall stress to plants – as a result, the lack of oxygen further worsens, aerobic processes are restricted or blocked and anaerobic processes develop with all the consequences of development of poor humus, unfavourable intermediate products and soil acidification;
- in soils with disturbed structure, metabolic processes are reduced and the energy becomes less accessible to plants;
- soil partially loses the ability to respond to harmful substances, which lowers its sanitary effectiveness;
- with acidification, the uptake of nutrients by plants is failing and the mobility of most of the potentially harmful elements increases as they are conversely taken more intensively by plants;
- destruction of soil structure contributes to reduced infiltration, increasing the risk of erosion occurrence and local accumulation of erosive wash material including risky substances;
- in loamy and clayey soils, the destructed structure may cause defects in growth and quality of plants, especially in extreme climatic situations (waterlogging, drought);
- in lighter granular soils, damage to their structure speeds up mineralization with production of nitrates, which are taken up by plants or washed out into groundwater to a greater extent.

Quite specifically, the impact of hauling technology on physical, hydrophysical and soil-mechanical properties can be quantified by Table 2.

Neither the study of compaction of the upper forest soil horizons nor the study of impacts of hauling technology on soil water movement is based on internationally recognized evaluation methods. In forestry literature we can find different approaches to the above-mentioned problems – they are evaluated by visual estimation, simple measurements of rut depth, as well as by complex methods using soil pressure probes. Dynamic penetration test (Herrick, Jones 2002) cannot measure instantaneous pressures on a measurement unit, however, its application in compaction evaluation allowed Neruda (2008) to express the following statements that are connected with requirements of forestry practice for its interaction with forestry research:

(1) after the first pass, maximum compaction is not detected, which is due to the soil horizon elasticity;

(2) a positive effect of brash (logging residues) covering the forest floor in places of forestry machinery movement has been confirmed;

(3) higher pressures produced by forestry mechanization traffic were measured on forest soils with dried-out surface, the highest values of pressure being reached during passes over small terrain irregularities due to the combination of machinery traction power and dynamic effects of their movement.

As mentioned above, the aim of the present study can be seen in the application of dynamic penetra-

Table 1. The critical values of bulk density and porosity at the moment when the compaction of surface soil horizons occurs according to Šimon and Lhotský (1989)

Soil textural classes	Clay	Sandy clay, silty clay	Loam	Sandy loam, sandy silt loam	Loamy sand	Sand
Bulk density ($g \cdot cm^{-3}$)	> 1.35	> 1.40	> 1.45	> 1.55	> 1.60	> 1.70
Porosity (%)	< 48	< 47	< 45	< 42	< 40	< 38

Table 2. The critical values of bulk density in its natural condition (g·cm^{-3}) in the first moment of plant root growth restriction according to Arshad and Coen (1992)

Soil textural classes	Minimum value of bulk density for the first moment of plant root growth restriction
Sand, loamy sand	1.80
Sandy loam, sandy silt loam	1.75
Loam, sandy clay loam	1.70
Sandy clay, silty clay	1.65
Sandy clay	1.55
Silty clay	1.45
Clay	1.40

tion test as a method for the study of compaction of the upper forest soil horizons. The investigation focused on the assessment of impacts of selected forestry hauling technology on selected localities of the Křtiny Training Forest Enterprise, Masaryk Forest, with special attention paid to dynamic penetration test as a method for the inspection of soil profile compaction in forestry. The stands and the intensity of forestry measures were chosen on the basis of similar parameters with regard to later interpretation of results that would also allow a comparison of changes in the characteristics between particular localities.

MATERIAL AND METHODS

As regards forestry mechanization, we used a universal wheeled tractor Zetor 7245 Horal System with the four-wheel drive (4 × 4) and standard tyres Mitas 11.2–24'' profile TD-19, on the front axle, and tyres 16.9–30'', profile TD-13, on the rear axle. Simultaneously, we tested a three-axle 16 t harvester PONSSE ERGO 16 and a four-axle forwarder Gremo 950 with the service weight of nearly 12 t. The forwarder was equipped with Nokian tyres of 700 × 22.5'' on all axles. All wheels of the forwarder were fitted with non-skid chains. For the performed field surveys, we used a lightweight dynamic penetrometer of the total weight 71 kg and with the following components/parameters:

- drop rammer with handles – 10 kg,
- impact anvil with a reading needle,
- sounding rod, ø 22 mm, length 1 m, threaded collar M 16,
- guiding rod, base plate, extracting extension with a lever, steel gauge of 1 m, hammering head with handles, grooved rod of 1 m – thread M 16, joining screws M 16 × 40 INBUS,
- small drive point – 90°, 5 cm^2, ø 24.2 mm,
- large drive point – 90°, 10 cm^2, ø 35.6 mm.

The survey was carried out on three study plots within the Křtiny Training Forest Enterprise, Masaryk Forest, a special-purpose facility of Mendel University in Brno. All study plots are situated in a special-purpose forest with high forest silvicultural system and shelterwood (small-area felling) or clear-cutting system of management. Generally we can say that the study plot in Babice nad Svitavou represented the group of forest types 3 A, i.e. lime-oak beech forest, and according to the framework management guidelines it represented management set of stands 306 Special-purpose beech management of drying and drier aceros and basic sites at medium altitudes. In Rudice, the study plots belonged to the group of forest types 4K, i.e. acidic beech stands, management set of stands 421 Special-purpose spruce management of acidic sites at medium altitudes.

Measurements by the dynamic penetration test as the level of compaction of the upper horizons in forest soils in conditions changed by the traffic of forestry mechanization were performed at three localities of the Křtiny Training Forest Enterprise, Masaryk Forest. Soil profiles were open and described there. Simultaneously field measurements of penetration with the lightweight dynamic penetrometer were also carried out, based on assessing the ability of soils to resist dynamic penetration of a rod with a cone, in relation to their lithological composition and physicomechanical properties; the measurement itself is defined by the ISO 22476-2 (2005) standard. Penetrometer measurements were repeated in the period after a harvesting operation and again 6 months later, i.e. in October 2007, April 2008 and October 2008.

Results from study plot No. 2 were obtained in a skidding trail with the total of 5 passes of the universal wheeled tractor Zetor 7245 Horal that had transported 12 m^3 of timber in semi-suspension. Control measurements were performed 15 m from the testing trail in a young stand unaffected by the described tractor operation. At this locality, 20 penetration tests were carried out in total, resulting in 18 representative transects, as in two cases the measurement was distorted by a stone and had to be excluded from the evaluation. Results from study plot No. 3 reflect the situation after mechanized thinning with a PONSSE ERGO 16 harvester and the following haulage with a Gremo 950 forwarder. Within the operation, 560 m^3 of timber were harvested, both roundwood assortments and pulpwood.

Results from study plot No. 4 document motomanual thinning followed by extraction and skidding works with the universal wheeled tractor Zetor 7245 Horal; 16.4 m^3 of timber were harvested in total.

The nomenclature of the forest soil units is given in IUSS Working Group WRB (2006).

Babice nad Svitavou – plot No. 2 (Stand No. 314B10)

Soil unit: Haplic Luvisol haLV
Pedogenetical characterization: intense illimerization on polygenetical loams overlying the debris of Devonian limestone
Site description: gentle slope of 7.5° (14%), northern exposition
Soil profile description:
0–2 Oi folic organic components of European beech origin, almost no herb debris,
2–5 Oe prominent accumulation of folic material in a fermentation horizon,
5–7 Oa highly humified,
7–13 Ah 10YR 3/1, sandy silt loam, faint colours due to humic compounds, fine-size aggregates, granular, fairly moist,
13–28 El 10YR 7/6, lighter in colour than the A horizon, without concretions, sandy loam, eluviation of clay also due to lateral movement of slope water,
28–60 Bt 5YR 4/6, silty clay, argillans, silicate clay moved into by illuviation, formation of prismatic structure, strongly cemented, indurated,
60↓ D underlying consolidated/fragmental limestone.

Rudice – plot No. 3 (Stand No. 146D8)

Soil unit: Haplic Luvisol haLV
Pedogenetical characterisation: very prominent stratigraphy with deep both eluvial and illuvial horizons, between master horizons ‑ overlaid by layers dominated by organic material – there is a fully developed transitional horizon
Site description: very gentle slope of 3°, eastern exposition
Soil profile description:
0–1 Oi fresh litter of Norway spruce,
1–2 Oe partly decomposed needles of Norway spruce,
2–4 Oa conspicuously accumulated, sticky humified organic material,
4–9 Ah 10YR 2/1, highly humic, silt loam, very friable, granular, medium-size aggregates, biologically active, both course and fine deep rootage,
9–33 El 10YR 7,5/6, albic horizon, a loss of silicate clay leaving a high content of silt and sand particles, finely-platy structure of weak grade, non-prominent rootage, nonsticky (not holding together),
33–55 EB 5YR 5/8, sandy clay, friable, horizon with characteristics of both the overlying E horizon and the underlying B horizon, non-prominent rootage, wet,
55–75 Bt 5YR 4/6, silty clay, clay films, no mottles, firm, sticky, wet,
75↓ D hard bedrock including limestone fragments, sufficiently coherent.

Rudice – plot No. 4 (Stand group No. 155A8)

Soil unit: Dystric Luvisol dyLV
Pedogenetical characterization: pedogenesis directly associated with the base saturation of particular horizons reaching 9.6% in Ah, 20% in Eh, 34.5% in El and 44.1% in EB brought about the mixed substrate with siliceous flintstone deposits
Site description: flat part of a vast, indistinctive ground wave
Soil profile description:
0–1 Oi mixed litter of Norway spruce, Scotch pine, European larch, blueberry and graminoids,
1–2 Oe unremarkable debris of decomposed plant material, abrupt boundary towards the lower Oa horizon, platy,
2–5 Oa prominent humified layer, gradual and diffuse boundary towards the A horizon,
5–8 Ah 10YR 3/1, sandy clay loam, loamy-skeletal, organic matter intimately mixed with the mineral fraction, friable,
8–22 Eh 2.5YR 8/2, sandy loam, sandy-skeletal, gradual colour boundaries, very friable, nonsticky, low degree of moisture,
22–35 El 2.5YR 8/4, sandy, light, loose, crumbly, holding together,
35–45 EB 2.5YR 6/6 sandy loam, loamy-skeletal, little affected by the pedogenetic process of illimerization, purely mineral layer, very brittle,
45↓ Bt 5YR 6/8 silty clay, argillans, clayey-skeletal, weakly cemented, hard stick slightly with pressure.

RESULTS

The results of the field dynamic penetration test are presented in Figs. 1–3, the results of laboratory testing of bulk density and wet bulk density are shown in Figs. 4–6. As regards the evaluation of the obtained data, it must be said that the dynamic penetration test measurements are derived from the angle of a decrease in the individual curves of penetration into the soil profile (individual curves have the shape of steeply broken curves that descend downwards at an angle). The angle of their descent graphically demonstrates the presence of

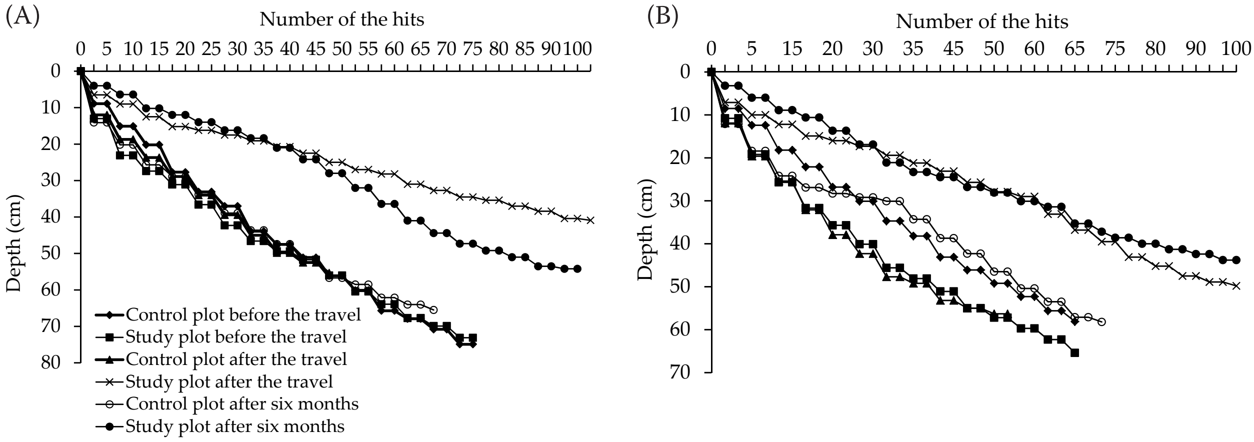

Fig. 1. Penetration curves on study plot No. 2, Babice nad Svitavou, Zetor 7245 universal wheeled tractor, three sets of measurements – (A) the first set and (B) the second set of measurement

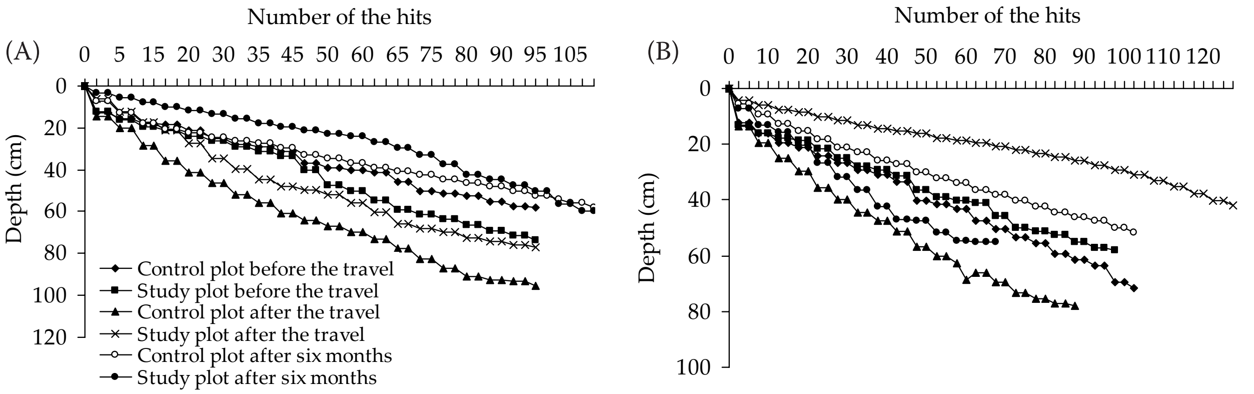

Fig. 2. Penetration curves on study plot No. 3, Rudice, PONSSE ERGO harvester and GREMO 950 forwarder, three sets of measurements – (A) the first set and (B) the second set of measurement

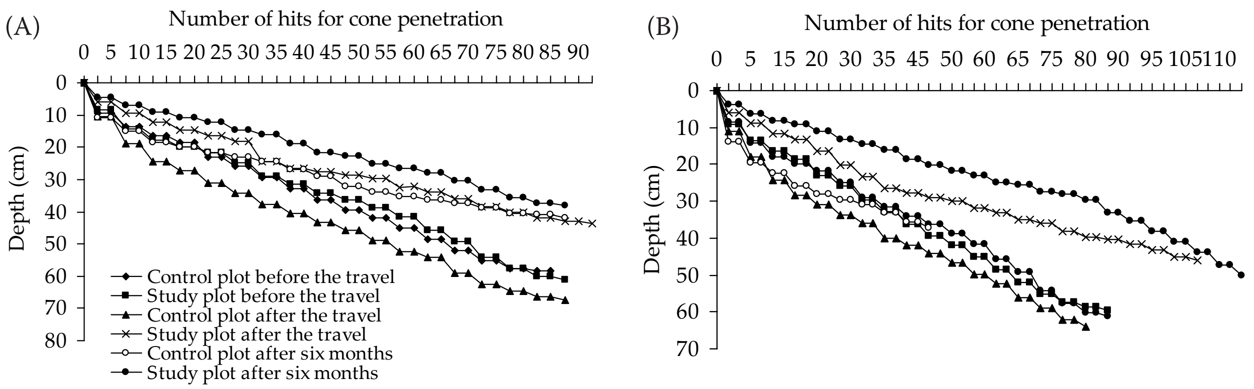

Fig. 3. Penetration curves on study plot No. 4, Rudice, Zetor 7245 universal wheeled tractor, three sets of measurements – (A) the first set and (B) the second set of measurement

compaction: the more compact the upper horizon/set of upper horizons, the more flat the resulting curve (smaller depth of cone penetration per number of strokes) and vice versa: the looser or easier disintegrating is the studied profile, the steeper is the descent of the resulting curve (greater depth of cone penetration per number of strokes). This way of interpretation with plotting the results into the final graphs provides accurate information on the stiffness vs. softness of soil at any depth of the examined horizon. The value measured in the track of the hauling machine is compared with the corresponding value from the control measurement without the impact of machinery.

Besides the naturally variable soil compaction on geologically different substrates, the obtained orig-

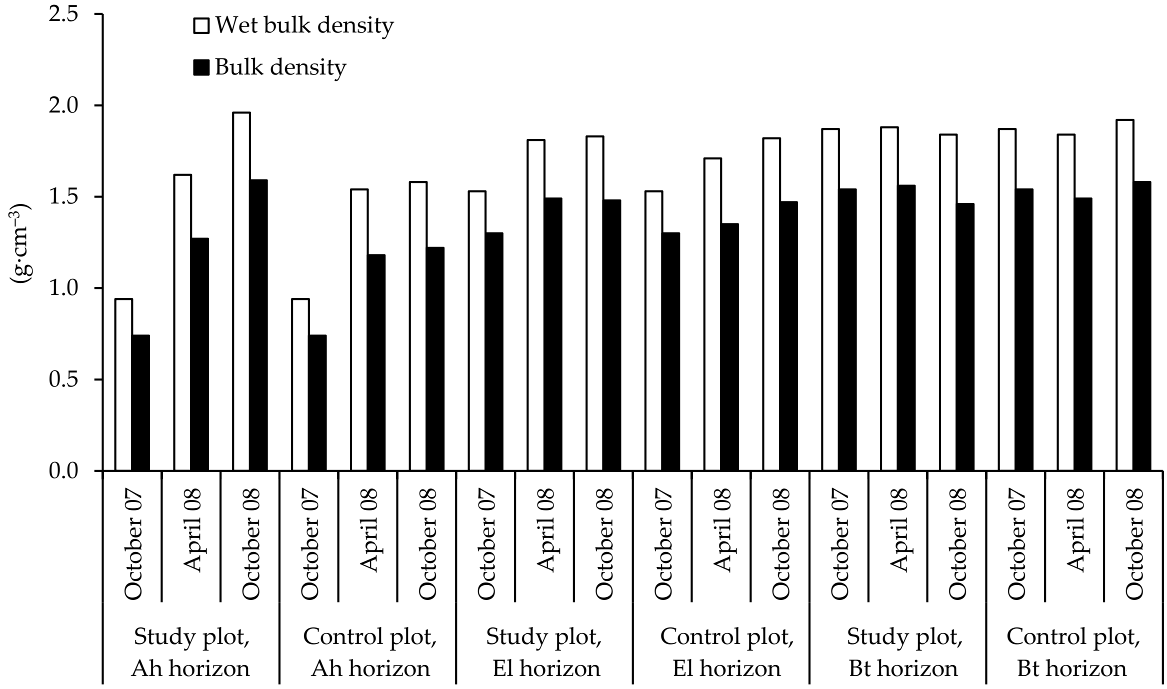

Fig. 4. Wet bulk density and bulk density for the particular soil horizons of study plot No. 2 and the control plot, Babice nad Svitavou, UWT

inal results document differences in the impact of particular forestry machines. From the presented results it is evident that the universal wheeled tractor had a more negative influence on the compaction of surface soil horizons compared to the multi-axle harvester and the forwarder in the conditions of identical geological substrate (study plots No. 3 and 4).

DISCUSSION

Exact evaluation of the impact of hauling technology on physical, hydrophysical and soil-mechanical properties has not been well-founded by any internationally recognized methodology so far. A nationally used reference methodology is for example the German methodology by Matthies et al. (1995)

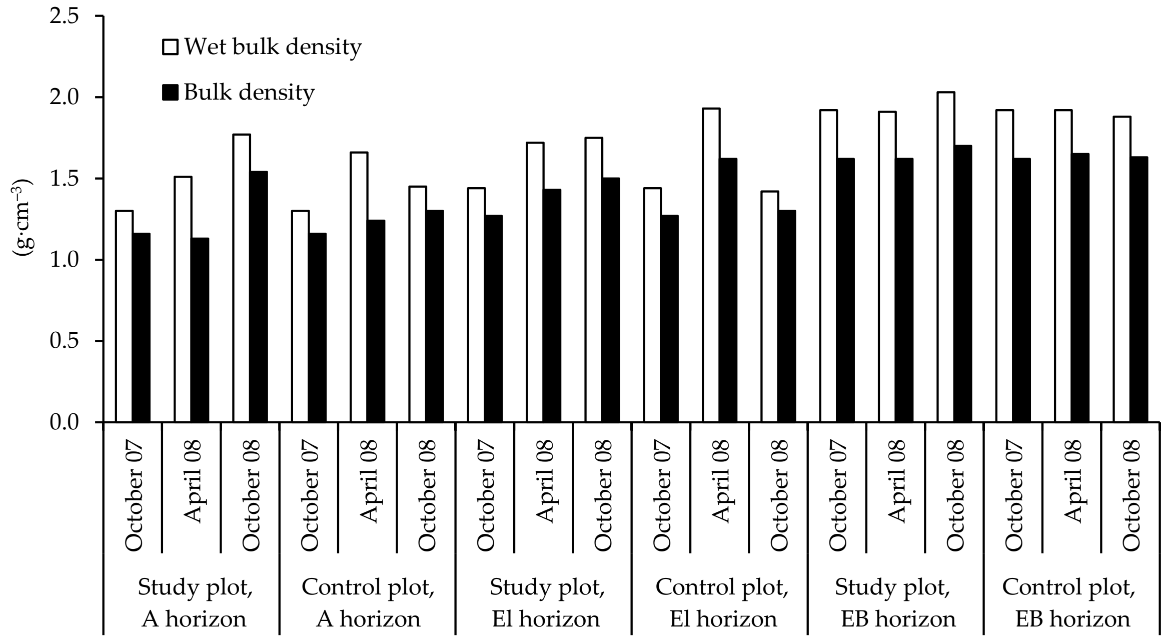

Fig. 5. Wet bulk density and bulk density for the particular soil horizons of study plot No. 3 and the control plot, Rudice, PONSSE ERGO harvester and GREMO 950 forwarder

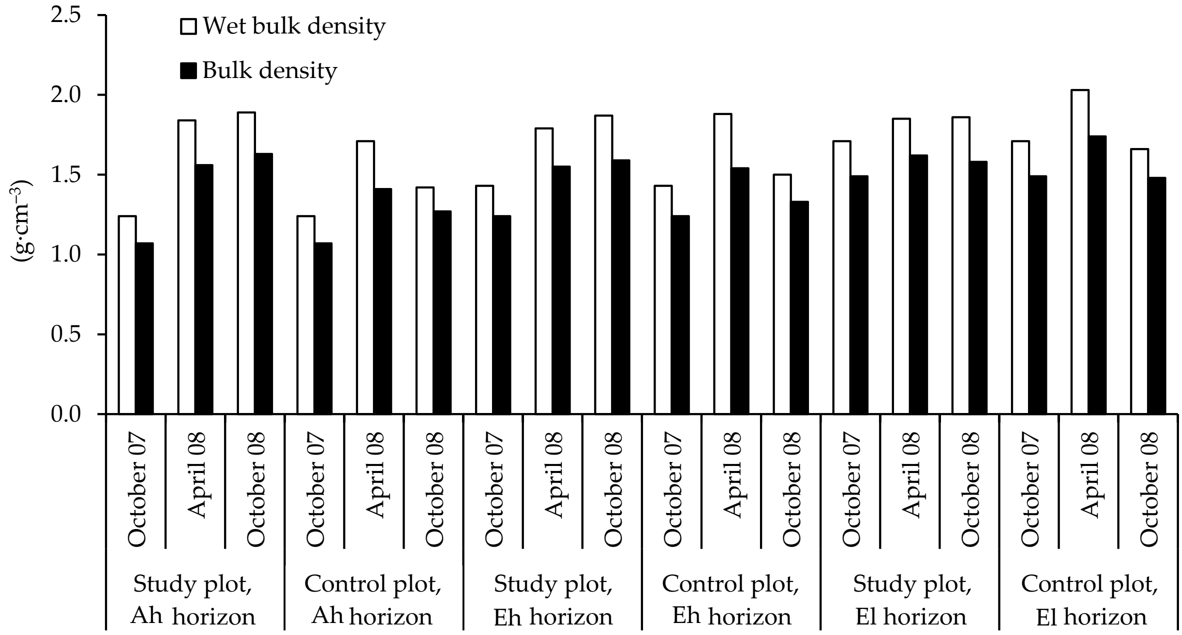

Fig. 6. Wet bulk density and bulk density for the particular soil horizons of study plot No. 4 and the control plot, Rudice, UWT

aimed at determination of the threat to forest soils according to site types in relation to their actual moisture conditions. In forestry, the terrain is basically classified as bearing or non-bearing, taking the above-mentioned pressure generated by adult man walking, or slightly higher pressure, as the limit load without negatively evaluated impact on the basic soil properties. However, significant information at this point is that forest soil damage is influenced not only by the applied pressures but also by the soil water content in the range of Atterberg limits of soil liquidity and plasticity. In connection with the impact of hauling technology on physical, hydrophysical and soil-mechanical properties it is not possible to see only the simple relations between the pressure generated by forestry mechanization traffic and soil damage, but also the fact that the machinery-generated pressures on forest soil spread to sides as well as to depth; magnitudes of these pressures decrease with distance from the place of contact between the wheel and the soil. Compaction must therefore be perceived as an accumulative process in which the pressures affecting the soil add up and as a result they cause irreversible changes.

On the basis of the present knowledge, it is possible to draw the following general conclusions for the needs of forestry practice:

(1) Specific pressure under a smaller-size tyre shows smaller spreading to sides and reaches smaller depths, i.e. it is assumed that a small tyre is loaded relatively less compared to a big one.

(2) If we compare two tyres of the same diameter but different width, the spreading of pressure to sides is smaller under the narrower tyre; however, this is true only when the soil is affected into a greater depth.

The same tyre behaves differently on different soils: the more yielding and wetter the soil, the smaller the spread of the specific pressure to sides and the greater the depth of the pressure effect.

Matys et al. (1990) considered from 20 to 60 strokes as the acceptable range of strokes per minute during the dynamic penetration test, specified by the depth. The speed of ramming is important as too high or too low speed affects the final outputs. As regards the study of compaction of the upper soil horizons in the conditions affected by forestry mechanization traffic, a systematic error of the measurements will increase with an increasing share of clay particles in the upper soil horizons in consequence of the increasing pore pressure of water, which causes a reduction of the soil shear strength, thus speeding up the cone penetration into the soil.

Regarding the methodology, the authors find it the most correct to perform the dynamic penetration test with the shortest possible technological breaks and with as constant speed of ramming as possible. Besides, when discussing the results of this method, it is necessary to consider not only the technical parameters of the penetrometer and the procedure of the test itself, but also the mineral composition of the surface horizon, bulk density of skeletal size-fraction and wet bulk density, as well as the presence of plant roots.

Dynamic penetration test is a field survey method, primarily designed for assessment of compaction in earth dams and road or railway embankments and also for determination of soil characteristics under a construction, utilizable in civil engineering. Discussion of the authors about the course of investigation in forest stands and the possibilities of evaluation of the obtained data stresses the fact that there are some natural limits of its applicability – especially due to locally thick rooting and high share of skeleton in forest soil. Regarding the original results presented in this paper, it is necessary to state that the critical depth of contact with a root or a stone was detected and the final curve was later smoothed out to correspond with the previous and the following measurement at the angle of descent; in this way, the error caused by the stone or root was partially eliminated.

Based on the performed field tests, the team of the authors sees the future of soil-mechanical properties of forest soils rather in the application of deflectometers – Klvač et al. (2010) documented the advantages of field testing with Loadman II USB deflectometer that can measure compaction on the principle of sensing the reactions of soil to a fall of a weight onto the bouncing area of the deflectometer. Kinetic energy is transmitted to soil and the built-in sensors measure the reaction of the soil. The built-in sensor – accelerometer – is placed in the upper part of the device and records the speed of the soil profile reaction and height of the weight rebound (rate of energy absorption by soil). An advantage of this equipment is that it can measure compaction practically in all soils, including Lithic Leptosols with maximum skeleton content, or very soft soils (e.g. Sapric Histosols), which is impossible with the penetrometer, as the authors know from their own experience.

CONCLUSION

With regard to the potentially newly open research in the field of interaction between soil mechanics and low-impact hauling technologies in Czech forestry, following the solved project QH71159 "Development of multicriterial evaluation of low-impact hauling technologies/Sophisticated model for environment friendly timber haulage evaluation", the authors would like to draw attention to the following facts/suggestions:

– regarding application of the results of this study in practice,
– to test the application of special forestry low-pressure tyres for the universal wheeled tractor,
– to test the impact of forestry mechanization operation at the time of winter harvesting, i.e. the influence of traffic over the frozen forest floor,
– to create a network of study plots at different soil units and define for each of them the depth of the track made by forestry mechanization traffic that signals the risk of irreversible damage to the distinctive forest soil,
– to take into account variability of terrain inclination,
– to consider the specifications of hauling technologies in stands of broadleaves vs. conifers,
– regarding the potentially newly open field surveys,
– to pay maximum attention to the selection of control plots so that they meet high criteria on comparability of soil conditions at the naturally very spatially heterogeneous forest sites,
– to test the impact of forestry mechanization operation at the time of winter harvesting, i.e. the influence of traffic over the frozen forest floor,
– to focus on assessment of changes over a longer time period with repeated measurements in shorter intervals, i.e. to evaluate the general ability of soils to cope with changes,
– to perform simultaneous measurements on several days including only detection of the immediate impact of pressures on soil, i.e. to obtain exact data on a statistically significantly provable impact of mechanization traffic (not followed by evaluation of the dynamics of the measured soil properties),
– regarding statistical conclusiveness of the results,
– to pay attention to exact mathematical characteristics of the relation between the soil horizon compression and decrease in hydraulic conductivity as well as of the percentage increase in resistance against the penetration of a cone of chosen shape into various depths of forest soil,
– to consistently observe the rule of three times of field surveys: just before the machinery operation, immediately after the operation and six months from the operation (and in this case, to pay attention to permanent fixation of the machinery traffic track),
– to choose forest stands with a longer hauling trail that would allow to perform a higher number of measurements.

In agreement with their presumption, the authors have proved that the traffic of forestry mechanization causes quantifiable compaction of soil profile. They have also demonstrated that each soil unit reacts differently to compaction – and also its return to the original state is different. Neruda (2008) reported that the remedy of damage to the soil profile caused by forestry mechanization traffic takes 10–15 years on average. The authors can neither confirm nor disprove this statement: the complex of measurements performed in 2009 only continued the limited measurements from previous years. Therefore, it would certainly be very suitable to further develop the initiated work and to continue measuring, with the objective to significantly prove, on a corresponding level of probability, tendencies of the soil to return to the original values over a longer time interval.

The authors have also documented negative changes of all the monitored properties as after a relatively short period of 6 months from the machinery traffic they have observed further changes. An important conclusion is that the values critical for vegetation growth were exceeded mainly in the subsurface horizons; however, here these properties were closer to the limits before the machinery operation.

On the basis of the performed investigations, the authors suggest that harvester technologies appear to be of lower impact from the viewpoint of their traffic. These technologies are suitable mainly thanks to the possibility of operation on low-pressure tyres or tracked wheels and higher number of axles; all of these parameters allow the more effective distribution of the weight of the handled load with subsequently lower compaction of surface soil horizons. However, in this case it still holds good that a lower influence on soil is to be expected on soils with a higher share of skeleton or soils with generally lower predisposition to compaction – especially in those periods when the moisture conditions prevent an increased impact of pressures on the soil structure.

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